INTRODUCTION: THEORY OF MEASUREMENT

Introduction to measurements Theory:

1.1 Purpose and performance of measurement systems

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

Table 1.1 lists **information variables** which are commonly generated by processes:

Thus a car generates displacement, velocity and acceleration variables, and a chemical reactor generates temperature, pressure and composition variables.

Table 1.1 Common information/measured variables.

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

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

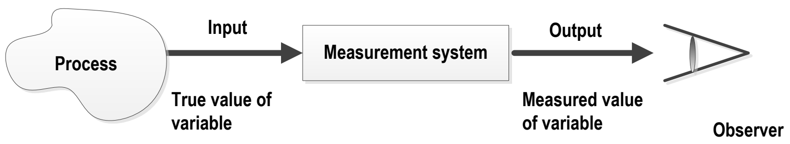


Figure 1.1 Purpose of measurement system

In an ideal measurement system, the measured value would be equal to the true value. The **accuracy** of the system can be defined as the closeness of the measured value to the true value. A perfectly accurate system is a theoretical ideal and the accuracy of a real system is quantified using **measurement system error** E, where

E = measured value − true value

E = system output − system input

Thus if the measured value of the flow rate of gas in a pipe is 11.0 m3/h and the true value is 11.2 m3/h, then the error E = −0.2 m3/h. If the measured value of the rotational speed of an engine is 3140 rpm and the true value is 3133 rpm, then E = +7 rpm. Error is the main performance indicator for a measurement system.

1.2 Structure of measurement systems

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

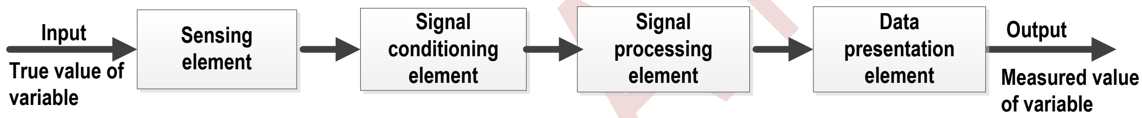


Figure 1.2 General structure of measurement system.

Sensing element

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

- Thermocouple where millivolt E.M.F. depends on temperature
- Strain gauge where resistance depends on mechanical strain
- Orifice plate where pressure drop depends on flow rate.

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

Signal conditioning element

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

- Deflection bridge which converts an impedance change into a voltage change
- Amplifier which amplifies millivolts to volts
- Oscillator which converts an impedance change into a variable frequency voltage.

Signal processing element

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

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

Typical calculations are:

- Computation of total mass of product gas from flow rate and density data
- Integration of chromatograph peaks to give the composition of a gas stream
- Correction for sensing element non-linearity.

Data presentation element

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

- Simple pointer–scale indicator
- Chart recorder
- Alphanumeric display
- Visual display unit (VDU).

1.3 Examples of measurement systems

Figure 1.3 shows some typical examples of measurement systems. Figure 1.3(a) shows a temperature system with a thermocouple sensing element; this gives a millivolt output. Signal conditioning consists of a circuit to compensate for changes in reference junction temperature, and an amplifier. The voltage signal is converted into digital form using an analogue-to-digital converter, the computer corrects for sensor non-linearity, and the measured value is displayed on a VDU.

In Figure 1.3(b) the speed of rotation of an engine is sensed by an electromagnetic tachogenerator which gives an a.c. output signal with frequency proportional to speed. The Schmitt trigger converts the sine wave into sharp-edged pulses which are then counted over a fixed time interval. The digital count is transferred to a computer which calculates frequency and speed, and the speed is presented on a digital display.

The flow system of Figure 1.3(c) has an orifice plate sensing element; this gives a differential pressure output. The differential pressure transmitter converts this into a current signal and therefore combines both sensing and signal conditioning stages. The ADC converts the current into digital form and the computer calculates the flow rate, which is obtained as a permanent record on a chart recorder. The weight system of Figure 1.3(d) has two sensing elements: the primary element is a cantilever which converts weight into strain; the strain gauge converts this into a change in electrical resistance and acts as a secondary sensor. There are two

signal conditioning elements: the deflection bridge converts the resistance change into millivolts and the amplifier converts millivolts into volts. The computer corrects for non-linearity in the cantilever and the weight is presented on a digital display.

The word '**transducer**' is commonly used in connection with measurement and instrumentation. This is a manufactured package which gives an output voltage (usually) corresponding to an input variable such as pressure or acceleration. We see therefore that such a transducer may incorporate both sensing and signal conditioning elements; for example a weight transducer would incorporate the first four elements shown in Figure 1.3(d).

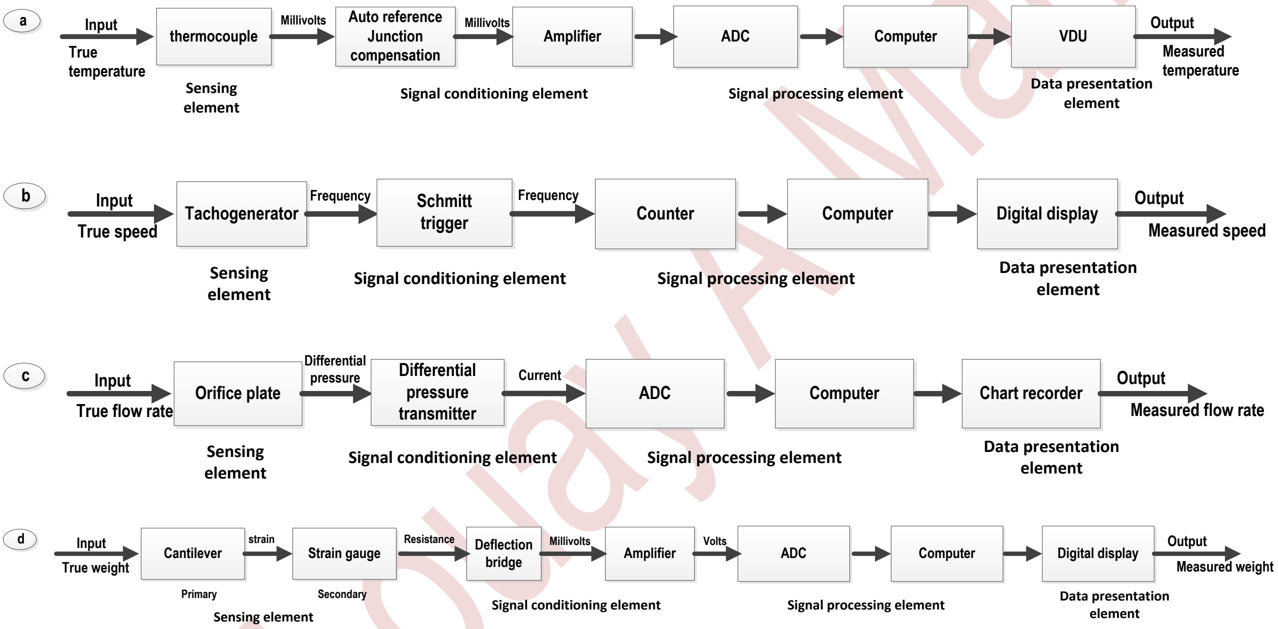


Figure 1.3 Examples of measurement systems.

