Basis of Instruments

Introduction

The measurement of a given quantity is essentially an act or result of comparison between the quantity (unknown) and a predefined standard. Since two quantities are compared the result is expressed in numerical values.

The main objective of measurement is to convert a physical quantity into a numerical value.

1. The apparatus used and the method adopted must be theoretically and practically proved.

2 Methods of measurement

The method of measurements may be broadly classified into 2 categories

(i) Direct method (ii) Indirect method

1. **Direct method**

- In this method, the measured quantity is directly compared against a standard
- This method often produces human errors and hence provides less accuracy.

2. **Indirect method**

- More accurate
- More sensitive
- Hence highly preferred

3 **Instrument:** Measuring instrument is a device that allows us to make comparison.

Essential characteristics of instrument

→ Operational power consumption should be negligible, that occurs the instrument should not change the value of measured quantity i.e, instrument should not alter the ambience but should only monitor

Characteristics of instrument, induces

(i) Accuracy

- It is the closeness of measured value against the true value.
- Accuracy is defined in terms of limits of errors for e.g, class 2 instrument = 2% error ⇒ 98% accuracy class 1 instrument = 1% error ⇒ 99% accuracy.

(ii) Precision:

- Measure of reproducibility of measurement: ability of instrument to give the same reading when repeated measurements are meant for a given input.
- Precision depend on number of significant figures more significant figure →More precision.

Q. Determine the number of significant figures in following

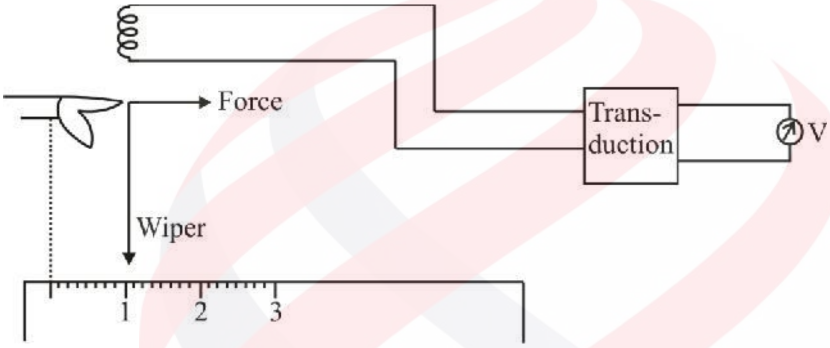
(a.) 6.02×10^{23} ; 3 significant figures

(b.) 503000 ; 3 significant figures

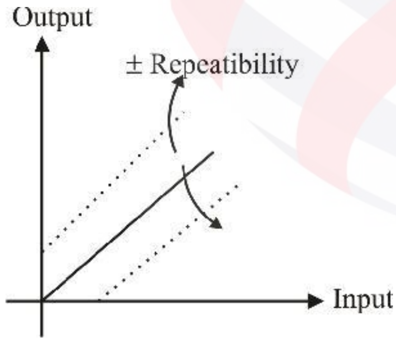
(c.) 20020 ; 4 significant figures

(iii) Sensitivity (Static sensitivity): Magnitude of output signal or response to the magnitude of input signal or the quantity being measured.

For example 1mm push / travel of a given wiper wild produce 1V. thus sensitivity would be 1V/mm



(iv) Reproducibility: It is the degree of closeness of a given instrument output for a constant input. i.e, if the input 5A current, no matter. How many times we used the instrument. It should display indicate 5A (as close as possible) only.



(v) Resolution/discrimination:

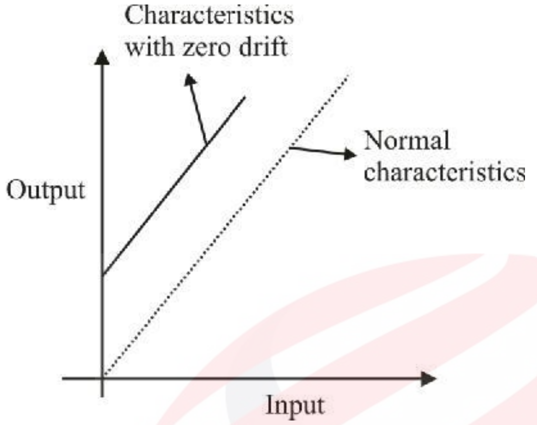
The smallest measurable input change that can be measured by instrument is called discrimination or resolution.

(vi) Threshold: The minimum value below which no o/p change can be detected is called threshold.

