PERFORMANCE CHARACTERISTICS

3. 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.

3.1 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.

3.1.1 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 3.1. 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 3.2. 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.

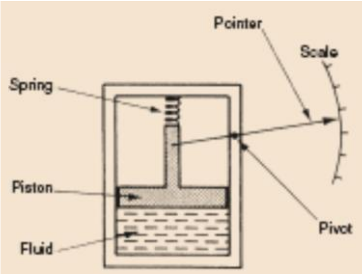

Figure3.1 passive pressure gauge.

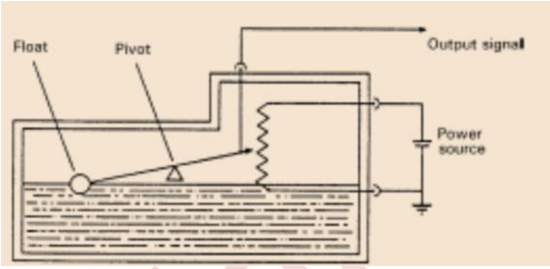

Figure3.2 petrol –tank level indicator

3.1.2 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 3.3, 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.

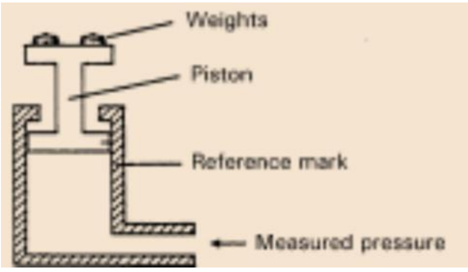

Figure 3.3 Dead-weight pressure gauge.

3.1.3 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 3.4 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.

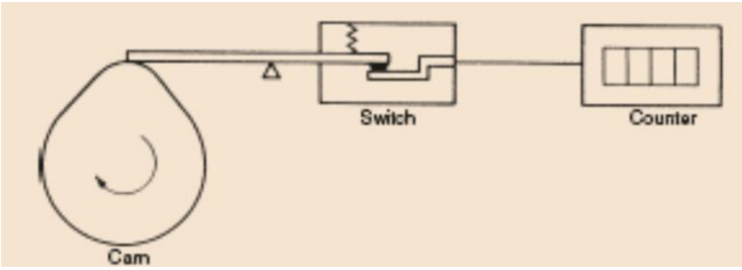

Figure3.4 revaluation counter

3.1.4 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.

3.2 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:

3.2.1 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 $\pm$1.0% f.s. ($\pm$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.

3.2.2 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.

3.2.3 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.

3.2.4 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.

3.2.5 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 3.5 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 3.6. (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.

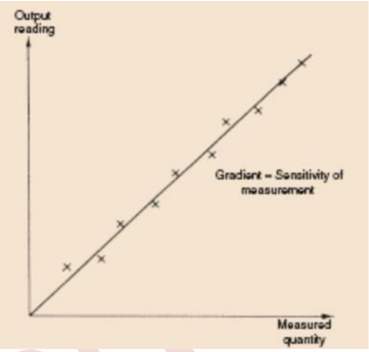

Figure 3.5 Instrument output characteristic.

3.2.6 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 Figure3.5. 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 2.3

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.

3.2.7 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.

3.2.8 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.

2.3.9 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 3.6a.

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 3.6b 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 3.6c.

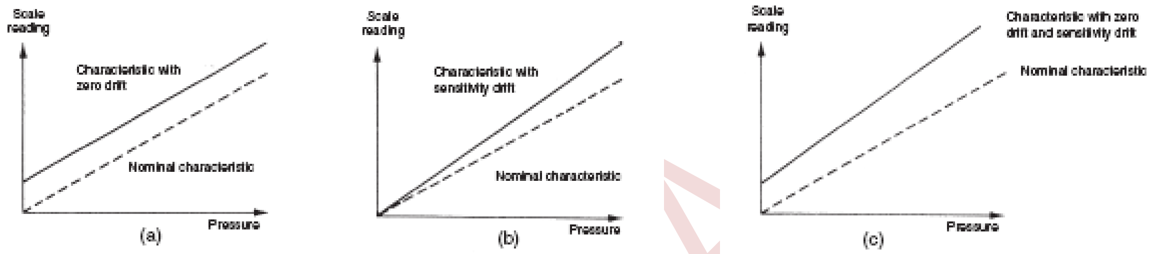

Figure 3.6 Effects of disturbance: (a) zero drift, (b) sensitivity drift, and (c) zero drift plus sensitivity drift.

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

3.2.10 Hysteresis Effects

Figure 3.7 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 noncoincidence 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 3.7. 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 (Figure 3.1). 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.