Calibration:

Principles of Calibration

Calibration: consists of comparing the output of the instrument or sensor under test against the output of an instrument of known accuracy when the same input (the measured quantity) is applied to both instruments. This procedure is carried out for a range of inputs covering the whole measurement range of the instrument or sensor. Calibration ensures that the measuring accuracy of all instruments and sensors used in a measurement system is known over the whole measurement range, provided that the calibrated instruments and sensors are used in environmental conditions that are the same as those under which they were calibrated. For use of instruments and sensors under different environmental conditions, appropriate correction has to be made for the ensuing modifying inputs. Whether applied to instruments or sensors, calibration procedures are identical, and hence only the term instrument will be with the understanding that whatever is said for instruments applies equally well to single measurement sensors.

Instrument calibration has to be repeated at prescribed intervals because the characteristics of any instrument change over a period. Changes in instrument characteristics are brought about by such factors as:

Mechanical wear

The effects of dirt

Dust

Fumes

Chemicals

Temperature change in the operating environment.

Control of Calibration Environment

Any instrument used as a standard in calibration procedures must be kept solely for calibration duties and must never be used for other purposes. Most particularly, it must not be regarded as a spare instrument that can be used for process measurements if the instrument normally used for that purpose breaks down. Proper provision for process instrument failures must be made by keeping a spare set of process instruments. Standard calibration instruments must be totally separate.

To ensure that these conditions are met, the calibration function must be managed and executed in a professional manner. This will normally mean setting aside a particular place within the instrumentation department of a company where all calibration operations take place and where all instruments used for calibration are kept. As far as possible this should take the form of a separate room rather than a sectioned-off area in a room used for other purposes as well. This will enable better environmental control to be applied in the calibration area and will also offer better protection against unauthorized handling or use of calibration instruments. The level of environmental control required during calibration should be considered carefully with

due regard to what level of accuracy is required in the calibration procedure, but should not be over specified, as this will lead to unnecessary expense. Full air conditioning is not normally required for calibration at this level, as it is very expensive, but sensible precautions should be taken to guard the area from extremes of heat or cold; also, good standards of cleanliness should be maintained.

While it is desirable that all calibration functions are performed in this carefully controlled environment, it is not always practical to achieve this. Sometimes, it is not convenient or possible to remove instruments from a process plant, and in these cases, it is standard practice to calibrate them in situ. In these circumstances, appropriate corrections must be made for the deviation in the calibration environmental conditions away from those specified. This practice does not obviate the need to protect calibration instruments and maintain them in constant conditions in a calibration laboratory at all times other than when they are involved in such calibration duties on plant.

As far as management of calibration procedures is concerned, it is important that the performance of all calibration operations is assigned as the clear responsibility of just one person. That person should have total control over the calibration function and be able to limit access to the calibration laboratory to designated, approved personnel only. Only by giving this appointed person total control over the calibration function can the function be expected to operate efficiently and effectively. Lack of such definite management can only lead to unintentional neglect of the calibration system, resulting in the use of equipment in an out-of-date state of calibration and subsequent loss of traceability to reference standards.

Professional management is essential so that the customer can be assured that an efficient calibration system is in operation and that the accuracy of measurements is guaranteed.

Calibration procedures that relate in any way to measurements used for quality control functions are controlled by the international standard ISO 9000 (this subsumes the old British quality standard BS 5750). One of the clauses in ISO 9000 requires that all persons using calibration equipment be adequately trained. The manager in charge of the calibration function is clearly responsible for ensuring that this condition is met. Training must be adequate and targeted at the particular needs of the calibration systems involved. People must understand what they need to know and especially why they must have this information. Successful completion of training courses should be marked by the award of qualification certificates. These attest to the proficiency of personnel involved in calibration duties and are a convenient way of demonstrating that the ISO 9000 training requirement has been satisfied.

Calibration Chain and Traceability

The calibration facilities provided within the instrumentation department of a company provide the first link in the calibration chain. Instruments used for calibration at this level are known as ***working standards***. As such, working standard instruments are kept by the instrumentation department of a company solely for calibration duties, and for no other purpose, and then it can be assumed that they will maintain their accuracy over a

reasonable period of time because use-related deterioration in accuracy is largely eliminated. However, over the longer term, the characteristics of even such standard instruments will drift, mainly due to aging effects in components within them. Therefore, over this longer term, a program must be instituted for calibrating working standard instruments at appropriate intervals of time against instruments of yet higher accuracy. The instrument used for calibrating working standard instruments is known as a ***secondary reference standard***. This must obviously be a very well-engineered instrument that gives high accuracy and is stabilized against drift in its performance with time. This implies that it will be an expensive instrument to buy. It also requires that the environmental conditions in which it is used be controlled carefully in respect of ambient temperature, humidity, and so on.

When the working standard instrument has been calibrated by an **authorized standards laboratory**, a calibration certificate will be issued. This will contain at least the following information:

- identification of the equipment calibrated
- calibration results obtained
- measurement uncertainty
- any use limitations on the equipment calibrated
- date of calibration
- authority under which the certificate is issued

The establishment of a company standards laboratory to provide a calibration facility of the required quality is economically viable only in the case of very large companies where large numbers of instruments need to be calibrated across several factories. In the case of small to medium size companies, the cost of buying and maintaining such equipment is not justified.

Instead, they would normally use the calibration service provided by various companies that specialize in offering a standards laboratory. What these specialist calibration companies do effectively is to share out the high cost of providing this highly accurate but infrequently used calibration service over a large number of companies. Such standards laboratories are closely monitored by national standards organizations.

National standards organizations usually monitor both instrument calibration and mechanical testing laboratories. The national standards organizations lay down strict conditions that a standards laboratory has to meet before it is approved. These conditions control laboratory management, environment, equipment, and documentation. The person appointed as head of the laboratory must be suitably qualified, and independence of operation of the laboratory must be guaranteed. The management structure must be such that any pressure to rush or skip calibration procedures for production reasons can be resisted. As far as the laboratory environment is concerned, proper temperature and humidity control must be provided, and high standards of cleanliness and housekeeping must be maintained. All equipment used for calibration purposes must be maintained to reference standards and supported by calibration certificates that establish this traceability.

Finally, full documentation must be maintained. This should describe all calibration procedures, maintain an index system for recalibration of equipment, and include a full inventory of apparatus and traceability schedules. Having met these conditions, a standards laboratory becomes an accredited laboratory for providing calibration services and issuing calibration certificates. This accreditation is reviewed at approximately 12 monthly intervals to ensure that the laboratory is continuing to satisfy the conditions for approval laid down.

Primary reference standards, describe the highest level of accuracy achievable in the measurement of any particular physical quantity. All items of equipment used in standards laboratories as secondary reference standards have to be calibrated themselves against primary reference standards at appropriate intervals of time. This procedure is acknowledged by the issue of a calibration certificate in the standard way.

National standards organizations maintain suitable facilities for this calibration. In the United States, this is the National Bureau of Standards, and in the United Kingdom it is the National Physical Laboratory. Similar national standards organizations exist in many other countries. In certain cases, such primary reference standards can be located outside national standards organizations. For instance, the primary reference standard for dimension measurement is defined by the wavelength of the orange-red line of krypton light, and it can therefore be realized in any laboratory equipped with an interferometer. In certain cases (e.g., the measurement of viscosity), such primary reference standards are not available and reference standards for calibration are achieved by collaboration between several national standards organizations who perform measurements on identical samples under controlled conditions [ISO 5725 (1994) and ISO 5725-2/Cor1 (2002)].

