2

Instrument types and performance characteristics
2.1 Review of instrument types

• Instruments can be subdivided into separate classes according to several criteria.
• These subclassifications 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

• An example of a **passive** instrument is the pressure-measuring device shown in Figure 2.1. The pressure of the fluid is translated into a movement of a pointer against a scale.
passive instruments

Fig. 2.1 Passive pressure gauge.
• 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.
Active instruments

Fig. 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 deadweight gauge shown in Figure 2.3, which is a null-type instrument.
Null-type instrument

Fig. 2.3 Deadweight pressure gauge.
2.1.3 Analogue and digital instruments

• An analogue instrument gives an output that varies continuously as the quantity being measured changes (Figure 2.1).

• 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.
Digital instruments

Fig. 2.4 Rev counter.
2.1.4 Indicating instruments and instruments with a signal output

- Instruments merely give an audio or visual indication of the magnitude of the physical quantity measured.

- Instruments that give an output in the form of a measurement signal whose magnitude is proportional to the measured quantity.
2.1.5 Smart and non-smart instruments

- The advent of the microprocessor has created a new division in instruments between those that do incorporate a microprocessor (smart) and those that don’t.
2.2 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°C 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.
2.2.1 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 figure rather than the accuracy figure for an instrument.

• Inaccuracy 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.
• If, for example, a pressure gauge of range 0–10 bar has a quoted inaccuracy of $\pm 1.0\%$ f.s. ($\pm 1\%$ of full-scale reading), then the maximum error to be expected in any reading is 0.1 bar.

• This means that when the instrument is reading 1.0 bar, the possible error is 10% of this value.
2.2.2 Precision/repeatability/reproducibility

- **Precision** is a term that describes an instrument’s degree of freedom from random errors.

- **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.

• The degree of repeatability or reproducibility in measurements from an instrument is an alternative way of expressing its precision. **Figure 2.5** illustrates this more clearly.
The figure shows the results of tests on three industrial robots that were programmed to place components at a particular point on a table.
2.2.3 Tolerance

- Tolerance is a term that is closely related to accuracy and defines the maximum error that is to be expected in some value.

- For example one resistor chosen at random from a batch having a nominal value 1000W and tolerance 5% might have an actual value anywhere between 950W and 1050 W.
2.2.4 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.
2.2.5 Linearity

• It is normally desirable that the output reading of an instrument is linearly proportional to the quantity being measured.
Sensitivity of measurement

2.2.6 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:

\[
\frac{\text{scale deflection}}{\text{value of measurand producing deflection}}
\]
Example

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.

<table>
<thead>
<tr>
<th>Resistance (Ω)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>307</td>
<td>200</td>
</tr>
<tr>
<td>314</td>
<td>230</td>
</tr>
<tr>
<td>321</td>
<td>260</td>
</tr>
<tr>
<td>328</td>
<td>290</td>
</tr>
</tbody>
</table>
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 $30^\circ\text{C}$, the change in resistance is 7. Hence the measurement sensitivity $= \frac{7}{30} = 0.233\Omega /^\circ\text{C}$. 
2.2.7 Threshold

- If the input to an instrument is gradually increased 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.
2.2.8 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.
2.2.9 Sensitivity to disturbance

• All calibrations and specifications of an instrument are only valid under controlled conditions of temperature, pressure etc.
• These standard ambient conditions are usually defined in the instrument specification.
• As variations occur in the ambient temperature etc., certain static instrument characteristics change.
• 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 or bias describes the effect where the zero reading of an instrument is modified by a change in ambient conditions.

• Sensitivity drift (also known as scale factor drift) defines the amount by which an instrument’s sensitivity of measurement varies as ambient conditions change.
Fig. 2.7 Effects of disturbance: (a) zero drift; (b) sensitivity drift; (c) zero drift plus sensitivity drift.
**Example**

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

<table>
<thead>
<tr>
<th>Load (kg)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection (mm)</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>
• It is then used in an environment at a temperature of 30°C and the following deflection/load characteristic is measured.