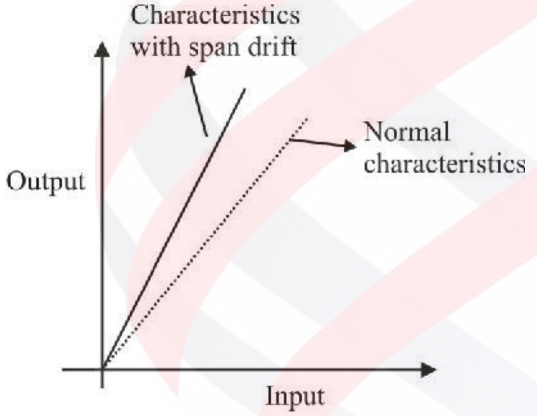
(vii) Drift: Lack of reproducibility leads to drift.

Drift are of 3 types

(a) Zero drift: If the whole calibration shift due to slippage, permanent set or heating.



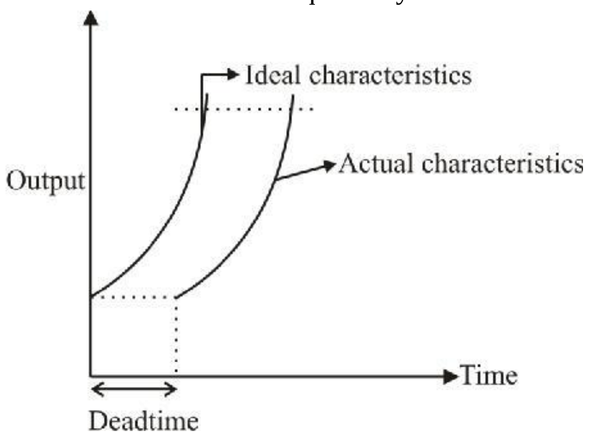
(b) Span drift: If there is proportional change, in the indication all along the upward scale.



(c) Zonal drift: In case the drift occurs only over a portion of span of an instrument.

Drift is undesired quality because it cannot be easily compensated

(viii) Deadtime: It is the time required by a measurement system to begin.



(ix) Deadzone: It is defined as the largest change of input quantity for which there is no output of the instrument.
The term " deadzone" is sometimes used interchangeably with term hysteresis.

(x) Calibration: Process of making adjustment on the scale so that instrument readings confirm to an accepted standard.

Practice questions:

1. Which one of the following is best definition of accuracy
(a.) It is the measure of consistency or reproducibility of measurements
(b.) It is the ratios of change in o/p signal to the change in i/p signal
(c.) It is the smallest change in measurable input
(d.) It is the closeness to with which an instrument reading approaches the true value of the quantity being measured

ANS: d

2. The following terms used in the context of an instrument are numbered as shown
I. Accuracy
II. Sensitivity
III. Precision
IV. Resolution

Match these with their possible definition listed below
P. Repeatability of readings or successive observation
Q. Smallest perceptible change in the output.
R. Deviation of output from the true value.
S. Minimum value of the input from true value
T. Ratio of change in instrument reading to the change in measured variable

ANS: I – R
II – T
III – P
IV – Q

3. A non linear pressure sensor has an input range of 0 to 10 bar and an output range of 0 to 5V. The output voltage at 4 bar is 2.2V. Non linearity in volts as a % of span is _______

ANS: 4%

$$\text{Sensitivity} = \frac{\text{change in output}}{\text{change in input}}$$

$$\therefore \quad S = \frac{5-0}{10-0} = 0.5\,\text{V bar}^{-1}$$

TV = 0.5×4 (Sensitivity $\times$ input)

(True value)

Or

Expected value = 2V

Measured value/observed value = 2.2

Error = M.V – T.V

$\therefore$ E = 0.2V

% of Non linear error as per

$$\text{FSD} = \frac{0.2 \times 100}{(5-0)} = \frac{20}{5} = 4\%$$

4. Which of the following reading is best precise.

(a.) 347 N

(b.) 347.7 N

(c.) 0.00071 N

(d.) 47.01N

ANS: c

EXP: 0.00071N is more precise

5 significant figures.

5. Threshold of a measurement system is

(a.) Smallest change in input which can be detected

(b.) A measure of linearity of the system

(c.) The smallest input which can be detected

(d.) A measure of precision of the system

ANS: c

6. The term 'precision' used in instrumentation

(a.) Gradual departure of the measured value from the caliburated value

(b.) Smallest increment in the measurand that can be detected by instrument

(c.) Maximum distance or angle through which any part of mechanical system may be moved in one direction without causing motion of the next part

(d.) The ability of the instrument to give output readings close to each other, when the input is constant.