Example of micrometers typical calibration chain:

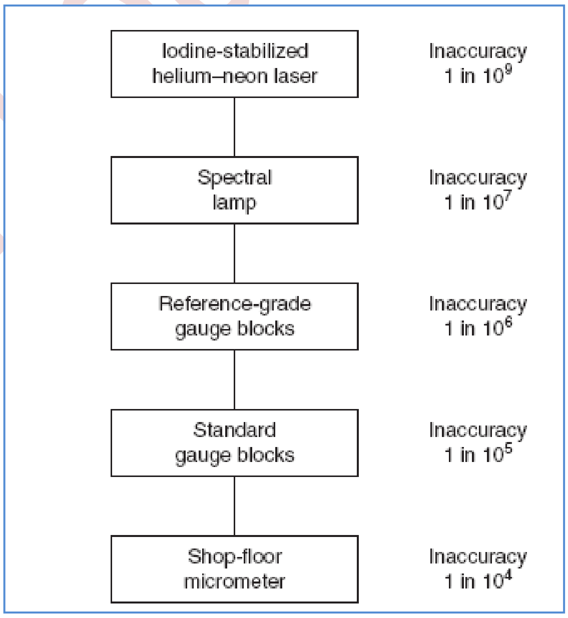


Figure 1.4 Typical calibration chain for micrometers.

To illustrate a typical calibration chain, consider the calibration of micrometers (Figure 1.4). A typical shop floor micrometer has an uncertainty (inaccuracy) of less than 1 in 10^4. These would normally be calibrated in the instrumentation department or standards laboratory of a company against laboratory standard gauge blocks with a typical uncertainty of less than 1 in 10^5. A specialist calibration service company would provide facilities for calibrating these laboratory standard gauge blocks against reference-grade gauge blocks with a typical uncertainty of less than 1 in 10^6. More accurate calibration equipment still is provided by national standards organizations. The National Bureau of Standards and National Physical Laboratory maintain two sets of standards for this type of calibration, a working standard and a primary standard. Spectral lamps are used to provide a working reference standard with an uncertainty of less than 1 in 10^7. The primary standard is provided by an iodine-stabilized helium–neon laser that has a specified uncertainty of less than 1 in 10^9. All of the links in this calibration chain must be shown in any documentation that describes the use of micrometers in making quality-related measurements.

Calibration Records

An essential element in the maintenance of measurement systems and the operation of calibration procedures is the provision of full documentation. This must give a full description of the measurement requirements throughout the workplace, instruments used, and calibration system and procedures operated. Individual calibration records for each instrument must be included within this.

This documentation is a necessary part of the quality manual, although it may exist physically as a separate volume if this is more convenient. An overriding constraint on the style in which the documentation is presented is that it should be simple and easy to read. This is often facilitated greatly by a copious use of appendices.

The starting point in the documentation must be a statement of what measurement limits have been defined for each measurement system documented. Such limits are established by balancing the costs of improved accuracy against customer requirements, and also with regard to what overall quality level has been specified in the quality manual. The technical procedures required for this, which involve assessing the type and magnitude of relevant measurement errors.

Instruments specified for each measurement situation must be listed next. This list must be accompanied by full instructions about the proper use of the instruments concerned. These instructions will include details about any environmental control or other special precautions that must be taken to ensure that the instruments provide measurements of sufficient accuracy to meet the measurement limits defined. The proper training courses appropriate to plant personnel who will use the instruments must be specified.

Having disposed of the question about what instruments are used, documentation must go on to cover the subject of calibration. Full calibration is not applied to every measuring instrument used in a workplace because ISO 9000 acknowledges that formal calibration procedures are not necessary for some equipment

where it is uneconomic or technically unnecessary because the accuracy of the measurement involved has an insignificant effect on the overall quality target for a product. However, any equipment excluded from calibration procedures in this manner must be specified as such in the documentation. Identification of equipment that is in this category is a matter of informed judgment.

For instruments that are the subject of formal calibration, documentation must specify what standard instruments are to be used for the purpose and define a formal procedure of calibration. This procedure must include instructions for the storage and handling of standard calibration instruments and specify the required environmental conditions under which calibration is to be performed. Where a calibration procedure for a particular instrument uses published standard practices, it is sufficient to include reference to that standard procedure in the documentation rather than to reproduce the whole procedure. Whatever calibration system is established, a formal review procedure must be defined in the documentation that ensures its continued effectiveness at regular intervals. The results of each review must also be documented in a formal way.

A standard format for the recording of calibration results should be defined in the documentation. A separate record must be kept for every instrument present in the workplace, irrespective of whether the instrument is normally in use or is just kept as a spare. A form similar to that shown in Figure 4.3 should be used that includes details of the instrument's description, required calibration frequency, date of each calibration, and calibration results on each occasion. Where appropriate, documentation must also define the manner in which calibration results are to be recorded on the instruments themselves.

Documentation must specify procedures that are to be followed if an instrument is found to be outside the calibration limits. This may involve adjustment, redrawing its scale, or withdrawing an instrument, depending on the nature of the discrepancy and the type of instrument involved. Instruments withdrawn will either be repaired or be scrapped. In the case of withdrawn instruments, a formal procedure for marking them as such must be defined to prevent them being put back into use accidentally.

Two other items must also be covered by the calibration document.

A) The traceability of the calibration system back to national reference standards must be defined and supported by calibration certificates (figure 1.6).

B)Training procedures must also be documented, specifying the particular training courses to be attended by various personnel and what, if any, refresher courses are required.

Kestrel® Pocket Weather® Meters
Certificate of Calibration – Air Speed

Figure 1.6 Example of temperature calibration simple.

Definitions and classification of variables:

Measurement Units

The first measurement units were those used in barter trade to quantify the amounts being exchanged and to establish clear rules about the relative values of different commodities. Such early systems of measurement were based on whatever was available as a measuring unit. For purposes of measuring length, the human torso was a convenient tool and gave us units of the hand, the foot, and the cubit. Although generally adequate for barter trade systems, such measurement units are, of course, imprecise, varying as they do from one person to the next. Therefore, there has been a progressive movement toward measurement units that are defined much more accurately.

The early establishment of standards for the measurement of physical quantities proceeded in several countries at broadly parallel times; in consequence, several sets of units emerged for measuring the same physical variable. For instance, length can be measured in yards, meters, or several other units. Apart from the major units of length, subdivisions of standard units exist such as feet, inches, centimeters, and millimeters, with a fixed relationship between each fundamental unit and its subdivisions. Yards, feet, and inches belong to the **Imperial system** of units, which is characterized by having varying and cumbersome multiplication factors relating fundamental units to subdivisions such as 1760 (miles to yards), 3 (yards to feet), and 12 (feet to inches). The **metric system** is an alternative set of units, which includes, for instance, the unit of the meter and its centimeter and millimeter subdivisions for measuring length.