<table>
<thead>
<tr>
<th>Load (kg):</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection (mm):</td>
<td>5</td>
<td>27</td>
<td>49</td>
<td>71</td>
</tr>
</tbody>
</table>

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.
• Bias (zero drift) = 5mm (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 per kg)/°C
2.2.10 Hysteresis effects

- Figure 2.8 illustrates the output characteristic of an instrument that exhibits hysteresis.
• If the input measured quantity to the instrument is steadily increased from a negative value, the output reading varies in the manner shown in curve (a). If the input variable is then steadily decreased, 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 2.8.
2.2.11 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 2.8.
2.3 Dynamic characteristics of instruments

- 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.

\[ a_n \frac{d^n q_0}{dt^n} + a_{n-1} \frac{d^{n-1} q_0}{dt^{n-1}} + \cdots + a_1 \frac{dq_0}{dt} + a_0 q_0 \]

\[ = b_m \frac{d^m q_i}{dt^m} + b_{m-1} \frac{d^{m-1} q_i}{dt^{m-1}} + \cdots + b_1 \frac{dq_i}{dt} + b_0 q_i \]
• where $q_i$ is the measured quantity, $q_0$ is the output reading and $a_0 \ldots a_n$, $b_0 \ldots b_m$ are constants.

• If we limit consideration to that of step changes in the measured quantity only, then equation reduces to:

$$a_n \frac{d^n q_0}{dt^n} + a_{n-1} \frac{d^{n-1} q_0}{dt^{n-1}} + \cdots + a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$
2.3.1 Zero order instrument

- If all the coefficients $a_1 \ldots a_n$ other than $a_0$ in equation are assumed zero, then:

$$a_0q_0 = b_0q_i \quad \text{or} \quad q_0 = \frac{b_0q_i}{a_0} = Kq_i$$

where $K$ is a constant known as the instrument sensitivity as defined earlier.
Fig. 2.10 Zero order instrument characteristic.
2.3.2 First order instrument

• If all the coefficients $a_2 \ldots a_n$ except for $a_0$ and $a_1$ are assumed zero in equation then:

$$a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$

If equation is solved analytically, the output quantity $q_0$ in response to a step change in $q_i$ at time $t$ varies with time in the manner shown in Figure 2.11.
Fig. 2.11 First order instrument characteristic.
\[
\frac{a_1}{a_0} \frac{dq_0}{dt} + q_0 = \frac{b_0}{a_0} q_i
\]

Defining \( K = \frac{b_0}{a_0} \) as the static sensitivity and \( \tau = \frac{a_1}{a_0} \) as the time constant of the system, equation becomes:

\[
\tau \frac{dq_0}{dt} + q_0 = K q_i
\]
2.3.3 Second order instrument

• If all coefficients \( a_3 \ldots \) an other than \( a_0, a_1 \) and \( a_2 \) in equation are assumed zero, then we get:

\[
a_2 \frac{d^2 q_0}{dt^2} + a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i
\]
\[
\frac{a_2}{a_0} \frac{d^2 q_0}{dt^2} + \frac{a_1}{a_0} \frac{dq_0}{dt} + q_0 = \frac{b_0}{a_0} q_i
\]

It is convenient to re-express the variables \(a_0\), \(a_1\), \(a_2\) and \(b_0\) in equation in terms of three parameters \(K\) (static sensitivity), \(\omega\) (undamped natural frequency) and \(\xi\) (damping ratio), where:

\[
\frac{1}{\omega^2} \frac{d^2 q_0}{dt^2} + \frac{2\xi}{\omega} \frac{dq_0}{dt} + q_0 = K q_i
\]

\[
K = \frac{b_0}{a_0}, \quad \omega^2 = \frac{a_0}{a_2}, \quad \xi = \frac{a_1 \omega}{2a_0}
\]
• The output responses of a second order instrument for various values of following a step change in the value of the measured quantity at time $t$ are shown in Figure 2.12.