Chapter 1

Introduction to Instruments and Their Representation

LEARNING OBJECTIVES

After learning this chapter, the reader should be able to

LO 1: Recognize the general importance of instrumentation systems

LO 2: List the applications of the instrument systems

LO 3: Define the functional elements of a measurement system

LO 4: Describe the functional elements of the instruments

LO 5: Classify various instruments

LO 6: Describe microprocessors based instrumentation

LO 7: Understand standards and calibrations

INTRODUCTION — LO 1

There have been significant developments in the field of instrumentation in the recent times. Presently, it encompasses the areas of detection, acquisition, control and analysis of data in almost all areas of science and technology. Even in our day-to-day life, instrumentation is indispensable. For example, an ordinary watch—an instrument for measuring time—is used by everybody. Likewise, an automobile driver needs an instrument panel to facilitate him in driving the vehicle properly. Modern-day state-of-the-art automobiles are equipped with a variety of sensors and indicators. The common automobile sensors are for knock detection, manifold pressure, coolant level and temperature, oil level and temperature, air intake temperature and flow rate, brake fluid and fuel levels, throttle position and speeds of the engine, crank shaft and wheels. In addition, these vehicles are provided with special Micro-Electro-Mechanical Systems (MEMS) to operate the safety airbags for passengers; Global Positioning System (GPS) for geographical information and on board computers/micro-processors for controlling and optimising comfort air-conditioning systems and engine operations at different loads and speeds.

Instrumentation is very vital to modern industries too. Figure 1.1 shows some typical application areas of instrumentation systems and has been discussed in detail in the following section. In fact, the use of instrumentation systems in certain areas like power plants, process industries, automatic production machines, bio-medical systems, consumer electronics, etc., have revolutionised the old concepts. Consequently, they have brought about tremendous savings in time and labour involved. Additionally, instrumentation systems act as extensions of human senses and quite often facilitate the retrieval of information from complex situations.

Nowadays 'Instrumentation' has become a distinct discipline. In fact, the use of instrumentation in a myriad of systems has proved to be extremely useful and cost effective. It invariably contributes significantly in evolving better quality control, higher plant utilization, better manpower productivity, material and energy savings alongwith speedier and accurate *data reductions*.

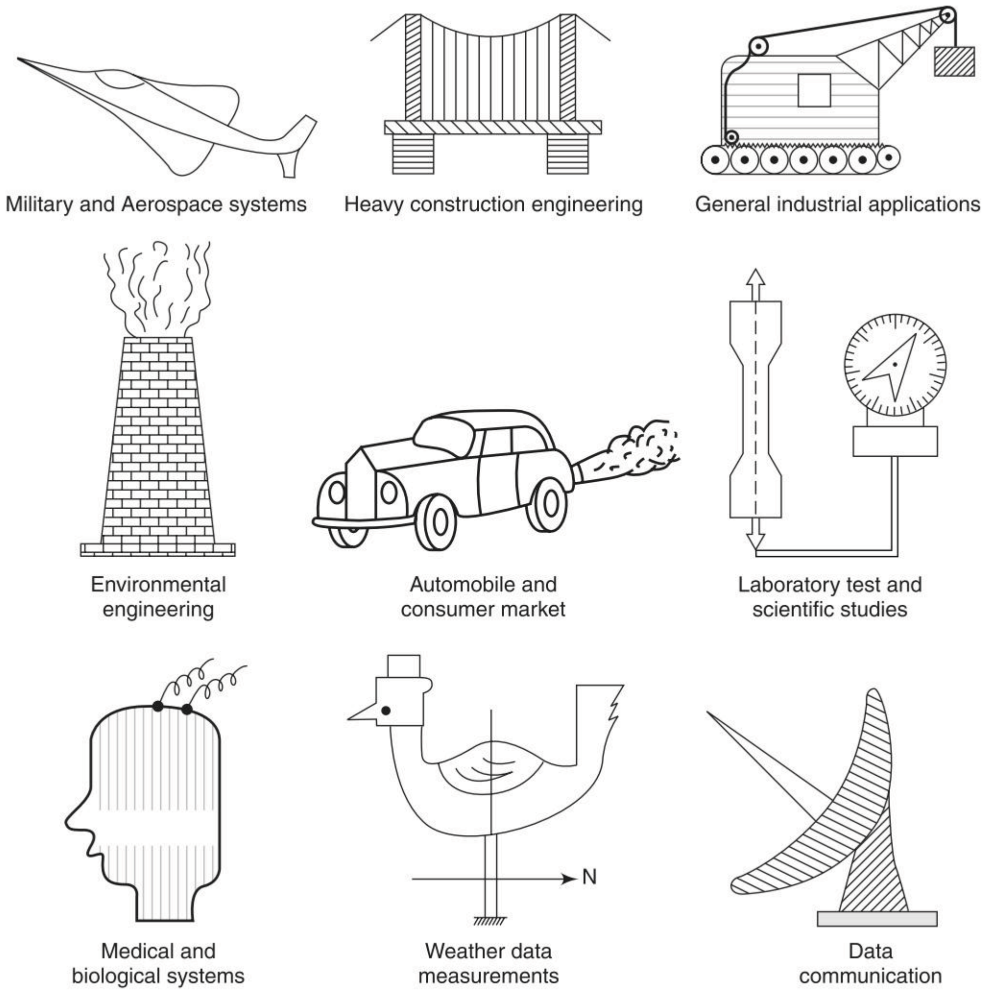

Fig. 1.1 Typical application areas of instrumentation systems

1.1 TYPICAL APPLICATIONS OF INSTRUMENT SYSTEMS LO 2

The objectives of performing experiments are too numerous to be enumerated. However, certain common motivating factors for carrying out the measurements are as follows:

Measurement of system parameters informations One of the important functions of the instruments is to determine the various parameters/informations of the system or a process. In addition, they present the desired information about the condition of the system in the form of visual indication/registering/recording/monitoring/suitable transmission according to the needs and requirements of the system. For example, a pressure gauge fitted on a steam boiler drum gives the visual indication of pressure of steam. Further, the deflection of pointer of speedometer monitors the speed of automobile at that moment. Again the potentiometric type of temperature recorder gives the printout of instantaneous values of temperatures with respect to time in the form of printout. In addition, condition-based system of operation is being used very widely these days in a number of situations like the medical care of patients or the maintenance of machines/systems where shut downs are costly/prohibitive, etc.

Control of a certain process or operation Another important application of measuring instruments is in the field of automatic control systems. The measurement system forms an integral part of such systems (Fig. 1.2) which in turn provides deliberate guidance or manipulation to maintain them at a set point or to change it according to a pre-set programme.

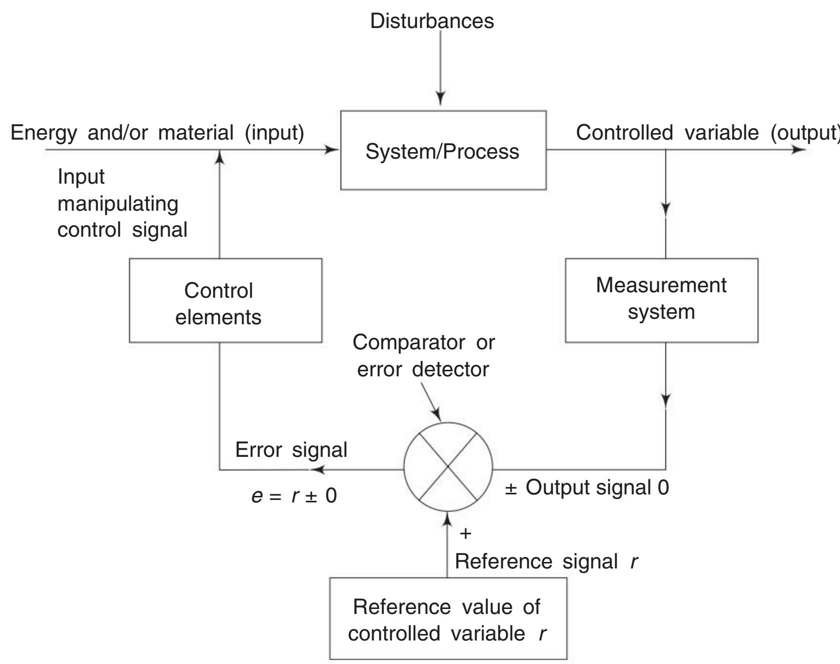

Fig. 1.2 A typical block diagram of automatic (feedback-type) control system

The very concept of any control in a system requires the measured discrepancy between the actual and the desired performance. It may be noted that for an accurate control of any physical variable in a process or an operation, it is important to have an accurate measurement system. Further, ***the accuracy of the control system cannot be better than the accuracy of measurement of the control variable***. For example, a thermostat fitted in a domestic refrigerator is a control device for maintaining the temperature in a specified range. Currently, automatic control systems are widely used in process industries like oil refineries, chemical plants, textile mills, etc. for controlling variables like temperature, pressure, humidity, viscosity, flow rate and other relevant parameters. Furthermore, they are also used in modern sophisticated systems like autopilots, automatic landing of aircraft, missile guidance, radar tracking systems, etc.

Simulation of system conditions Sometimes, it may be necessary to simulate experimentally the actual conditions of complex situations for revealing the true behaviour of the system under different governing conditions. Generally, a scale model may be employed for this purpose where the similarity of significant features between the model and the full-scale prototype are preserved. In such cases, analytical tools like dimensional analysis may also be employed to translate the experimental results on the model to the prototype. The lift, drag and other relevant parameters of aerodynamic bodies are usually obtained by testing the models in controlled air streams generated in wind tunnels that simulate the flow conditions experienced by aerodynamic bodies. The information thus obtained is used in the design and development of the prototype.

Experimental design studies The design and development of a new product generally involves trial-and-error procedures which generally involve the use of empirical relations, handbook data, the standard practices mentioned in design codes as well as design equations based on scientific theories and principles. In spite of this, we sometimes have to resort to experimental design studies to supplement design and development work. For example, a design team of experienced aircraft designers put in a number of years of effort to produce a prototype aircraft. The prototype is flown by a test pilot to determine the various performance/operating parameters. The prototype test data is then used to improve further the design calculations and a modified prototype is produced. This is carried on till the desired design performance is achieved. Thus, experimental design studies quite often play an important role in the design and development of the new products/systems.