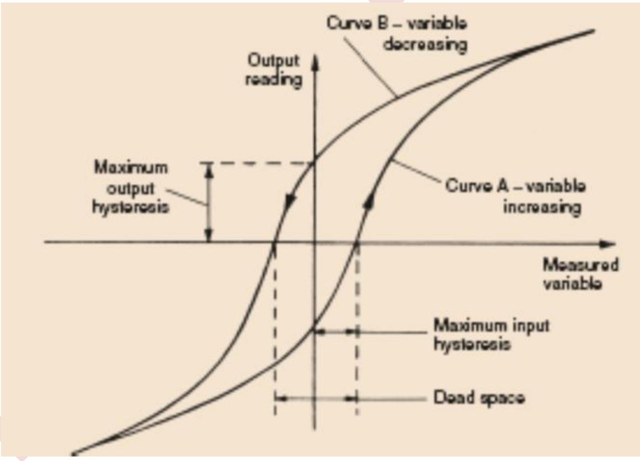

Figure3.7 Instrument characteristic with hysteresis.

3.2.11 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 2.7. 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 2.7.

3.3 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 (3.1), which collectively apply to nearly all measurement systems.

3.3.1. 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 (3.1) 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 3.8. 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.

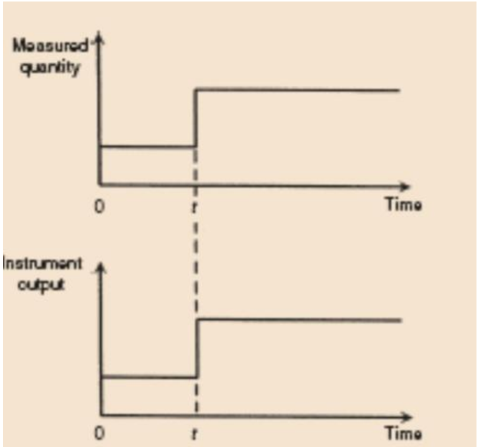

Figure3.8 Zero-order instrument characteristic

3.3.2 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 3.9. The time constant t of the step response is time taken for the output quantity q0 to reach 63% of its final value.

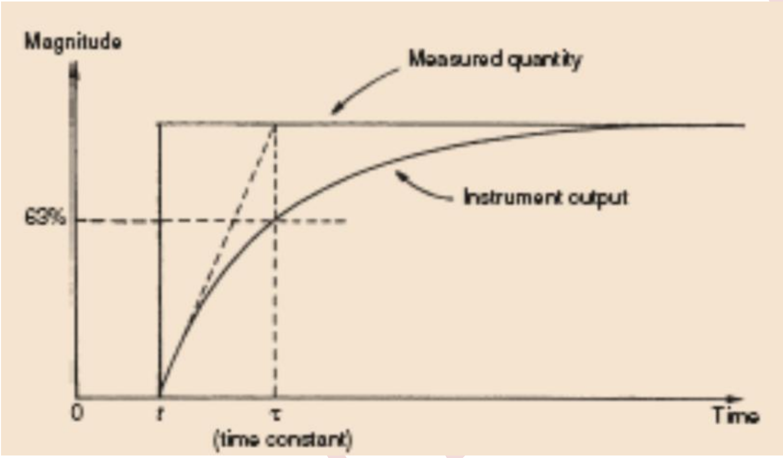

Figure 3.9 First order instrument characteristic

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 3.9.

3.3.3 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 3.10.

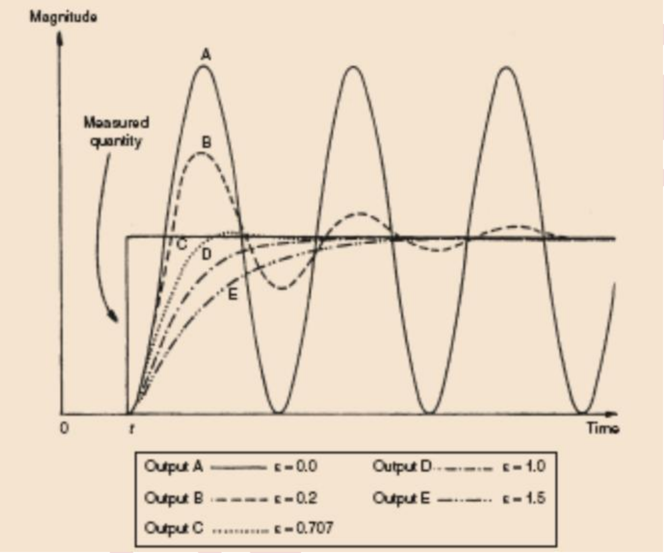

Figure3.10 Second order response characteristics