Table 1.1 Definitions of Standard Units

(a) Fundamental Units		
Physical Quantity	**Standard**	**Definition**
Length	Meter/ symbol	Length of path traveled by light in an interval of 1/299,792,458 seconds
Mass	Kilogram kg	Mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second s	9.192631770 x10^9 cycles of radiation from vaporized cesium 133 (an accuracy of 1 in 10^{12} or one second in 36,000 years)
Temperature	Degrees K	Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K
Current	Amphere A	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 meter apart in vacuum and producing a force of 2 x 10^{-7} newtons per meter length of conductor
Luminous intensity	Candela cd	source emitting monochromatic radiation at a frequency of 540 terahertz (Hz x 10^{12}) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle, which, having its vertex at the center of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole mol	Number of atoms in a 0.012-kg mass of carbon 12
(b) Supplementary Fundamental Units		
Plane angle	Radian rad	
Solid angle	Steradian sr	

As a result of this, an internationally agreed set of standard units (SI units or Syste`mes internationales d'unite´s) has been defined, and strong efforts are being made to encourage the adoption of this system throughout the world. In support of this effort, the SI system of units is used exclusively in this book. However, it should be noted that the Imperial system is still widely used in the engineering industry, particularly in the United States. The full range of fundamental SI measuring units and the further set of units derived from them are given in Tables 1.1 and 1.2.

Table 1.2 Derived SI Units

Quantity	**Standard Unit**	**Symbol**	**Derivation Formula**
Area	Square meter	m^2	
Volume	cubic meter	m^3	
Velocity	meter per second	m/s	
Acceleration	metre per second squared	m/s^2	
Angular velocity	radian per second	rad/s	
Angular acceleration	radian per second squared	rad/s^2	
Density	kilogram per cubic meter	kg/m^3	
Specific volume	cubic meter per kilogram	m^3/kg	
Mass flow	rate kilogram per second	kg/s	
Volume flow rate	cubic meter per second	m^3/s	
Force	newton	N	$kg\text{-}m/s^2$
Pressure	pascal	Pa	N/m^2

Torque	newton meter	N-m	
Momentum	kilogram meter per second	kg-m/s	
Moment of inertia	kilogram meter squared	kg-m^2	
Kinematic viscosity	square meter per second	m^2/s	
Dynamic viscosity	newton second per square meter	N-s/m^2	
Work, energy, heat	joule	J	N-m
Specific energy	joule per cubic meter	J/m^3	
Power	watt	W	J/s
Thermal conductivity	watt per meter Kelvin	W/m-K	
Electric charge	coulomb	C	A-s
Voltage, e.m.f., pot diff	volt	V	W/A
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	V/A
Electric capacitance	farad	F	A-s/V
Electric inductance	henry	H	V-s/A
Electric conductance	siemen	S	A/V
Resistivity	Ohm-meter	Ω-m	
Permittivity	farad per meter	F/m	
Permeability	henry per meter	H/m	
Current density	ampere per square meter	A/m^2	
Magnetic flux	weber	Wb	V-s
Magnetic flux	density tesla	T	Wb/m^2
Magnetic field strength	ampere per meter	A/m	
Frequency	hertz	Hz	s^{-1}
Luminous flux	lumen	lm	cd-sr
Luminance	candela per square meter	cd/m^2	
Illumination	lux	lx	lm/m^2
Molar volume	cubic meter per mole	m^3/mol	
Molarity	mole per kilogram	mol/kg	
Molar energy	joule per mole	J/mol	

TYPES OF INSTRUMENTS

2. Introduction

Two of the important aspects of measurement covered in the opening chapter concerned how to choose appropriate instruments for a particular application and a review of the main applications of measurement. Both of these activities require knowledge of the characteristics of different classes of instruments and, in particular, how these different classes of instrument perform in different applications and operating environments.

2.1 Instrument Types:

Instruments can be subdivided into separate classes according to several criteria. These sub classifications are useful in broadly establishing several attributes of particular instruments such as accuracy, cost, and general applicability to different applications.

2.1.1 Active and Passive Instruments

Instruments are divided into active or passive ones according to whether instrument output is produced entirely by the quantity being measured or whether the quantity being measured simply modulates the magnitude of some external power source. This is illustrated by examples:

An example of a *passive instrument* is the pressure-measuring device shown in Figure 2.1. The pressure of the fluid is translated into movement of a pointer against a scale. The energy expended in moving the pointer is derived entirely from the change in pressure measured: there are no other energy inputs to the system.

An example of an *active instrument* is a float-type petrol tank level indicator as sketched in Figure 2.2. Here, the change in petrol level moves a potentiometer arm, and the output signal consists of a proportion of the external voltage source applied across the two ends of the potentiometer. The energy in the output signal comes from the external power source: the primary transducer float system is merely modulating the value of the voltage from this external power source.

In *active instruments*, the external power source is usually in electrical form, but in some cases, it can be other forms of energy, such as a pneumatic or hydraulic one. One very important difference between active and passive instruments is the level of measurement resolution that can be obtained. With the simple pressure gauge shown, the amount of movement made by the pointer for a particular pressure change is closely defined by the nature of the instrument. While it is possible to increase measurement resolution by making the pointer longer, such that the pointer tip moves through a longer arc, the scope for such improvement is clearly restricted by the practical limit of how long the pointer can conveniently be. In an *active instrument*, however, adjustment of the magnitude of the

external energy input allows much greater control over measurement resolution. While the scope for improving measurement resolution is much greater incidentally, it is not infinite because of limitations placed on the magnitude of the external energy input, in consideration of heating effects and for safety reasons.

In terms of cost, passive instruments are normally of a more simple construction than active ones and are therefore less expensive to manufacture. Therefore, a choice between active and passive instruments for a particular application involves carefully balancing the measurement resolution requirements against cost.

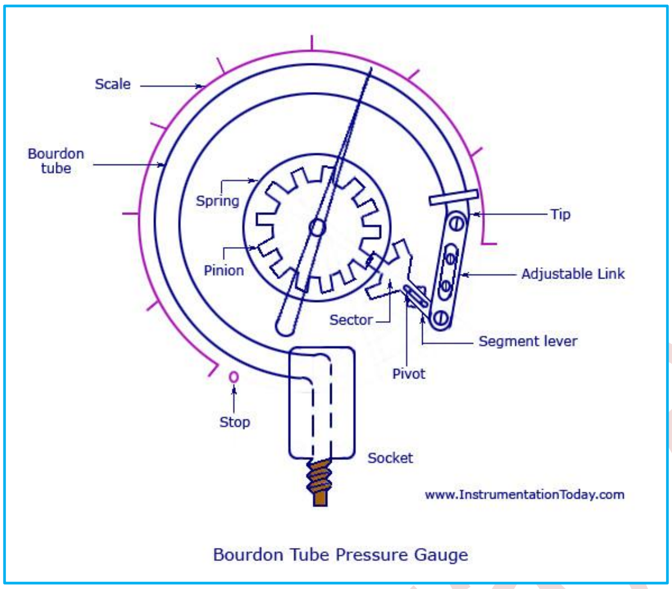


Figure 2.1 passive pressure gauge.