To perform various manipulations In a number of cases, the instruments are employed to perform operations like signal addition, subtraction, multiplication, division, differentiation, integration, signal linearisation, signal sampling, signal averaging, multi-point correlations, ratio controls, etc. In certain cases, instruments are also used to determine the solution of complex differential equations or other mathematical manipulations. A simple pocket calculator is an example of a mathematical processing instrument, to some extent. Further, the modern large-memory computers are instruments that are capable of varied types of mathematical manipulations.

Testing of materials, maintenance of standards and specifications of products Most countries have standards organisations that specify material standards and product specifications based on extensive tests and measurements. These organisations are meant to protect the interests of consumers. They ensure that the material/products meet the specified requirements so that they function properly and enhance the reliability of the system. For example, an aircraft engine is subjected to extensive endurance tests by the civil aviation authorities as per their specifications, before it is certified to be airworthy.

Verification of physical phenomena/scientific theories Quite often experimental data is generated to verify a certain physical phenomenon. Coulomb postulated that the friction between two dry surfaces is proportional to the normal reaction and is independent of the area of contact. His hypothesis has since been verified experimentally and is now known as Coulomb's law of dry friction. In fact, such examples are numerous. Whenever a scientist or an engineer proposes any hypothesis predicting the system's behaviour, it needs to be checked experimentally to put the same on a sound footing.

In addition, experimental studies play an important role in formulating certain empirical relations where adequate theory does not exist. For example, a number of empirical relations for the friction factor of turbulent flow in pipes (where theoretical basis is inadequate) have been formulated till date by various investigators based on their hypotheses in which numerical constants have been evaluated from experimental data.

Furthermore, experimental studies may be motivated by the hope of developing new theories, discovering new phenomena or checking the validity of a certain hypothesis which may have been developed using some simplifying assumptions.

Quality control in industry It is quite common these days to have continuous quality control tests of mass produced industrial products. This enables to discover defective components that are outright rejected at early stages of production. Consequently, the final assembly of the machine/system is free from defects. This improves the reliability of the product considerably. For example, a boiler plate has to undergo a number of quality control tests before it is put in actual operation. The various tests are:

X-ray examination of the plate for defects like blow holes, cracks, etc.; metallographic examination for metallurgical defects; periodic strength tests of the samples, etc.

1.2 FUNCTIONAL ELEMENTS OF A MEASUREMENT SYSTEM LO 3

A generalised 'Measurement System' consists of the following:

1. Basic Functional Elements, and
2. Auxiliary Functional Elements.

Basic Functional Elements are those that form the integral parts of all instruments. These are shown in Fig. 1.3 using *thick lines*. They are the following:

1. *Transducer Element* that senses and converts the desired input to a more convenient and practicable form to be handled by the measurement system.
2. *Signal Conditioning or Intermediate Modifying Element* for manipulating/processing the output of the transducer in a suitable form.
3. *Data Presentation Element* for giving the information about the measurand or measured variable in the quantitative form.

Auxiliary Functional Elements are those which may be incorporated in a particular system depending on the type of requirement, the nature of measurement technique, etc. They are:

1. *Calibration Element* to provide a built-in calibration facility.
2. *External Power Element* to provide electronically regulated power supply for the working of one or more of the elements like the transducer element, the signal conditioning element, the data processing element or the feedback element.
3. *Feedback Element* to control the variation of the physical quantity that is being measured. In addition, feedback element is provided in the null-seeking potentiometric or Wheatstone bridge devices to make them automatic or self-balancing.
4. *Microprocessor Element* to facilitate the manipulation of data for the purpose of simplifying or accelerating the data interpretation. It is always used in conjunction with analog-to-digital converter which is incorporated in the signal conditioning element.

1.2.1 Some Examples of Identification of Functional Elements in Instruments

Bourdon tube pressure gauge A Bourdon tube pressure gauge is shown in Fig. 1.4(a) along with a block diagram (Fig. 1.4(b)) showing its functional elements. The pressure applied to the hollow oval-shaped bent tube, known as the Bourdon tube, deforms the cross-section of the tube as well as causes a relative motion, proportional to the applied pressure, of the free end of the tube with respect to its fixed end. Thus, this tube acts as a transducer element as it converts the desired input, i.e. pressure into a displacement x at its free end. This displacement is amplified by the combined lever and the gearing arrangement which may be referred to as the signal conditioning elements. Finally, the movement of the pointer attached to the gear on a scale gives an indication of the pressure and thus the pointer and the scale constitute the data presentation elements of the Bourdon tube pressure gauge.

Bourdon pressure gauge with electrical read-out The use of the linear variable differential transducer (LVDT) for sensing the movement of the tip of the Bourdon tube shown in Fig. 1.5(a) improves the performance of the pressure measuring device. The main advantage is that the output of the instrument is electrical and is quite convenient for suitable signal conditioning operations. Further, to achieve other desirable features like linearity, rapidity of response and a small volume displacement, a very stiff and short Bourdon tube is used. The block diagram of this instrument is shown in Fig. 1.5(b). The first block

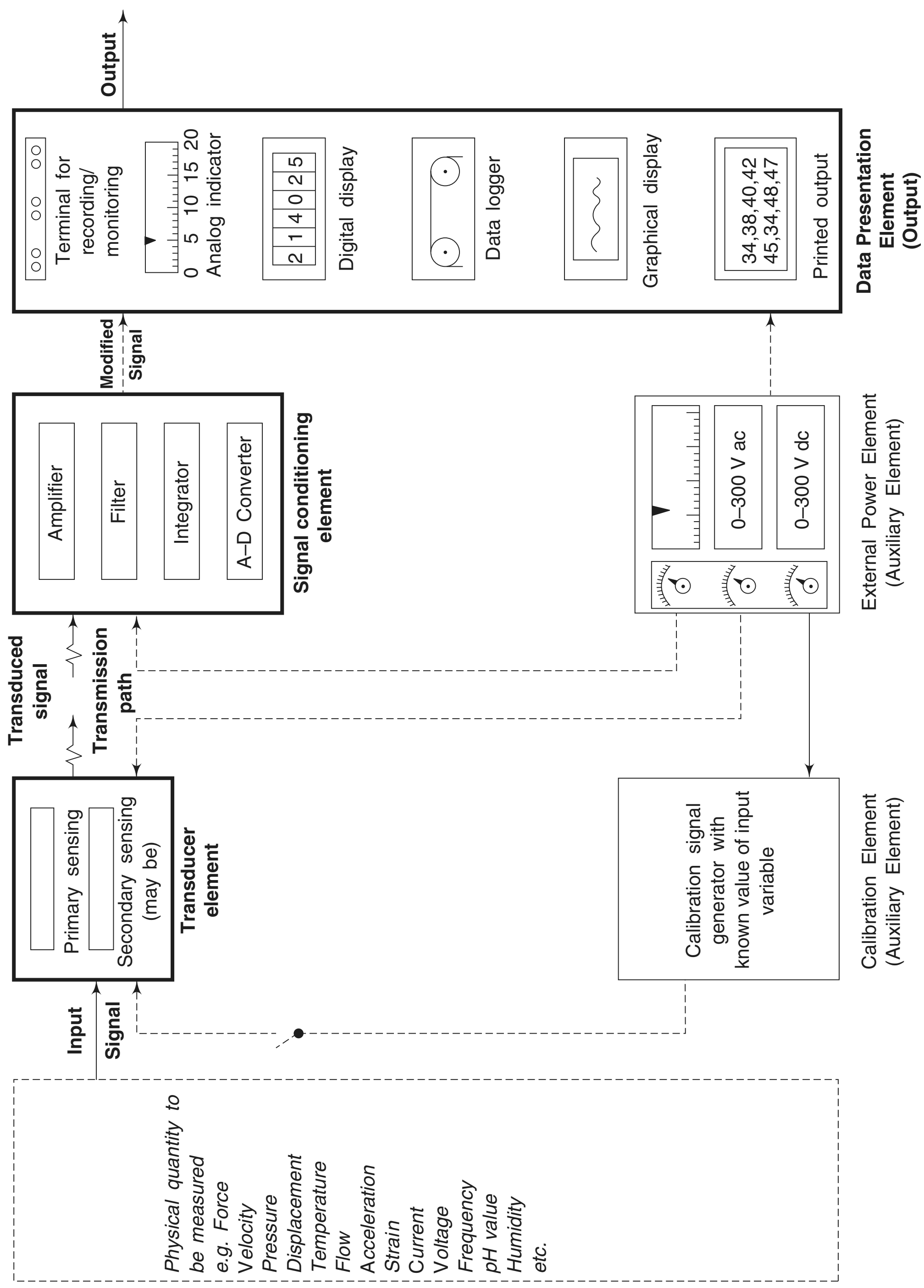

Fig. 1.3 Basic and auxiliary functional elements of a measurement system

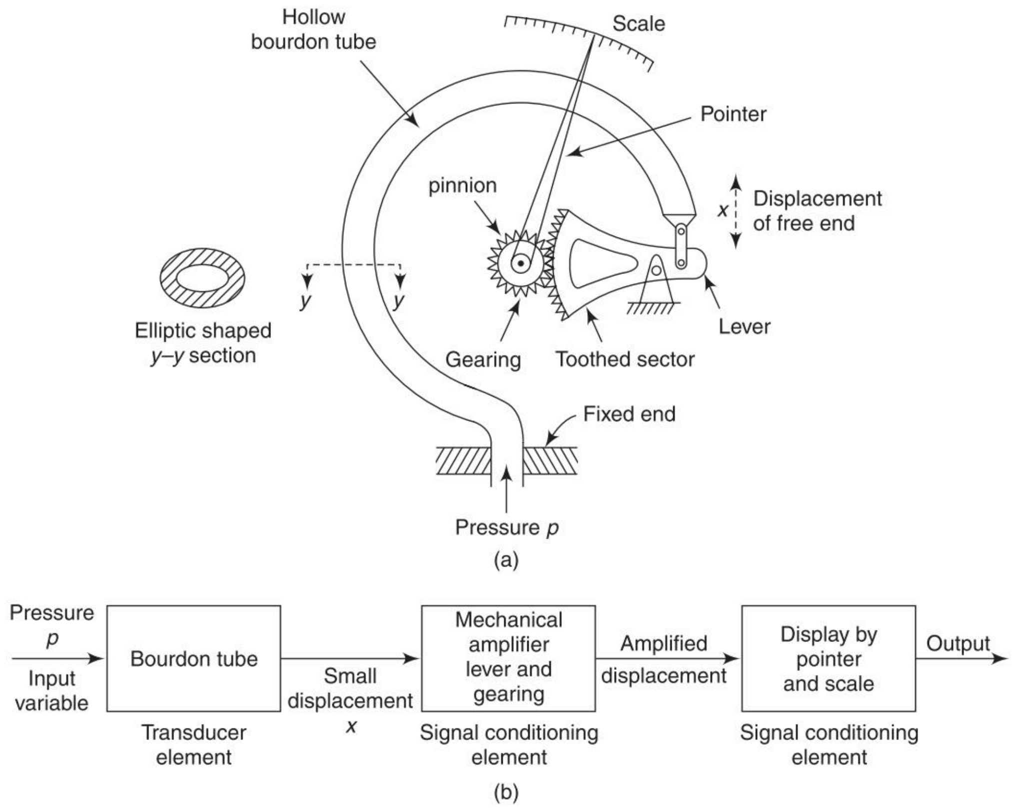

Fig. 1.4 (a) Schematic diagram of Bourdon tube pressure gauge (b) Functional elements of the Bourdon tube pressure gauge