ANS: d

EXP: The most repeatable value or reproduceable value out of set of records is called precision.

ERROR ANALYSIS

1. **Error: deviation of measured value from the true value.**
   - Accuracy of an instrument is generally specified in-terms of error
   - Objective of error analysis is to compensate the error occurring due to various reasons
2. **Classification of error:**
   Errors are classified on the basis of four things
   (a.) Source
   (b.) Mode of propagation
   (c.) Probability of occurrence
   (d.) Magnitude of error

Types of error:

1. **Gross error:**
   Occurs due to human factors e.g., Inexperience, carelessness and improper use.
2. **Systematic errors:**
   All instrument related errors are systematic occurring due to substandard material used in fabrications.
   Various forms of systematic error
   (a) Environmental errors
   Occurs due to external factors such as temperature, stray magnetic field, stray electrostatic fields, ultraviolet exposure, power line parasitic capacitance etc;

   (b) Observational error
   Occurs due to improper observational methodology e.g, error due to parallax.

3. **Random errors**
   - Occurs due to unknown cause
   - Net magnitude is negligible, because cause and effect generally cancel each other
   - Magnitude of random errors is approximated by statistical methods, such as mean, deviations, variance, etc

1.2.1 Conclusion:
- Systematic error is an indication of accuracy. Symmetric error ↑↑ ⇒ Accuracy ↓↓
- Random error is an indicator of precision. Random error ↑↑ ⇒ Precision ↓↓

Another method for classification of error is mathematical

(i) Limiting error: If the deviation of measured value from the true value is specified by the manufacturer himself, then such a deviation is defined as limiting error or guarantee error.

(ii) Absolute error: If the error is specified in terms of unit then it is absolute error.
Absolute limiting error:
$A_a = A_s + \delta A$
A_a = Measured value
A_s = true/nominal value

δA = Absolute limiting error

|Absolute error| = MV – TV

(iii) Relative error: If the error is specified in the ratio and % then it is relative error.

As the absolute value of error doesn't convey any information, it is always specified in true value

∴ % error or relative error = $\frac{MV - TV}{TV} \times 100$

In this section we will discuss certain features which are common to all electrical measuring instruments. We will first consider various torques acting on its moving system. In an indicating instrument, it is essential that the moving system is acted upon by three distinct torque (or forces) for satisfactory working. There torques are:

1. A deflecting or operating torque, T_d
2. A controlling torque, T_c
3. A dampling torque, T_v.

A Deflecting (Or the Operating) Torque

The deflecting torque, causes the moving system of the instrument to move from its zero position. It may be produced by utilizing any one of the effects of current or voltage in the instrument such as magnetic effect, electromagnetic induction effect, heating effect, electrostatic effect etc. The actual method of producing a deflecting torque depends upon the type of the instruments.

The deflecting torque has to supply the following torque-components presents in an instrument.

(*a*) The torque required to overcome the torque due to the inertia of the moving system, $J(d^2\theta / dt^2)$, where J is the moment of inertia and θ is the movement (rotation in radians).

(*b*) The torque required to overcome the controlling torque, $T_c (\equiv k_c \theta)$.

(*c*) The torque required to overcome the damping torque, $T_v \left(= k_v \frac{d\theta}{dt} \right)$, where k_v is damping torque constant.

(d) The torque requirred to overcome the frictional (coulomb) torque. This component is minimized by appropriate design considerations.

The controlling torque developed in an instrument has two functions:

(*a*) It limits the movement of the moving system and ensures that the magnitude of the deflections always remains the same for a given value of the quantity to be measured.

(*b*) It brings back the moving system to its zero position where the quantity being measured is removed or made zero.

The controlling torque is dependent on the magnitude of deflection produced. The moving system is deflected from zero to such a position that the controlling torque at that deflected position is equal to the deflecting torque. The controlling torque increases in magnitude with the deflection till it balances the deflecting torque. That is, for a steady deflection, Controlling torque, T_c = Deflection or operating torque, T_d

The controlling torque is entered in all commercial instruments by any one of the following three ways.