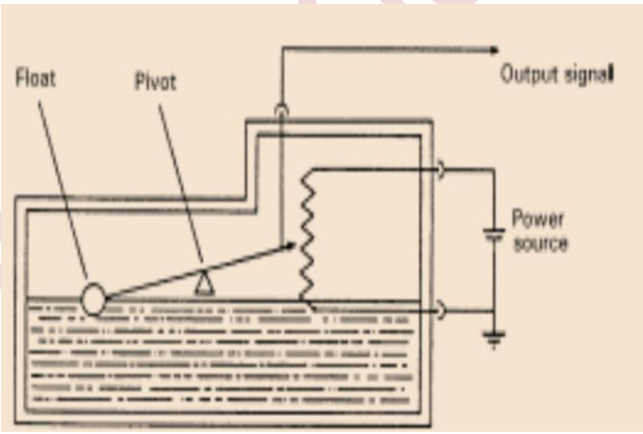


Figure 2.2 petrol –tank level indicator

2.1.2 Null-Type and Deflection-Type Instruments

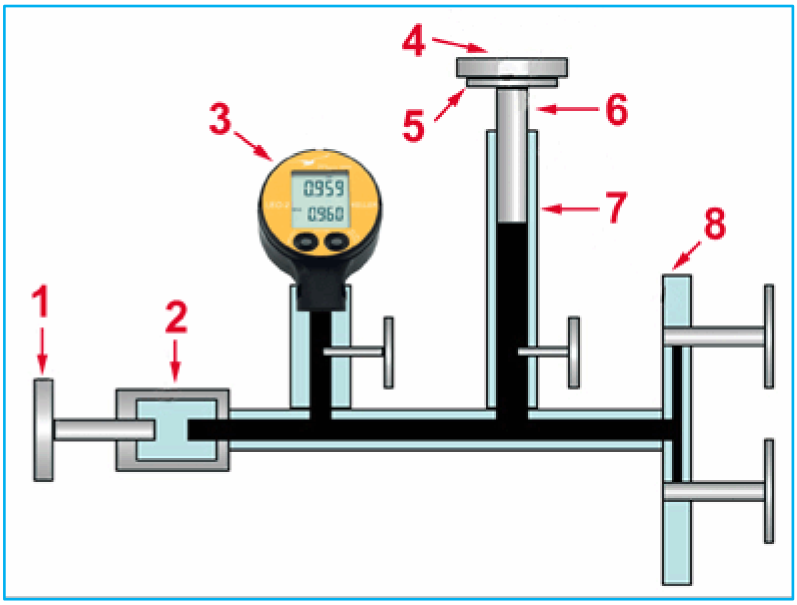
The *pressure gauge* just mentioned is a good example of a *deflection type* of instrument, where the value of the quantity being measured is displayed in terms of the amount of movement of a pointer. An alternative type of pressure gauge is the dead-weight gauge shown in Figure 2.3, which is a null-type instrument. Here, weights are put on top of the piston until the downward force balances the fluid pressure. Weights are added until the piston reaches a datum level, known as the null point. Pressure measurement is made in terms of the value of the weights needed to reach this null position.

The accuracy of these two instruments depends on different things. For the *first* one it depends on the linearity and calibration of the spring, whereas for the *second* it relies on calibration of the weights. As calibration of weights is much easier than careful choice and calibration of a linear-characteristic spring, this means that the second type of instrument will normally be the more accurate. This is in accordance with the general rule that null-type instruments are more accurate than deflection types.

In terms of usage, a deflection-type instrument is clearly more convenient. It is far simpler to read the position of a pointer against a scale than to add and subtract weights until a null point is reached. A deflection-type instrument is therefore the one that would normally be used in the workplace. However, for calibration duties, a null-type instrument is preferable because of its superior accuracy. The extra effort required to use such an instrument is perfectly acceptable in this case because of the infrequent nature of calibration operations.

Figure 2.3 Dead-weight pressure gauge.

1 - Hand pump
2 - Testing Pump
3 - Pressure Gauge to be calibrated
4 - Calibration Weight
5 - Weight Support
6 - Piston
7 - Cylinder
8 - Filling Connection



2.1.3 Analogue and Digital Instruments

An analogue instrument gives an output that varies continuously as the quantity being measured changes. The output can have an infinite number of values within the range that the instrument is designed to measure. The deflection-type of pressure gauge described is a good example of an analogue instrument. As the input value changes, the pointer moves with a smooth continuous motion. While the pointer can therefore be in an infinite number of positions within its range of movement, the number of different positions that the eye can discriminate between is strictly limited; this discrimination is dependent on how large the scale is and how finely it is divided.

A *digital instrument* has an output that varies in discrete steps and so can only have a finite number of values. The rev counter sketched in Figure 2.4 is an example of a digital instrument. A cam is attached to the revolving body whose motion is being measured, and on each revolution the cam opens and closes a switch. The switching operations are counted by an electronic counter. This system can only count whole revolutions and cannot discriminate any motion that is less than a full revolution.

The distinction between *analogue* and *digital* instruments has become particularly important with rapid growth *in the application of microcomputers to automatic control systems*. Any digital computer system, of which the microcomputer is but one example, performs its computations in digital form. An instrument whose output is in digital form is therefore particularly advantageous in such applications, as it can be interfaced directly to the control computer. *Analogue instruments* must be interfaced to the microcomputer by an analogue to- digital (A/D) converter, which converts the analogue output signal from the instrument into an equivalent digital quantity that can be read into the computer. This conversion has *several disadvantages*. *First*, the A/D converter adds a significant cost to the system. *Second*, a finite time is involved in the process of converting an analogue signal to a digital quantity, and this time can be critical in the control of fast processes where the accuracy of control depends on the speed of the controlling computer. Degrading the speed of operation of the control computer by imposing a requirement for A/D conversion thus impairs the accuracy by which the process is controlled.

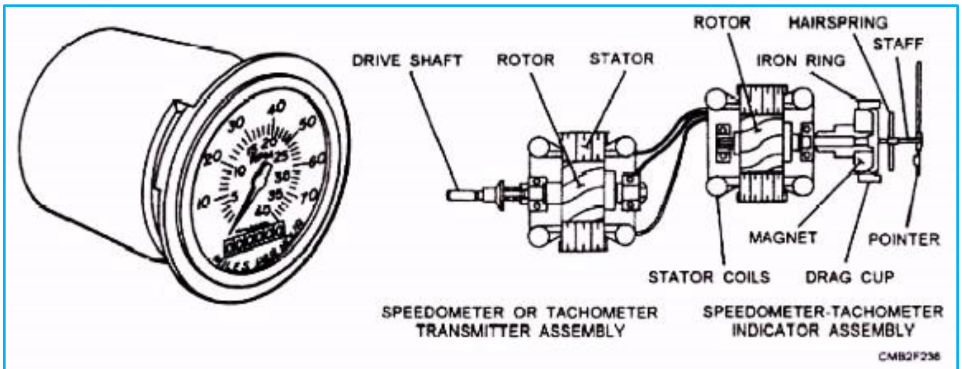


Figure2.4 revaluation counter

2.1.4 Indicating Instruments and Instruments with a Signal Output

The final way in which instruments can be divided is between those that merely give an audio or visual indication of the magnitude of the physical quantity measured and those that give an output in the form of a measurement signal whose magnitude is proportional to the measured quantity.

The class of indicating instruments normally includes all null-type instruments and most passive ones. Indicators can also be further divided into those that have an analogue output and those that have a digital display. A common *analogue indicator* is the liquid-in-glass thermometer. Electronic forms of bathroom scales have a digital output consisting of numbers presented on *an electronic* display. One major drawback with indicating devices is that human intervention is required to read and record a measurement. This process is particularly prone to error in the case of analogue output displays, although digital displays are not very *prone to error unless the human reader is careless.*

Instruments that have a signal-type output are used commonly as part of automatic control systems. In other circumstances, they can also be found in measurement systems where the output measurement signal is recorded in some way for later use. Usually, the measurement signal involved is an electrical voltage, but it can take other forms in some systems, such as an electrical current, an optical signal, or a pneumatic signal.