shown in the figure is of the transducer elements. This is because the transduced voltage signal due to the applied pressure is produced by the combined effect of two transducer elements, viz. by the Bourdon tube and the LVDT that may be termed primary and secondary transducer elements, respectively. The output of the transducer elements is processed by the signal conditioning element involving the amplification of the signal and also the filtration of spurious signals present in the transducer signal. Finally, the pressure is indicated in terms of a reading on a suitable analog or digital voltmeter, depending on the form in which the output is desired.

Electrodynamic displacement measuring device For the measurement of linear displacement, a device incorporating the electrodynamic principle is shown in Fig. 1.6(a) along with its block diagram in Fig. 1.6(b). In this device, for measuring the displacement x, a coil wound on a hollow cylinder of non-magnetic material is attached to the moving object. The movement of the coil with respect to a fixed magnet induces a voltage proportional to the rate of change of magnetic flux which in turn is proportional to the velocity of the coil. Thus, the coil and the magnet constitute the transducer element as they produce a voltage signal V_1, proportional to the instantaneous velocity of the object during the course of displacement x of the object. In the signal conditioning element, the transducer signal is suitably amplified and then integrated so that the voltage V_2 is proportional to the displacement. Finally, the output voltage V_2 is indicated on a cathode ray oscilloscope (CRO) which forms the data presentation element of the instrument.

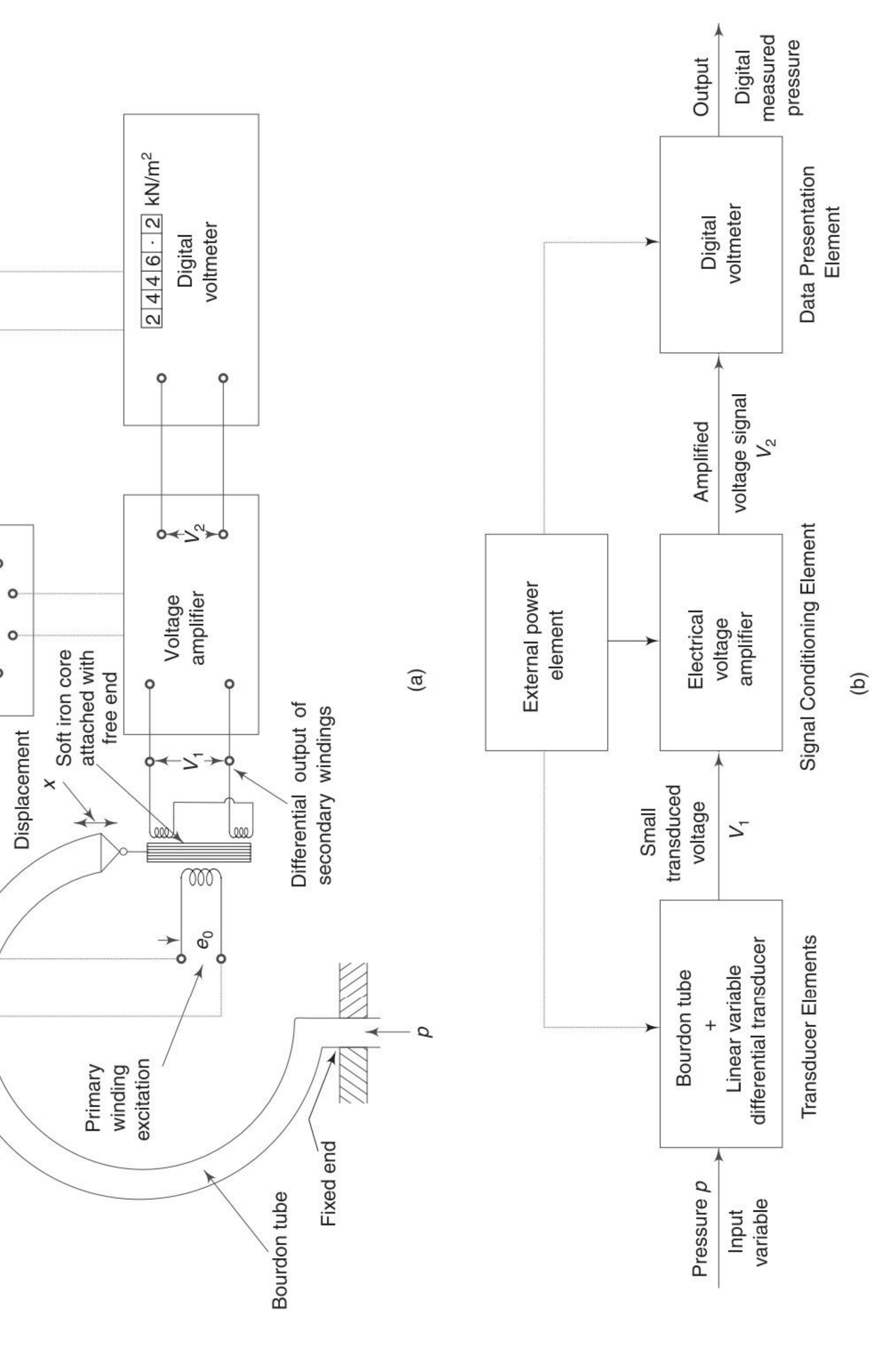

Fig. 1.5 (a) Schematic diagram of Bourdon tube pressure gauge with digital read out (b) Functional elements of the digital read out pressure gauge

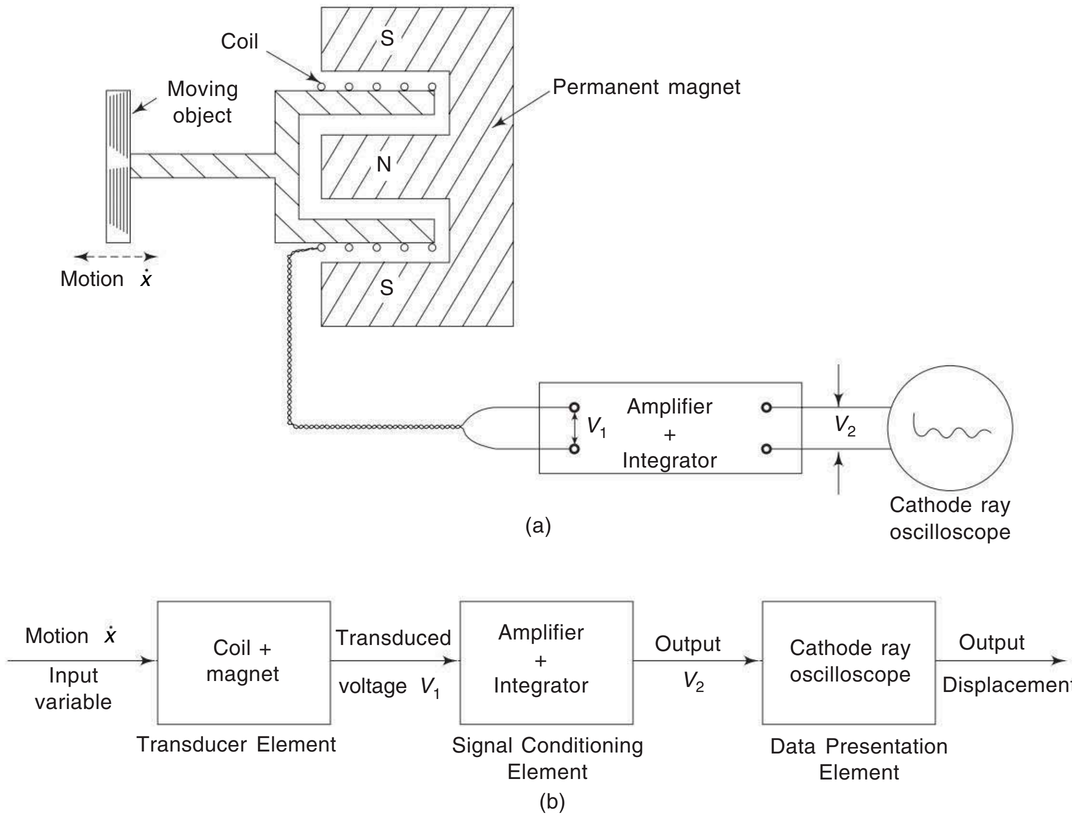

Fig. 1.6 (a) Schematic diagram of Electrodynamic type of displacement measuring instrument (b) Functional elements of the Electrodynamic type of displacement measuring instrument

D'Arsonval Type of Galvanometer For the measurement of either dc voltage V or current I, a permanent magnet moving coil (PMMC) type of galvanometer is shown in Fig. 1.7(a). Herein, the input current I (or current proportional to voltage V) flows in the coil suspended in the magnetic field causes a tangential force on the axial conductors of the coil. This generates a torque T proportional to the input current I. This torque is balanced by means of twin spiral springs, namely, the upper and lower spiral springs. This results in the output θ of the pointer, attached to the shaft, which gives the output indication q_o on the circular scale.