Spring Control

Figure shows a spindle free to turn between two pivots. The moving system is attached to the spindle. Two phosphor-bronze hair springs *A* and *B* wound in opposite directions are also shown whose inner ends are attached to the spindle. The outer end of spring *A* is connected to a leaver which is pivoted the adjustment of which gives zero setting. However, the outer end of *B* is fixed. When the pointer is deflected one spring unwinds itself while the other is twisted. This twist in the spring produces restoring (controlling) torque, which is proportional to the angle of deflection of the moving systems. Let *E* be the young-modulus for the material of the spring and (radians) be the deflection of the moving system to which one end of the spring is attached. Then, the controlling torque developed in the spiral spring is given by

$$T_c = \frac{Ebt^3}{12l}\theta$$

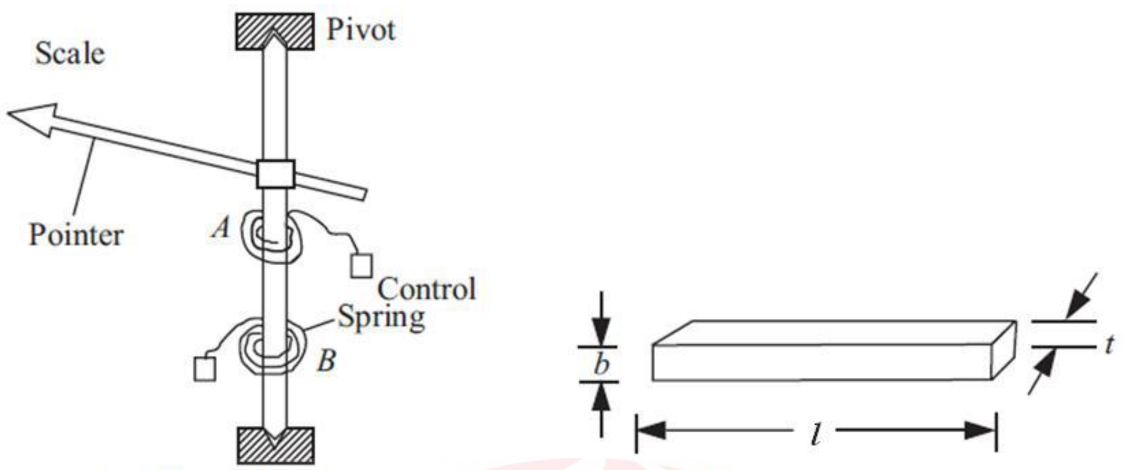
or $$T_C = k_s\theta$$

where l = Total length of spring strip (m)

b = depth of the strip (m)

t = thickness of the strip (m)

k_s = spring constant



(*a*) Pivoted-moving system with spring control

(*b*) Spring in strip form

The controlling spring must meet the following requirements:

• The stress developed in the spring must be well below the elastic limit of the spring material at the maximum deflection of the moving system. This is essential to avoid fatigue and to preserve stability over a long period. For this, we must have

$$\frac{l}{t} = \frac{E\theta}{2S_{\max}}$$

where S_{max} = maximum stress which must not exceed. For a full scale deflection θ = 90°, the ratio *l*/*t* is about 3000 in a good instruments.

• It springs are used as leads of current to the instrument, their cross-sectional area must be sufficient to carry the current without overheating them failing which the consistency will be impaired. The spring material should also have the following properties:

* It should have low resistance

* The temperature coefficient should also be low.

• The springs must be of non-magnetic material.

In a permanent magnet moving coil type instrument the deflecting torque is proportional to the current passing through them. Thus the operating torque, T_d , is directly proportional to the current,

$$T_d = KI$$

Then for spring control instrument, the controlling torque, T_C is

$T_c = K_s\theta$

The pointer comes to rest when the deflecting torque (T_d) and the controlling or restoring torque (T_c) are equal, *i.e.*, T_d is equal and opposite to T_C.

At equilibrium, $T_d = T_c$

Therefore, $KI = K_s\theta$

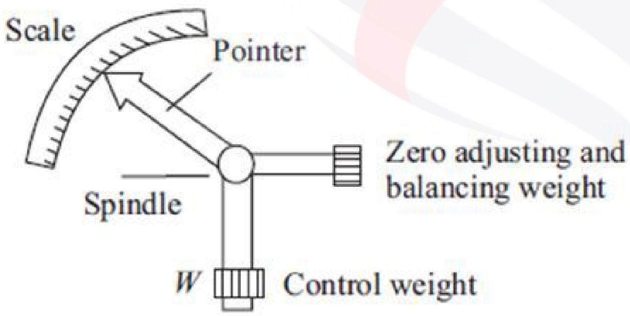
$\therefore$ $I = \dfrac{K_S\theta}{K}$

This equation shows that the current is directly proportional to the deflection and since equation is a linear relation, the scale with spring controlled instrument for deflecting torque given by equation will be uniform throughout the scale.