PERFORMANCE CHARACTERISTICS

3.0 Static Characteristics of Instruments:

If we have a thermometer in a room and its reading shows a temperature of 20°C, then it does not really matter whether the true temperature of the room is 19.5 or 20.5°C. Such small variations around 20°C are too small to affect whether we feel warm enough or not. Our bodies cannot discriminate between such close levels of temperature and therefore a thermometer with an inaccuracy of ±0.5°C is perfectly adequate.

If we had to measure the temperature of certain chemical processes, however, a variation of 0.5°C might have a significant effect on the rate of reaction or even the products of a process. A measurement inaccuracy much less than ±0.5°C is therefore clearly required.

Accuracy of measurement is thus one consideration in the choice of instrument for a particular application. Other parameters, such as sensitivity, linearity, and the reaction to ambient temperature changes, are further considerations. These attributes are collectively known as the static characteristics of instruments and are given in the data sheet for a particular instrument. It is important to note that values quoted for instrument characteristics in such a data sheet only apply when the instrument is used under specified standard calibration conditions. Due allowance must be made for variations in the characteristics when the instrument is used in other conditions.

The static characteristics are:

3.1.1 Accuracy and Inaccuracy (Measurement Uncertainty):

The ***accuracy*** of an instrument is a measure of how close the output reading of the instrument is to the correct value. In practice, it is more usual to quote the inaccuracy or measurement uncertainty value rather than the accuracy value for an instrument.

Inaccuracy or measurement uncertainty is the extent to which a reading might be wrong and is often quoted as a percentage of the full-scale (f.s.) reading of an instrument.

The aforementioned example carries a very important message. Because the maximum measurement error in an instrument is usually related to the full-scale reading of the instrument, *measuring quantities that are substantially less than the full-scale reading means that the possible measurement error is amplified*. For this reason, it is an important system design rule that instruments are chosen such that their range is appropriate to the spread of values being measured in order that the best possible accuracy is maintained in instrument readings. Clearly, if we are measuring pressures with expected values between 0 and 1 bar, we would not use an instrument with a measurement range of 0–10 bar.

Example 3.1

A pressure gauge with a measurement range of 0–10 bar has a quoted inaccuracy of ±1.0% f.s. (±1% of full-scale reading).

(a) What is the maximum measurement error expected for this instrument?

(b) What is the likely measurement error expressed as a percentage of the output reading if this pressure gauge is measuring a pressure of 1 bar?

Solution

(a) The maximum error expected in any measurement reading is 1.0% of the full-scale reading, which are 10 bars for this particular instrument. Hence, the maximum likely error is 1.0% x10 bar = **0.1 bar**.

(b) The maximum measurement error is a constant value related to the full-scale reading of the instrument, irrespective of the magnitude of the quantity that the instrument is actually measuring. In this case, as worked out earlier, the magnitude of the error is 0.1 bar. Thus, when measuring a pressure of 1 bar, the maximum possible error of 0.1 bar is **10%** of the measurement value.

3.1.2 Precision/Repeatability/Reproducibility:

Precision is a term that describes an instrument's degree of freedom from random errors. If a large number of readings are taken of the same quantity by a high-precision instrument, then the spread of readings will be very small. Precision is often, although incorrectly, confused with accuracy. High precision does not imply anything about measurement accuracy. A high-precision instrument may have a low accuracy. *Low accuracy measurements from a high-precision instrument are normally caused by a bias in the measurements, which is removable by recalibration.*

The terms ***repeatability*** and reproducibility mean approximately the same but are applied in different contexts. ***Repeatability*** describes the closeness of output readings when the same input is applied repetitively over a short period of time, with the same measurement conditions, same instrument and observer, same location, and same conditions of use maintained throughout.

Reproducibility describes 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. Both terms thus describe the spread of output readings for the same input. This spread is referred to as repeatability if the measurement conditions are constant and as reproducibility if the measurement conditions vary.

3.1.3 Tolerance:

Tolerance is a term that is closely related to accuracy and defines the maximum error that is to be expected in some value. While it is not a static characteristic of measuring instruments, it is mentioned here because the accuracy of some instruments is sometimes quoted as a tolerance value. When used correctly, tolerance describes the maximum deviation of a manufactured component from some specified value. For instance, crankshafts are machined with a diameter tolerance quoted as so many micrometers (10^{-6} m), and electric circuit components such as resistors have tolerances of perhaps 5%.

Example 3.2

A packet of resistors bought in an electronics component shop gives the nominal resistance value as 1000 Ω and the manufacturing tolerance as ±5%. If one resistor is chosen at random from the packet, what is the minimum and maximum resistance value that this particular resistor is likely to have?

Solution

The minimum likely value is 1000 Ω – 5% = 950 Ω.

The maximum likely value is 1000 Ω + 5% = 1050 Ω.

3.1.4 Range or Span:

The range or span of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure.

3.1.5 Linearity:

It is normally desirable that the output reading of an instrument is linearly proportional to the quantity being measured. The Xs marked on Figure 3.1 show a plot of typical output readings of an instrument when a sequence of input quantities is applied to it. Normal procedure is to draw a good fit straight line through the Xs, as shown in Figure 3.1. (While this can often be done with reasonable accuracy by eye, it is always preferable to apply a mathematical least-squares line-fitting technique).

Nonlinearity is then defined as the maximum deviation of any of the output readings marked X from this straight line. Nonlinearity is usually expressed as a percentage of full-scale reading.

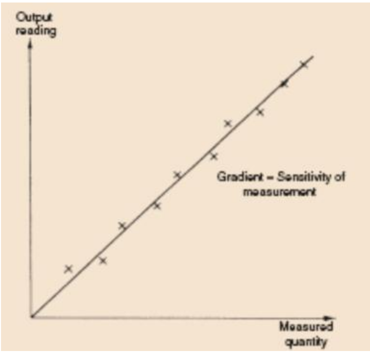


Figure 3.1 Instrument output characteristic.

3.1.6 Sensitivity of Measurement:

The sensitivity of measurement is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount. Thus, sensitivity is the ratio:

$$= \frac{scale\ of\ deflection}{value\ of\ measurand\ producing\ deflection}$$

The sensitivity of measurement is therefore the slope of the straight line drawn on Figure 3.1. If, for example, a pressure of 2 bar produces a deflection of 10 degrees in a pressure transducer, the sensitivity of the instrument is 5 degrees/bar (assuming that the deflection is zero with zero pressure applied).

Example 3.3

The following resistance values of a platinum resistance thermometer were measured at a range of temperatures. Determine the measurement sensitivity of the instrument in ohms/°C.

Resistance (Ω)	Temperature (°C)
307	200
314	230
321	260
328	290

Solution

If these values are plotted on a graph, the straight-line relationship between resistance change and temperature change is obvious.

For a change in temperature of 30°C, the change in resistance is 7Ω. Hence the measurement sensitivity = 7/30 = 0.233 Ω/°C.