D'Arsonal electromagnetic movement can be conveniently represented in the form of a block diagram shown in Fig. 1.7(b) showing its various functional elements.

- The transducer element converts the input current I in amperes (A) into a torque T (in N.m) with a transfer function K_T in the form of (N.m)/A.
- The signal conditioning element converts the torque T (in N.m) into an angular displacement θ with transfer function K_S in the form of θ/(N.m).
- The data-presentation element converts the angular displacement θ into scale deflection q_0 (in mm) with transfer function K_D in the form of θ/mm.

* For detailed discussion of D'Arsonval galvanometer, refer Ch. 22.

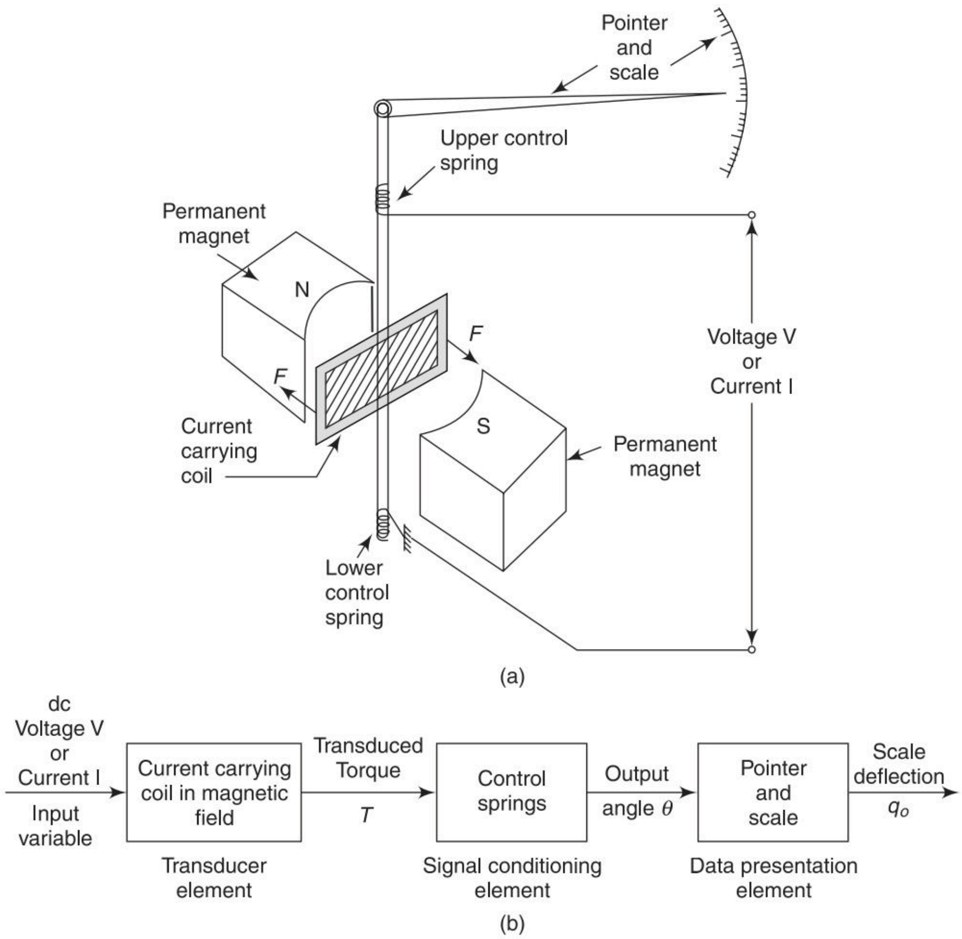

Fig. 1.7 (a) Schematic diagram of a Permanent Magnet Moving Coil (PMMC) galvanometer (b) Functional elements of the PMMC galvanometer

The transfer functions K_T, K_S and K_D can be expressed as follows:

$$\text{Input current } I\ (\text{A}) \times K_T = \text{Torque } T(\text{N.m}) \tag{1.1}$$

$$\text{Torque } (\text{N}\cdot\text{m}) \times K_S = \text{Angle } \theta \tag{1.2}$$

and

$$\text{Angle } \theta \times K_D = \text{scale deflection } q_o \text{ (mm)} \tag{1.3}$$

From the above equations, we get,

$$\text{Input current } (I) \times (K_T) \times (K_S) \times (K_D) = \text{Scale deflection } q_o \tag{1.4}$$

$$\text{Alternatively, } \frac{dq_o}{dI} = (K_T) \times (K_S) \times (K_D) \text{ mm/A} \tag{1.5}$$

It may be noted that the transfer functions K_T, K_S and K_D are generally constants for steady–state conditions. These values are generally referred as sensitivities or gain or amplifications of the respective functional elements. Further, the overall sensitivity or transfer function of any instrument can be represented as

$$[K]_{\text{overall}} \text{ of the instrument} = (K_T) \times (K_S) \times (K_D) \tag{1.6}$$

Problem 1.1 An elastic type of pressure-measuring instrument is of diaphragm type. The central deflection of the diaphragm was found to be 0.25 mm of an applied pressure of 10^6 Pa. The output displacement of diaphragm has been fed to an LVDT (linear variable differential transducer) with a built-in amplifier having a sensitivity of 40 V/mm. Finally, the output is displayed on an analog voltmeter which has a radius of scale line as 60 mm and has a voltage range from zero to 10 volts in an arc of 150°. Determine the sensitivity of the given diaphragm gauge in terms of mm/bar (1 bar = 10^5 Pa).

Solution The block diagram of the pressure-measuring instrument is shown in Fig. 1.8.

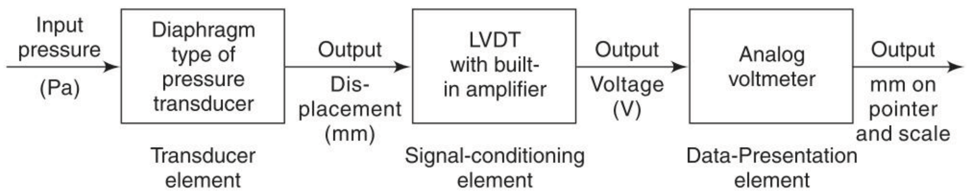

Fig. 1.8 Block diagram of diaphragm type of electro-mechanical pressure gauge.

Since the central deflection of the diaphragm gauge is 0.25 mm for an applied pressure of 10^6 Pa; therefore, the sensitivity of the transducer element K_T becomes:

$$K_T = \frac{0.25}{10^6} = 2.5 \times 10^{-7} \text{ mm/Pa.}$$

Further, the output of the transducer is modified by the LVDT system with a built-in amplifier, and the sensitivity K_S of the signal–conditioning system is given as

$$K_S = 40 \text{ V/mm.}$$

Finally the output of the signal–conditioning element is fed to the data presentation element, i.e., an analog voltmeter whose sensitivity K_D can be evaluated is as follows:

$$K_D = \frac{\text{movement of the pointer in mm on the scale}}{\text{voltage range of the voltmeter}}$$

$$= \frac{\left(60 \times 150° \times \frac{2\pi \text{ rad}}{360°}\right)}{10} \text{ mm/V} = 15.7 \text{ mm/V}$$

Using Eq. 1.6, the overall sensitivity of the diaphragm pressure gauge becomes

$$(K)_{\text{overall}} \text{ of diaphragm pressure gauge} = (K_T) \times (K_S) \times (K_D)$$

$$= (2.5 \times 10^{-7}) \times (40) \times (15.7) \text{ mm/Pa}$$

$$= 15.7 \times 10^{-5} \text{ mm/Pa}$$

$$= \frac{15.7}{(10^5 \text{ Pa})} = 15.7 \text{ mm/bar}$$

1.3 BRIEF DESCRIPTION OF THE FUNCTIONAL ELEMENTS OF THE INSTRUMENTS — LO 4

The roles of the various functional elements of the instrument have been explained earlier. The *integrated effect* of all the functional elements results in a useful measurement system. To facilitate mass production, easy maintenance and repairs, the current practice is to have modular type of instruments in which the various functional elements are fabricated in the form of modules or as a combination of certain sub-modules. The brief descriptions of the various functional elements are as follows:

1.3.1 Transducer Element

Normally, a transducer senses the desired input in one physical form and converts it to an output in another physical form. For example, the input variable to the transducer could be pressure, acceleration or temperature and the output of the transducer may be displacement, voltage or resistance change depending on the type of transducer element. Sometimes the dimensional units of the input and output signals may be same. In such cases, the functional element is termed a *transformer*. Some typical examples of transducer elements commonly used in practice are mentioned in Table 1.1.

Table 1.1 ***Typical examples of transducer elements***

S. No.	*Input variable to transducer*	*Output variable of transducer*	*Principle of operation*	*Type of device*
(1)	*(2)*	*(3)*	*(4)*	*(5)*
1.	Temperature	Voltage	An emf is generated across the junctions of two dissimilar metals or semiconductors when that junction is heated	Thermocouple
2.	Temperature	Displacement	There is a thermal expansion in volume when the temperature of liquids or liquid metals is raised and this expansion can be shown as displacement of the liquid in the capillary	Liquid in Glass Thermometer
3.	Temperature	Resistance change	Resistance of pure metal wire with positive temperature coefficient varies with temperature	Resistance Thermometer
4.	Temperature	Resistance change	Resistance of certain metal oxides with negative temperature varies exponentially with temperature	Thermistor
5.	Temperature	Pressure	The pressure of a gas or vapour varies with the change in temperature	Pressure Thermometer
6.	Displacement	Inductance change	The differential voltage of the two secondary windings varies linearly with the displacement of the magnetic core	Linear Variable Differential Transducer (LVDT)
7.	Displacement	Resistance change	Positioning of a slider varies the resistance in a potentiometer or a bridge circuit	Potentiometric Device
8.	Motion	Voltage	Relative motion of a coil with respect to a magnetic field generates a voltage	Electrodynamic Generator
9.	Flow rate	Pressure	Differential pressure is generated between the main pipeline and throat of the Venturimeter/Orificemeter	Venturimeter/Orifice-meter

(*Contd.*)

(*Contd.*)