3.1.7 Threshold:

If the input to an instrument is increased gradually from zero, the input will have to reach a certain minimum level before the change in the instrument output reading is of a large enough magnitude to be detectable. This minimum level of input is known as the threshold of the instrument. Manufacturers vary in the way that they specify threshold for instruments. Some quote *absolute values*, whereas others quote threshold as a *percentage of full-scale readings*. As an illustration, a car speedometer typically has a threshold of about 15 km/h. This means that, if the vehicle starts from rest and accelerates, no output reading is observed on the speedometer until the speed reaches 15 km/h.

3.1.8 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. Like threshold, resolution is sometimes specified as an absolute value and sometimes as a percentage of f.s. deflection. 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. This value of 5 km/h thus represents the resolution of the instrument.

3.1.9 Sensitivity to Disturbance:

All calibrations and specifications of an instrument are only valid under controlled conditions of temperature, pressure, and so on. These standard ambient conditions are usually defined in the instrument specification. As variations occur in the ambient temperature, certain static instrument characteristics change, and the sensitivity to disturbance is a measure of the magnitude of this change. Such environmental changes affect instruments in two main ways, known as zero drift and sensitivity drift. **Zero drift** is sometimes known by the alternative term, bias. Zero drift or bias describes the effect where the zero reading of an instrument is modified by a change in ambient conditions. This causes a constant error that exists over the full range of measurement of the instrument. The mechanical form of a bathroom scale is a common example of an instrument prone to zero drift. It is quite usual to find that there is a reading of perhaps 1 kg with no one on the scale. If someone of known weight 70 kg were to get on the scale, the reading would be 71 kg, and if someone of known weight 100 kg were to get on the scale, the reading would be 101 kg. *Zero drift is normally removable by calibration.* In the case of the bath room scale just described, a thumbwheel is usually provided that can be turned until the reading is zero with the scales unloaded, thus removing zero drift.

The typical unit by which such zero drift is measured is volts/°C. This is often called the zero drift coefficient related to temperature changes. If the characteristic of an instrument is sensitive to several environmental parameters, then it will have several zero drift coefficients, one for each environmental parameter. A typical change in the output characteristic of a pressure gauge subject to zero drift is shown in Figure 3.2a.

Sensitivity drift (also known as scale factor drift) defines the amount by which an instrument's sensitivity of measurement varies as ambient conditions change. It is quantified by sensitivity drift

coefficients that define how much drift there is for a unit change in each environmental parameter that the instrument characteristics are sensitive to. Many components within an instrument are affected by environmental fluctuations, such as temperature changes: for instance, the modulus of elasticity of a spring is temperature dependent. Figure 3.2b shows what effect sensitivity drift can have on the output characteristic of an instrument. Sensitivity drift is measured in units of the form (angular degree/bar)/°C. If an instrument suffers both zero drift and sensitivity drift at the same time, then the typical modification of the output characteristic is shown in Figure 3.2c.

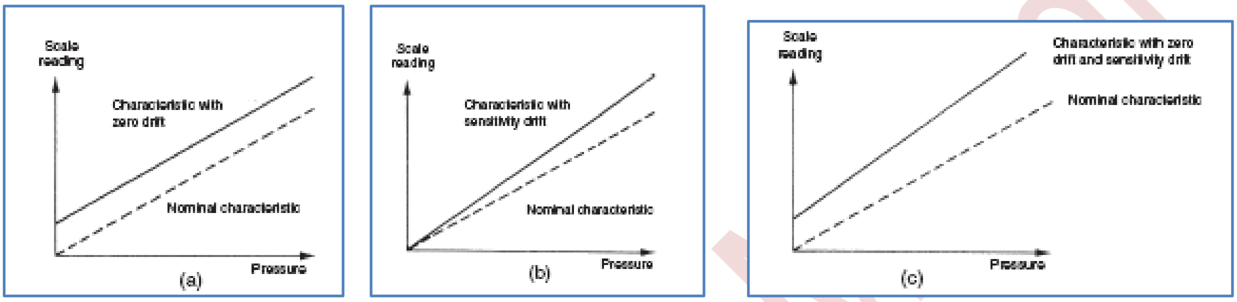


Figure 3.2 Effects of disturbance: (a) zero drift, (b) sensitivity drift, and (c) zero drift plus sensitivity drift.

Example 3.4
The following table shows output measurements of a voltmeter under two sets of conditions:

(a) Use in an environment kept at 20°C which is the temperature that it was calibrated at.

(b) Use in an environment at a temperature of 50°C.

Voltage readings at calibration temperature of 20°C(assumed correct)	Voltage readings at temperature of 50°C
10.2	10.5
20.3	20.6
30.7	40.0
40.8	50.1

Determine the zero drift when it is used in the 50°C environment, assuming that the measurement values when it was used in the 20°C environment are correct. Also calculate the zero drift coefficients.

Solution
Zero drift at the temperature of 50°C is the constant difference between the pairs of output readings, that is, 0.3 volts.
The zero drift coefficients are the magnitude of drift (0.3 volts) divided by the magnitude of the temperature change causing the drift (30°C). Thus the zero drift coefficients is 0.3/30= 0.01 volts/°C.

Example 3.5

A spring balance is calibrated in an environment at a temperature of 20°C and has the following deflection/load characteristic:

Load (kg)	0	1	2	3
Deflection (mm)	0	20	40	60

It is then used in an environment at a temperature of 30°C, and the following deflection/load characteristic is measured:

Load (kg)	0	1	2	3
Deflection (mm)	5	27	49	71

Determine the zero drift and sensitivity drift per °C change in ambient temperature.

Solution

At 20°C, deflection/load characteristic is a straight line. Sensitivity = 20 mm/kg.

At 30°C, deflection/load characteristic is still a straight line. Sensitivity = 22 mm/kg.

Zero drift (bias)= 5 mm (the no-load deflection)

Sensitivity drift = 2 mm/kg

Zero drift/°C= 5/10 = 0.5 mm/°C

Sensitivity drift/°C= 2/10 = 0.2 (mm/kg)/°C

3.1.10 Hysteresis Effects

Figure 3.3 illustrates the output characteristic of an instrument that exhibits hysteresis. If the input measured quantity to the instrument is increased steadily from a negative value, the output reading varies in the manner shown in curve A. If the input variable is then decreased steadily, the output varies in the manner shown in curve B. The non-coincidence between these loading and unloading curves is known as hysteresis. Two quantities are defined, maximum input hysteresis and maximum output hysteresis, as shown in Figure 3.3. These are normally expressed as a percentage of the full-scale input or output reading, respectively.

Hysteresis is found most commonly in instruments that contain springs, such as a passive pressure gauge. It is also evident when friction forces in a system have different magnitudes depending on the direction of movement, such as in the pendulum-scale mass-measuring device. Devices such as the mechanical fly ball (a device for measuring rotational velocity) suffer hysteresis from both of the aforementioned sources because they have friction in moving parts and also contain a spring. Hysteresis can also occur in instruments that contain electrical windings formed round an iron core, due to magnetic hysteresis in the iron. This occurs in devices such as the variable inductance

displacement transducer, the linear variable differential transformer, and the rotary differential transformer.