(1)	*(2)*	*(3)*	*(4)*	*(5)*
10.	Flow velocity	Resistance change	Resistance of a thin wire/film is varied by convective cooling in stream of gas/liquid flows	Hot Wire Anemometer (gas flows). Hot Film Anemometer (liquid flows)
11.	Pressure	Movement of a liquid column	The impressed pressure is balanced by the pressure generated by a column of liquid	Manometer
12.	Pressure	Displacement	The application of pressure causes displacement in elastic elements	Bourdon Gauge
13.	Vacuum pressure	Resistance change	Resistance of a heating element varies with the corresponding change in thermal conductivity	Pirani Gauge
14.	Force	Displacement	The application of force against a spring changes its length in proportion to the applied force	Spring Balance
15.	Force/torque	Resistance change	The resistance of metallic wire or semiconductor element is changed by elongation or compression due to externally applied stress	Resistance Strain Gauge
16.	Force	Voltage	An emf is generated when external force is applied on certain crystalline materials such as quartz	Piezo-electric Device
17.	Liquid level/thick-ness	Capacitance change	Variation of the capacitance due to the changes in effective dielectric constant	Dielectric gauge
18.	Speech/music/noise	Capacitance change	Sound pressure varies the capacitance between a fixed plate and a movable diaphragm	Condenser Microphone
19.	Light intensity	Voltage	A voltage is generated in a semi-conductor junction when radiant energy stimulates the photoelectric cell	Light Meter/Solar Cell
20.	Light intensity	Resistance change	Resistance of certain semiconductors, which are light dependant resistors, varies with the intensity of light.	Photoconductive cell
21.	Light radiations	Current	Secondary electron emission due to incident radiations on the photo-sensitive cathode causes an electronic current	Photomultiplier tube
22.	Humidity	Resistance change	Resistance of a conductive strip changes with the moisture content	Resistance Hygrometer
23.	Blood flow/any other gas or liquid or two-phase flow	Frequency shift	The difference in the frequency of the incident and reflected beams of ultrasound known as Doppler's frequency shift is proportional to the flow velocity of the fluid	Doppler Frequency Shift Ultrasonic Flow Meter
24.	Magnetic flux/ current	Hall effect voltage change	Hall effect voltage change is produced across a semiconductor plate in the di-rection perpendicular to both impressed magnetic field and applied current	Hall effect sensor

It may be noted that in certain cases, the transduction of the input signal may take place in two stages or even in the three or more stages namely, primary transduction, secondary transduction, tertiary transduction, etc. For example, in Fig. 1.5(a), the Bourdon tube acts as a primary transducer as it converts the pressure into displacement. The LVDT attached to the free end of the Bourdon tube is the secondary transducer as it converts displacement into electrical voltage. This way the combined effect of primary and secondary transducers coverts the pressure signal into a corresponding voltage signal.

Desirable characteristics of a transducer element: The following points should be borne in mind while selecting a transducer for a particular application:

1. The transducer element should recognise and sense the desired input signal and should be insensitive to other signals present simultaneously in the measurand. For example, a velocity transducer should sense the instantaneous velocity and should be insensitive to the local pressure or temperature.
2. It should not *alter* the event to be measured.
3. The output should preferably be *electrical* to obtain the advantages of modern computing and display devices.
4. It should have good *accuracy*, i.e. it should sense the measurand up to the desirable least count value.
5. It should have good *reproducibility* (i.e. precision).
6. It should have *amplitude* linearity.
7. It should have adequate *frequency response* (i.e., good dynamic response).
8. It should not induce phase distortions (i.e. should not induce time lag between the input and output transducer signals).
9. It should be able to withstand hostile environments without damage and should maintain the accuracy within acceptable limits.
10. It should have high signal level and low impedance.
11. It should be easily available, reasonably priced and compact in shape and size (preferably portable).
12. It should have good reliability and ruggedness. In other words, if a transducer gets dropped by chance, it should still be operative.
13. Leads of the transducer should be sturdy and not be easily pulled off.
14. The rating of the transducer should be sufficient and it should not break down. In other words, it should sense the measurand in the desired measuring range and its overload capacity should preferably be nearly 300% of the maximum measured value, to ensure safety of the instrument in case of accidental overloading.

1.3.2 Signal Conditioning Element

The output of the transducer element is usually too small to operate an indicator or a recorder. Therefore, it is suitably processed and modified in the signal conditioning element so as to obtain the output in the desired form.

The transducer signal may be fed to the signal conditioning element by means of either mechanical linkages (levers, gears, etc.), electrical cables, fluid transmission through liquids or through pneumatic transmission using air. For remote transmission purposes, special devices like radio links or telemetry systems may be employed.

The signal conditioning operations that are carried out on the transduced information may be one or more of the following:

Amplification The term amplification means increasing the amplitude of the signal without affecting its waveform. The reverse phenomenon is termed *attenuation,* i.e. reduction of the signal amplitude while retaining its original waveform. In general, the output of the transducer needs to be amplified in order to operate an indicator or a recorder. Therefore, a suitable amplifying element is incorporated in the signal conditioning element which may be one of the following depending on the type of transducer signal.

1. *Mechanical Amplifying Elements* such as levers, gears or a combination of the two, designed to have a multiplying effect on the input transducer signal.
2. *Hydraulic/Pneumatic Amplifying Elements* employing various types of valves or constrictions, such as venturimeter/orificemeter, to get significant variation in pressure with small variation in the input parameters.
3. *Optical Amplifying Elements* in which lenses, mirrors and combinations of lenses and mirrors or lamp and scale arrangement are employed to convert the small input displacement into an output of sizeable magnitude for a convenient display of the same.
4. *Electrical Amplifying Elements* employing transistor circuits, integrated circuits, etc. for boosting the amplitude of the transducer signal, which is generally very low. In such amplifiers we have either of the following:

$$\text{Voltage amplification} = \frac{\text{output voltage}}{\text{input voltage}} = \frac{V_o}{V_i} \tag{1.7}$$

or

$$\text{Current amplification} = \frac{\text{output current}}{\text{input current}} = \frac{I_o}{I_i} \tag{1.8}$$

or

$$\text{Gain} = \frac{\text{output power}}{\text{input power}} = \frac{V_o I_o}{V_i I_i} \tag{1.9}$$

Signal filtration The term signal filtration means the removal of unwanted noise signals that tend to obscure the transducer signal. The signal filtration element could be any of the following depending on the type of situation, nature of signal, etc.

1. *Mechanical Filters* that consist of mechanical elements to protect the transducer element from various interfering extraneous signals. For example, the reference junction of a thermocouple is kept in a thermos flask containing ice. This protects the system from the ambient temperature changes.
2. *Pneumatic Filters* consisting of a small orifice or venturi to filter out fluctuations in a pressure signal.
3. *Electrical Filters* are employed to get rid of stray pick-ups due to electrical and magnetic fields. They may be simple *R–C* circuits or any other suitable electrical filters compatible with the transduced signal.

Other signal conditioning operators Other signal conditioning operators that can be conveniently employed for electrical signals are

1. Signal Compensation/Signal Linearisation/Zero Setting/Scale Adjustments
2. Differentiation/Integration.
3. Analog-to-Digital Conversion.
4. Signal Averaging/Signal Sampling, etc.
5. Signal Modulation/Signal Demodulation for transmission and receiving of weak signals.

1.3.3 Data Presentation Element

This element gathers the output of the signal conditioning element and presents the same to be read or seen by the experimenter. This element should

1. have as fast a response as possible,
2. impose as little drag on the system as possible, and
3. have very small inertia, friction, stiction, etc. (hence using light rays and electron beams is advantageous).

This element may be either of the visual display type, graphic recording type or a magnetic tape. In the visual display type element, devices such as pointer and scale/panel meter, multi-channel CRO, storage CRO, etc. may be employed. The graphic recording type of element gives a permanent record of the input data. The device in this element may be pen recorders using heated stylus, ink recorders on paper charts, optical recording systems such as mirror galvanometer recorders or ultraviolet recorders on special photosensitive paper. Further, a magnetic tape may be used to acquire input data which could be reproduced at a later date for analysis.

In case the output of the signal conditioning element is in digital form, then the same may be displayed visually on a digital display device. Alternatively, it may be suitably recorded either on punched cards, perforated paper tape, magnetic type, typewritten page or a combination of these systems for further processing.

1.4 CLASSIFICATION OF INSTRUMENTS LO 5

Instruments may be classified according to their application, mode of operation, manner of energy conversion, nature of output signal and so on. All these classifications usually result in overlapping areas. However, the instruments commonly used in practice may be broadly categorised as follows:

1.4.1 Deflection and Null Types

A deflection type instrument is that in which the physical effect generated by the measuring quantity produces an equivalent opposing effect in some part of the instrument which in turn is closely related to some variable like mechanical displacement or deflection in the instrument. For example, the unknown weight of an object can be easily obtained by the deflection of a spring caused by it on the spring balance as shown in Fig. 1.9. Similarly, in a common Bourdon gauge, the pressure to be measured acts on the C-type spring of the gauge, which deflects and produces an internal spring force to counter balance the force generated by the applied pressure. The deflection of the spring is however magnified by an electrical device like LVDT (Fig. 1.5(a)) or by using suitable lever and gear mechanisms (Fig. 1.4(a)) to be read off from the scale of the instrument.

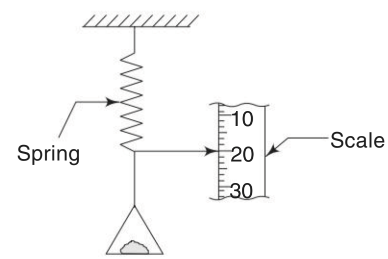

Fig. 1.9 A typical spring balance—A deflection type weight measuring instrument

Deflection instruments are simple in construction and operation. In addition, they generally have a good dynamic response. However, the main disadvantage of these instruments are that they interfere with the state of the measured quantity and a small error termed as loading error may be introduced due to this in the measurements.

A null type instrument is the one that is provided with either a manually operated or automatic balancing device that generates an equivalent opposing effect to nullify the physical effect caused by the quantity to be measured. The equivalent null-causing effect in turn provides the measure of the quantity. Consider a simple situation of measuring the mass of an object by means of an equal-arm beam balance shown in Fig. 1.10. An unknown mass, when placed in the pan, causes the beam and pointer to deflect. Masses of known values are placed on the other pan till a balanced or null condition is obtained by means of the pointer. The main advantage of the null-type devices is that they do not interfere with the state of the measured quantity and thus measurements of such instruments are extremely accurate. However, these devices, especially those of the manual type, are quite slow in operation and consequently their dynamic response is quite poor. But, their speed and dynamic response can be improved considerably by using certain feedback type of automatic balancing devices such as instrument servo-mechanisms. Nowadays the instruments of this type are of great importance.

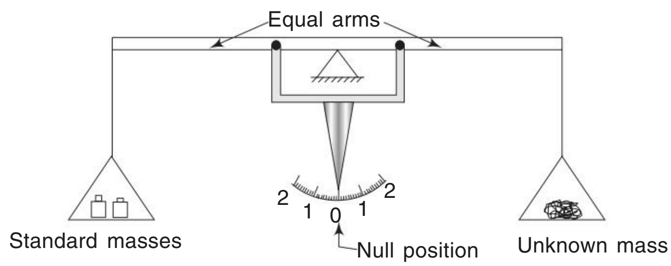

Fig. 1.10 A schematic diagram of an Equal arm beam balance

1.4.2 Manually Operated and Automatic Types

Any instrument which requires the services of human operator is a manual type of instrument. The instrument becomes automatic if the manual operation is replaced by an auxiliary device incorporated in the instrument. An automatic instrument is usually preferred because the dynamic response of such an instrument is fast and also its operational cost is considerably lower than that of the corresponding manually operated instrument. A commonly used null-bridge resistance thermometer is shown in Fig. 1.11 which requires manual operation for obtaining the null position. However, the manual operation can be dispensed with by incorporating an automatic self-balancing feedback device known as *instrument servo-mechanism.*

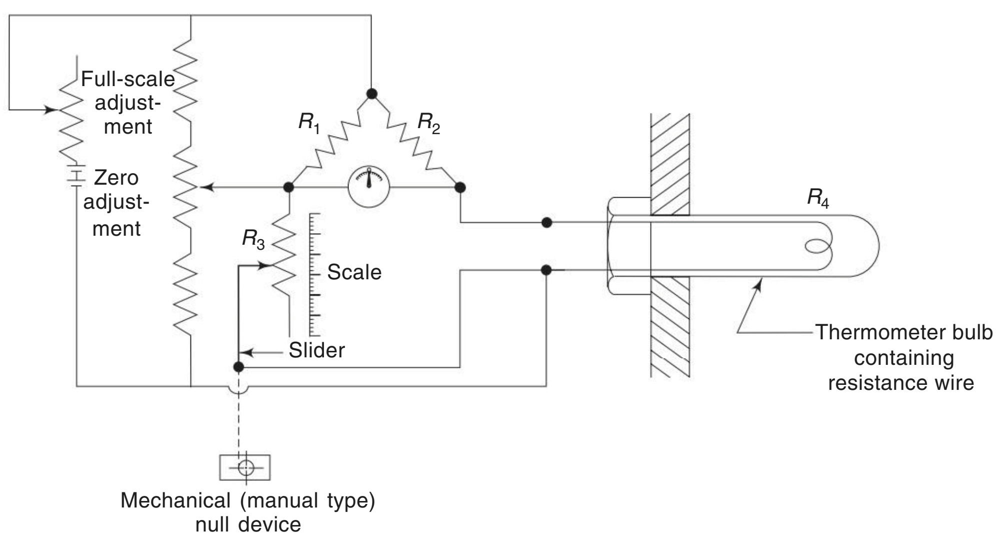

Fig. 1.11 Manual type null-bridge resistance thermometer

The block diagram of the automatic self-balancing feedback measuring system is shown in Fig. 1.12. In this device, the amplified output of the error detector actuates the control element (a reversible servo-motor) which in turn causes the movement of an inverse transducer (generally a displacement transducer), the output of which is fed to the error detector after suitable signal condition-

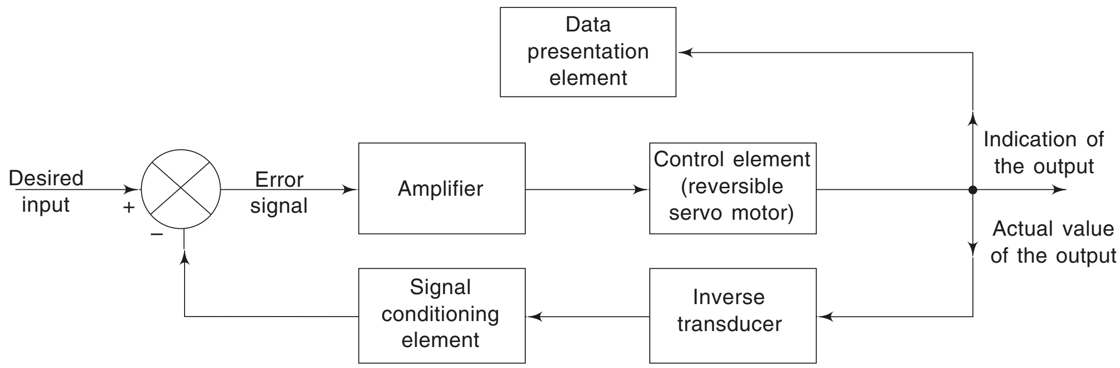

Fig. 1.12 A typical block diagram of feedback type measurement system

ing. This way, the feedback loop performs *tracking* of the desired input automatically (i.e. without any human operator) till the error signal vanishes. Further, the device is designed to indicate the value of the desired input on the data presentation element when the error signal becomes zero. In fact, such a device is specially suitable for null-seeking potentiometric or Wheatstone bridge devices, etc.

Figure 1.13 shows a typical automatic null-bridge resistance thermometer in which a mirror type galvanometer (an error detector) is used in conjunction with a photoelectric device. The advantage of this system is that the galvanometer is not subjected to any physical load since it is used to direct light on to a photo cell. The photo cell receives the light due to reflection from the galvanometer mirror whose angular position is a measure of the unbalanced voltage in the bridge circuit. The photo cell is a part of

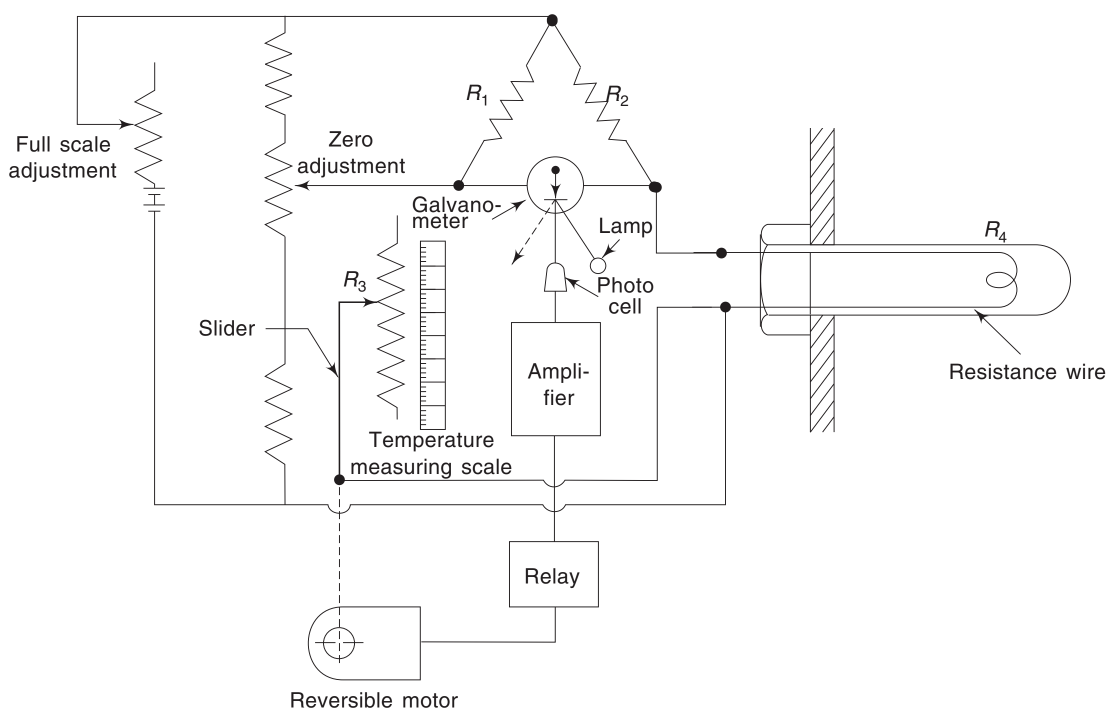

Fig. 1.13 Automatic type null-bridge resistance thermometer

the input circuit to the amplifier and its resistance controls the input voltage to the amplifier. The amplifier now drives the reversible motor (through a relay switch) which in turn causes the movement of the slider (inverse transducer), the output of which tends to bring the bridge circuit in the null position. When the null condition is reached, the motor would stop running and consequently the movement of the slider on the variable resistance element would also cease at that particular point. Thus, corresponding to this point the temperature can be read off from the calibrated scale of the instrument.

Servo-controlled or self-balancing automatic devices are widely used in industry because they do not require the constant attention of the operator. Further, they have the advantage of giving remote indication and are also suitable for continuous recording. The commonly used devices are: self-balancing recording potentiometer, hot wire anemometer, electro-magnetic flow meter, torque sensor, servo-manometer, capacitance pick-up, servo-controlled accelerometer, etc.

1.4.3 Analog and Digital Types

Analog instruments are those that present the physical variables of interest in the form of continuous or stepless variations with respect to time. These instruments usually consist of simple functional elements. Therefore, the majority of present-day instruments are of analog type as they generally cost less and are easy to maintain and repair. For example, D'Arsonval type ammeter and Bourden pressure gauge indicate the magnitude current and pressure respectively in the analog form.