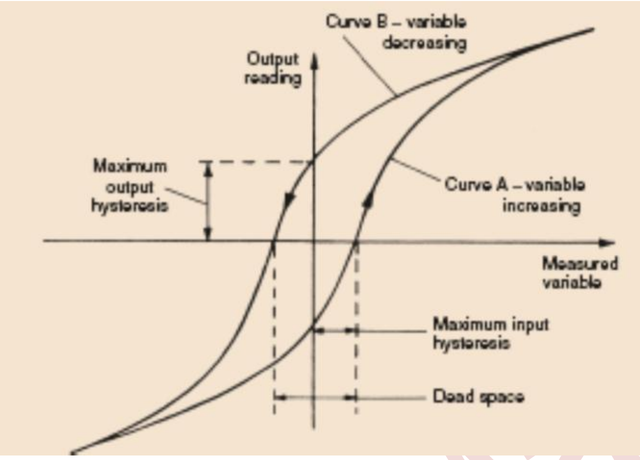


Figure3.3 Instrument characteristic with hysteresis.

3.1.10.1 Dead Space:

Dead space is defined as the range of different input values over which there is no change in output value. Any instrument that exhibits hysteresis also displays dead space, as marked on Figure 3.3. Some instruments that do not suffer from any significant hysteresis can still exhibit a dead space in their output characteristics, however. Backlash in gears is a typical cause of dead space and results in the sort of instrument output characteristic shown in Figure 3.3.

3.2 Dynamic Characteristics of Instruments:

The static characteristics of measuring instruments are concerned only with the steady-state reading that the instrument settles down to, such as accuracy of the reading.

The dynamic characteristics of a measuring instrument describe its behavior between the time a measured quantity changes value and the time when the instrument output attains a steady value in response. As with static characteristics, any values for dynamic characteristics quoted in instrument data sheets only apply when the instrument is used under specified environmental conditions. Outside these calibration conditions, some variation in the dynamic parameters can be expected.

$$a_n * \frac{d^n q_o}{dt^n} + a_{n-1} * \frac{d^{n-1} q_o}{dt^{n-1}} + \cdots + a_1 * \frac{dq_o}{dt} + a_o q_o = b_o q_i \qquad 3.1$$

Further simplification can be made by taking certain special cases of Equation (2.1), which collectively apply to nearly all measurement systems.

3.2.1. Zero-Order Instrument

If all the coefficients $a_1 \ldots a_n$ other than a_0 in Equation (3.1) are assumed zero, then:

$$a_o q_o = b_o q_i \;\; or \;\; q_o = b_o q_i \,/\, a_o = k q_i \qquad 3.2$$

Where *k* is a constant known as the instrument sensitivity as defined earlier.

Any instrument that behaves according to Equation (2.1) is said to be of a zero-order type. Following a step change in the measured quantity at time t, the instrument output moves immediately to a new value at the same time instant t, as shown in Figure 3.4. A potentiometer, which measures motion is a good example of such an instrument, where the output voltage changes instantaneously as the slider is displaced along the potentiometer track.

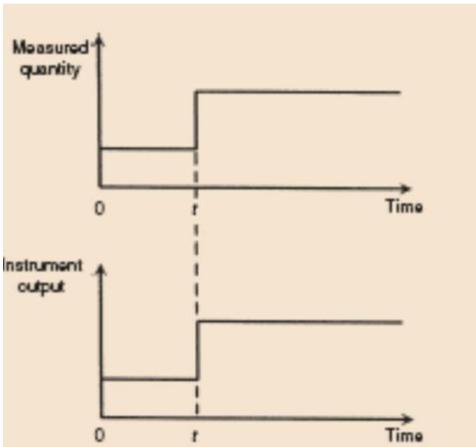


Figure 3.4 Zero-order instrument characteristic

3.2.2 First-Order Instrument:

If all the coefficients $a_2 \ldots a_n$ except for a_o and a_1 are assumed zero in Equation (3.1) then

$$a_1 * \frac{dq_o}{dt} + a_o q_o = b_o q_i \qquad 3.3$$

Any instrument that behaves according to Equation (3.3) is known as a first-order instrument.

If Equation (3.3) is solved analytically, the output quantity q_0 in response to a step change in qi at time t varies with time in the manner shown in Figure 3.5. The time constant t of the step response is time taken for the output quantity q0 to reach 63% of its final value.

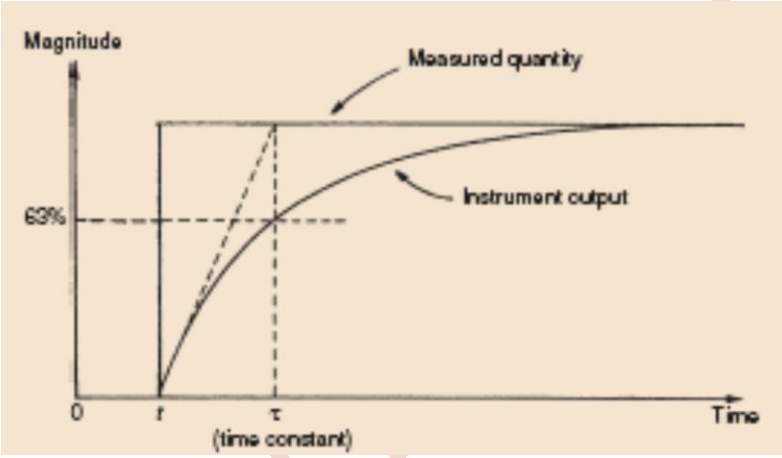


Figure 3.5 First order instrument characteristic

The thermocouple is a good example of a first-order instrument. It is well known that if a thermocouple at room temperature is plunged into boiling water, the output e.m.f. does not rise instantaneously to a level indicating 100°C, but instead approaches a reading indicating 100°C in a manner similar to that shown in Figure 2.9.

3.2.3 Second-Order Instrument:

If all coefficients a3 . . . an other than a_0, a_1, and a_2 in Equation (3.1) are assumed zero, then we get

$$a_2 * \frac{d^2 q_o}{dt^2} + a_1 * \frac{dq_o}{dt} + a_o q_o = b_o q_i \qquad 3.4$$

The output responses of a second-order instrument for various values of x following a step change in the value of the measured quantity at time t are shown in Figure 3.6.

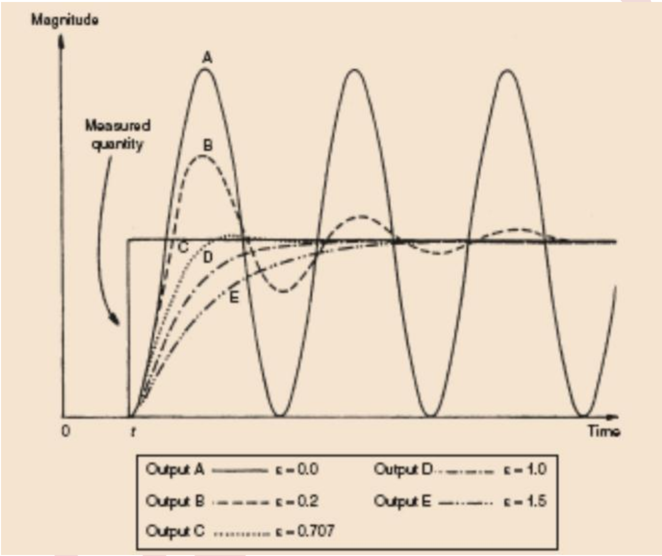


Figure 3.6 Second order response characteristics