On the other hand, digital instruments are those in which the physical variables are represented by digital quantities which are discrete and vary in steps. Further, each digital number is a fixed sum of equal steps which is defined by that number. The relationship of the digital outputs with respect to time gives the information about the magnitude and the nature of the input data. The main drawback of such devices is that they are unable to indicate the quantity which is a part of the step value of the instrument. For example, a digital revolution counter cannot indicate, say, 0.65 of a revolution as it measures only in steps of one revolution. However, there are number of distinct advantages of these instruments. The main advantage of the digital representations centres on the on-line use of digital computers for data processing. This has afforded vast possibilities in the areas of computer-assisted decision making, computer-aided design, computer-operated automatic control systems, etc.

Another advantage of digital signals is their noise immunity during transmission. For example, it is easier to recognise the transmitted digital pulse which may be in the form of binary 1 or binary 0 than to distinguish the analog value of voltage say 10.1 or 10.0 or 9.99 V. In other words, it is easier to detect the presence or absence of an electrical pulse (in digital mode) than to discern the precise value of the analog signal in the presence of noise induced along the transmission path.

In addition, several techniques of coding have been developed for digital signals only. Therefore, in order to take advantage of the error detection and error correction capabilities, it is necessary to convert analog data into digital form.

The analog-to-digital conversion is carried out in two steps. In the first step, the analog data is discretised by sampling the data after every time interval t_s known as sampling time. In the second step, the corresponding digital value is assigned a 4-bit binary code so that analog-to-digital conversion becomes compatible with the codes used in the digital computer. A typical analog signal sampling for corresponding digital values is shown in Fig. 1.14.

1.4.4 Self-Generating and Power-Operated Types

In self-generating (or passive) instruments, the energy requirements of the instruments are met entirely from the input signal. For example, an exposure meter of a camera, which is in effect, a photovoltaic cell (shown in Fig. 1.15) is a self-generating (passive) instrument. In this instrument, the incident light

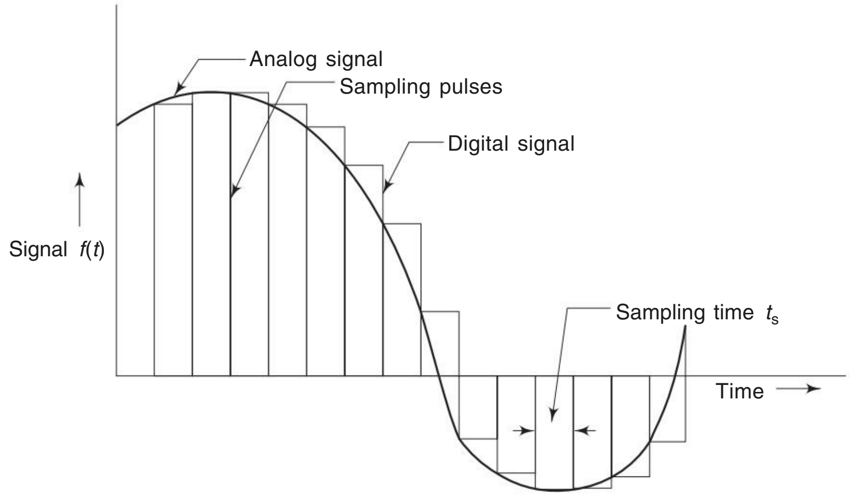

Fig. 1.14 A typical analog signal sampling for corresponding digital values

energy whose intensity is being measured, supplies the entire energy for generating the proportional amount of output voltage in the semiconductor junction. Some other common examples of such instruments are: Simple Bourdon gauge (Fig. 1.4(a)) for the measurement of pressure, mercury-in-glass thermometer for the measurement of temperature, Pitot tube for the measurement of fluid flow velocity, a tachogenerator for measurement of rpm, etc.

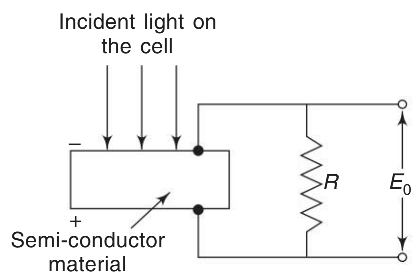

Fig. 1.15 Schematic diagram of a photovoltaic cell (self-generating type of instrument)

On the other hand, power-operated (or active) instruments are those that require some source of auxiliary power such as compressed air, electricity, hydraulic supply, etc. for their operation. In these devices, the input signal supplies only a small portion of the output power. A differential transformer (Fig. 1.5(a)) which is used in the measurement of displacement, force, pressure, etc. is an example of a power-operated instrument. This is because it needs external power to energise its primary as well as two secondary windings. In addition it needs external power in the intermediate element if the output of the differential transformer needs any signal conditioning like amplification, etc.

1.4.5 Contacting and Non-Contacting Types

A contacting type of instrument is one that is kept in the measuring medium itself. A clinical thermometer, Bourdon pressure gauge and a voltmeter in an electrical circuit are examples of such instruments.

On the other hand, there are instruments that are of non-contacting or proximity type. These instruments measure the desired input even though they are not in close contact with the measuring medium. For example, an optical pyrometer monitors the temperature of, say, a blast furnace, but is kept out of contact with the blast furnace. Similarly, a variable reluctance tachometer (Fig. 1.16), which measures the rpm of a rotating body, is also a proximity type of instrument. In this, the toothed rotor made of ferromagnetic material causes variation of flux in the magnetic circuit due to changes in air gap. This in turn induces an emf that is in the form of pulses. The output of the instrument is fed to a frequency counter from which the rpm of the rotor can be determined.

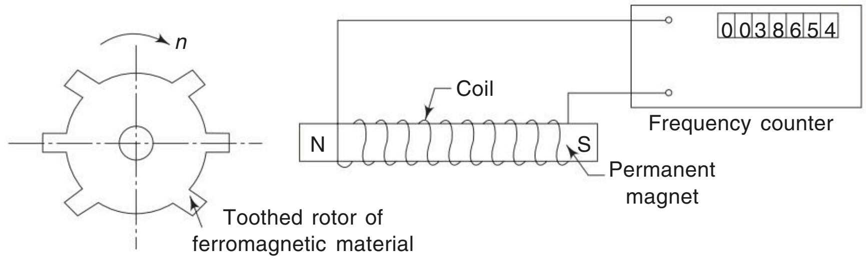

Fig. 1.16 Schematic diagram of variable reluctance tachometer (proximity type of instrument)

1.4.6 Dumb and Intelligent Types

A dumb or conventional instrument is that in which the input variable is measured and displayed, but the data is processed by the observer. For example, a Bourdon pressure gauge is termed as a dumb instrument because though it can measure and display a car tyre pressure but the observer has to judge whether the car tyre air inflation pressure is sufficient or not.

Currently, the advent of microprocessors has provided the means of incorporating Artificial Intelligence (AI) to a very large number of instruments. Intelligent or smart instruments process the data in conjunction with microprocessor (μP) or an on-line digital computer to provide assistance in noise reduction, automatic calibration, drift correction, gain adjustments, etc. In addition, they are quite often equipped with diagnostic sub-routines with suitable alarm generation in case of any type of malfunctioning.

An intelligent or smart instrument may include some or all of the following:

1. The output of the transducer in electrical form.
2. The output of the transducer should be in digital form. Otherwise it has to be converted to the digital form by means of anolog-to-digital converter (A–D converter).
3. Interface with the digital computer.
4. Software routines for noise reduction, error estimation, self-calibration, gain adjustment, etc.
5. Software routines for the output driver for suitable digital display or to provide serial ASCII coded output.

It may noted that further details of the intelligent or smart instruments are discussed in Ch. 20.

1.5 MICROPROCESSOR-BASED INSTRUMENTATION LO 6

Present-day highly competitive global economy has resulted in the production of best quality products at lowest prices. Currently, highly versatile micro processor chips designed and developed on Very Large Scale Integration (VLSI, i.e. 10^8 circuits/cm^2) have provided very convenient means of adding Artificial Intelligence (AI) into many of our every day facilities. These include automatic teller machines (ATMs) of banks, automatic washing machines, automatic fuel control systems in automobiles, burglar alarms and a large number of modern-day instruments.

In microprocessor (μp)-based instruments, μp forms one of the auxiliary functional elements of the instrument. The word microprocessor has two parts. The first part 'micro' refers to its micro-miniature size/dimensions. Further, the second part signifies its vast potential to perform complex computations at fantastically high speeds, together with pre-programmed logic/software which enhances significantly the capabilities and effectiveness of the instruments. As mentioned in the previous Sub-section 1.4.6, the μp-based instruments are commonly termed as smart or intelligent instruments. Currently, the micro-miniaturisation has resulted in offering these smart instruments of the size of a pocket calculator. Presently, a hand-held oscilloscope weighing less than 500 g can be programmed with soft-key operation to work as voltmeter, analog-to-digital converter or spectrum analyser or a PC note book. Similarly, pocket-size thermocouple sensor of digital type, portable velocity meter, micro-size pressure pick-ups are now common place and are used regularly.

Microprocessor, by itself, is an operational computer. It is incorporated with additional circuits for memory and input/output devices to shape it in the form of a digital computer. A digital computer system essentially has an *Arithmetic and Logic Unit*, control unit, Memory, Input and Output devices, which are shown in Fig. 1.17. Input devices include key board, floppy diskettes, compact Discs (CDs), manually-operated or voice-operated mouse, scanner input, A-D converters or digital transducers in case computers are used for measurement and control applications. Further, the output devices include printers plotters or Visual Display Unit (VDU), etc.

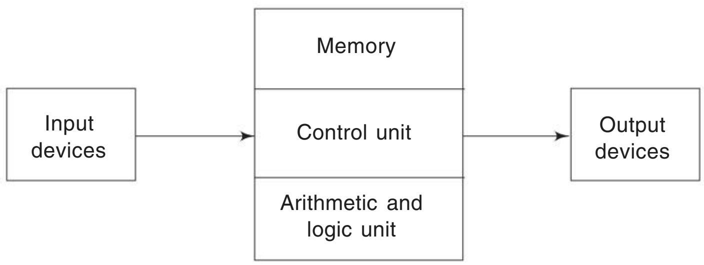

Fig. 1.17 Digital computer system

Figure 1.18 shows a typical Digital Computer-based Measurement System. A process or a plant or a system may have to simultaneously measure multiple variables like pressure, temperature, velocity, viscosity, flow rate, etc. A computer-based measurement system has the capability of processing all the inputs and present the data in real time.

A digital computer is fed with a 'sequential list of instructions' termed as a computer program for suitable processing/manipulation of the data. Quite often, Artificial Intelligence (AI) in the form of Artificial Neural Networks (ANNs) or Fuzzy Logic (FL) may be incorporated. With this, the tasks of decision-making in various processes are usually done by the computer itself and not by any human operator.

1.5.1 Advantages and Disadvantages of Computer-Based Instrumentation Systems

Advantages

1. They are suitably programmed to automatically carry out the mundane tasks of drift correction, noise reduction/elimination, non-linearity correction, gain adjustments, range and span adjustments, automatic calibration, etc.
2. These instruments have signal conditioning and display which are compact, rugged and reliable. Further, they are capable of performing in tough, industrial, consumer, military, automobile and environmental conditions.
3. Quite often they have built-in diagnostic subroutines, which can detect the fault and automatically correct the same. Alternatively, if it cannot correct the fault, it generates a suitable alarm.
4. The measurement, processing and display of the data of the process variables are done in real time i.e., it is on-line type process information in the desired form and units.
5. Such instruments can be adjusted/programmes with a remote control.
6. They have lower costs, higher accuracy and more flexibility.

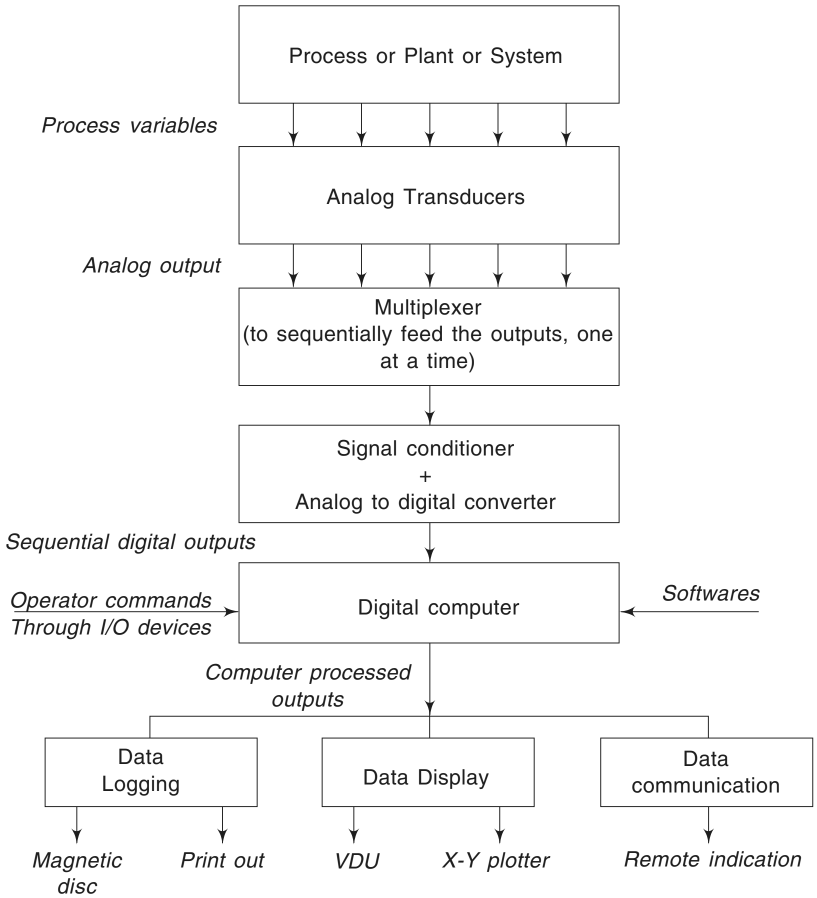

Fig. 1.18 A typical digital computer based measurement system

7. Due to the compact size, they are mostly of portable type.
8. They have a low consumption of the order of 40 mW and thus can be battery operated.
9. They do not require skilled operation because of the incorporation of user-friendly subroutines.

Disadvantages

1. They cannot replace the computer programmer/designer of the instruments, i.e., they cannot modify the programmes themselves.
2. These number crunching machines invariably need the processing data in the digital form.
3. The commercial computer softwares become obsolete very fast and periodically updating the same involves extra expenditure.
4. They are prone to virus problems and due to this, they suddenly become sick and inoperative.

1.6 STANDARDS AND CALIBRATION LO 7

Basically, measurement is an act of a quantitative comparison between a predefined standard and the unknown magnitude of a physical quantity. In order that the results are meaningful, the following two requirements must be met in the act of measurement:

1. The standard that is used for comparison must be well-established, highly accurate and reproducible; and
2. The measurement devices and the calibration procedures adopted in the act of measurement must have proven reliability.

1.6.1 Standards of Measurements

A standard of measurement is defined as the physical representation of the unit of measurement. A unit of measurement is generally chosen with reference to an arbitrary material standard or to a natural phenomenon that includes physical and atomic constants. For example, the S.I. unit of mass, namely kilogram, was originally defined as the mass of a cubic decimetre of water at its temperature of maximum density, i.e. at 4°C. The material representation of this unit is the International Prototype kilogram which is preserved at the International Bureau of Weights and Measures at Sévrés, France. Further, prior to 1960, the unit of length was the carefully preserved platinum–iridium bar at Sévrés, France. In 1960, this unit was redefined in terms of optical standards, i.e. in terms of the wavelength of the orange-red light of Kr^{86} lamp. The standard metre is now equivalent to 1 650 763.73 wavelengths of Kr^{86} orange-red light. Similarly, the original unit of time was the mean solar second which was defined as 1/86400 of a mean solar day. However, the current internationally recognised unit of universal time is based on a cesium clock. It is now defined in terms of frequency of the cesium transition to its hyperfine state unperturbed by external fields, which occurs at 9 192 631 770 Hz. The use of cesium clock gives an accuracy exceeding 1 μs per day. Therefore, it is considered as the primary time and the frequency standard. In fact, a number of standards have been developed for other units of measurements including standards for fundamental as well as dervied quantities which may include mechanical, electrical, thermal, optical, etc. parameters (Appendix A 1).

There are different types of standards of measurements. They can be classified according to their function and type of application. They are briefly described as follows:

International standards International standards are devices designed and constructed to the specifications of an international forum. They represent the units of measurements of various physical quantities to the highest possible accuracy that is attainable by the use of advanced techniques of production and measurement technology. These standards are maintained by the International Bureau of Weights and Measures at Sévrés, France. For example, the International Prototype kilogram, wavelength of Kr^{86} orange–red lamp and cesium clock are the international standards for mass, length and time, respectively. However, these standards are not available to an ordinary user for purposes of day-to-day comparisons and calibrations.

Primary standards Primary standards are devices maintained by standards organisations/national laboratories in different parts of the world. These devices represent the fundamental and derived quantities and are calibrated independently by absolute measurements. One of the main functions of maintaining primary standards is to calibrate/check and certify secondary reference standards. Like international standards, these standards also are not easily available to an ordinary user of instruments for verification/calibration of working standards.

Secondary standards Secondary standards are basic reference standards employed by industrial measurement laboratories. These are maintained by the concerned laboratory. One of the important functions of an industrial laboratory is the maintenance and periodic calibration of secondary standards against primary standards of the national standards laboratory/organisation. In addition, secondary standards are freely available to the ordinary user of instruments for checking and calibration of working standards.

Working standards These are high-accuracy devices that are commercially available and are duly checked and certified against either the primary or secondary standards. For example, the most widely used industrial working standard of length are the precision gauge blocks made of steel. These gauge blocks have two plane parallel surfaces a specified distance apart, with accuracy tolerances in the 0.25–0.5 micron range (1 micron = 10^{-6} m). Similarly, a standard cell and a standard resistor are the working standards of voltage and resistance, respectively. Working standards are very widely used for calibrating general laboratory instruments, for carrying out comparison measurements or for checking the quality (range of accuracy) of industrial products.

1.6.2 Calibration

Calibration is the act or result of quantitative comparison between a known standard and the output of the measuring system measuring the same quantity. In a way, the process of calibration is in effect the procedure for determining the scale of the measuring system. If the output-input response of the system is linear, then a single-point calibration is sufficient, wherein only a single known standard value of the input is employed. However, if the system response is non-linear, then a set of known standard inputs to the measuring system are employed for calibrating the corresponding outputs of the system. The process of calibration involves the estimation of uncertainty between the values indicated by the measuring instrument and the true value of the input. In fact, calibration procedure is the process of checking the inferior instrument against a superior instrument of known traceability certified by a reputed standards organisation/national laboratory. Herein, the term ‘traceability’ of a calibrating device refers to its certified accuracy when compared with superior standard of highest possible accuracy. Calibration procedures can be classified as follows:

Primary calibration When a device/system is calibrated against primary standards, the procedure is termed primary calibration. After primary calibration, the device is employed as a secondary calibration device. The standard resistor or standard cell available commercially are examples of primary calibration.

Secondary calibration When a secondary calibration device is used for further calibrating another device of lesser accuracy, then the procedure is termed secondary calibration. Secondary calibration devices are very widely used in general laboratory practice as well as in the industry because they are practical calibration sources. For example, standard cell may be used for calibrating a voltmeter or an ammeter with suitable circuitry.

Direct calibration with known input source Direct calibration with a known input source is in general of the same order of accuracy as primary calibration. Therefore, devices that are calibrated directly are also used as secondary calibration devices. For example, a flow meter such as a turbine flow meter may be directly calibrated by using the primary measurements such as weighing a certain amount of water in a tank and recording the time taken for this quantity of water to flow through the meter. Subsequently, this flow meter may be used for secondary calibration of other flow metering devices such as an orificemeter or a venturimeter.

Indirect calibration Indirect calibration is based on the equivalence of two different devices that can be employed for measuring a certain physical quantity. This can be illustrated by a suitable example, say a turbine flow meter. The requirement of dynamic similarity between two geometrically similar flow meters is obtained through the maintenance of equal Reynold’s number, i.e.

$$\frac{D_1 \rho_1 V_1}{\mu_1} = \frac{D_2 \rho_2 V_2}{\mu_2}$$

where the subscripts 1 and 2 refer to the ‘standard’ and the meter to be calibrated, respectively. For such a condition, the discharge coefficients of the two meters are directly comparable.