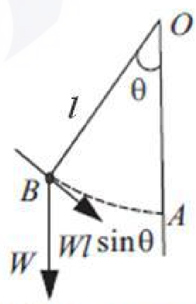
Gravity Control

In gravity controlled instruments, as shown in figure a small adjustable weight is attached to the spindle of the moving system such that the deflecting torque produced by the instrument has to act against the action of gravity. Thus a controlling torque is obtained. This weight is called the *control weight*. Another adjustable weight is also attached in the moving system for zero adjustment and balancing purpose. This weight is called *Balance weight.*

When the control weight is in vertical position as shown in figure (*a*), the controlling torque is zero and hence the pointer must read zero. However, if the deflecting torque lifts the controlling weight from position *A* to *B* as shown in figure (*b*) such that the spindle rotates by an angle θ then due to gravity a restoring (or controlling) torque is exterted on the moving system.



(*a*) Gravity controlled moving system at zero deflection



(*b*) Moving system rotated by θ radian

The controlling (or restoring) torque, T_C is given by

$T_C = Wl\sin\theta = k_g \sin$

where W is the control weight; l is the distance of the control weight from the axis of rotation of the moving system; and k_g is the gravity constant.

Equation shows the controlling torque can be varied quite simply by adjustment of the position of the control weight upon the arm which carries it.

Again, if the deflecting torque is directly proportional to the current, I *i.e.*,

$$T_d = kI$$

We have at the equilibrium position

$$T_d = T_c$$

or $$kI = k_g \sin\theta$$

or $$I = \frac{k_g}{k}\sin\theta$$

This relation shows that current I is proportional to sin θ and not θ. Hence in gravity controlled instruments the scale is not uniform. It is cramped for the lower readings, instead of being uniformly divided, for the deflecting torque assumed to be directly proportional to the quantity being measured.

Advantanges of Gravity Control

1. It is cheap and not affected by temperature variations.
2. It does not deteriorate with time.
3. It is not subject to fatigue.

Disadvantages of Gravity Control

1. Since the controlling torque is proportional to the sine of the angle of deflection, the scale is not uniformly divided but cramped at its lower end.
2. It is not suitable for use in portable instruments (in which spring control is always preferred).
3. Gravity control instruments must be used in vertical position so that the control weight may operate and also must be leveled otherwise they will give zero error.

In view of these reasons, gravity control is not used for indicating instruments in general and portable instruments in particular.

Damping Torque

We have already seen that the moving system of the instrument will tend to move under the action of the deflecting torque. But on account of the control torque, it will try to occupy a position of rest when the two torques are equal and opposite. However, due to inertia of the moving system, the pointer will not come to rest immediately but oscillate about its final deflected position as shown in below figure and takes appreciable time to come to steady state.

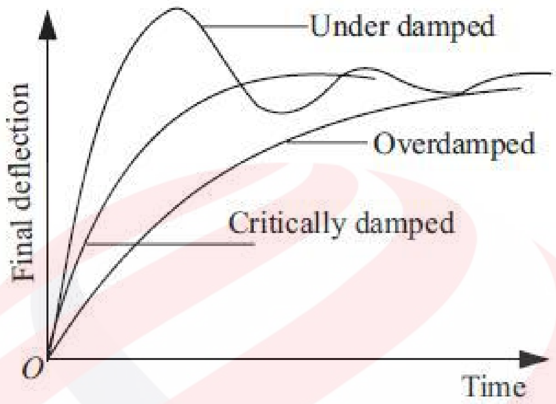


Figure : *Dynamic response of a measuring instrument*

To overcome this difficulty a damping torque is to be developed by using a damping device attached to the moving system. The damping torque is proportional to the speed of rotation of the moving system, that is

$$T_v = k_v \frac{d\theta}{dt}$$

where k_v = damping torque constant

$\frac{d\theta}{dt}$ = speed of rotation of the moving system

Depending upon the degree of damping introduced in the moving system, the instrument may have any one of the following conditions as depicted in Figure.

1. Under damped condition: The response is oscillatory

2. Over damped condition: The response is sluggish and it rises very slowly from its zero position to final position.

3. Critically damped condition: When the response settles quickly without any oscillation, the system is said to be critically damped.

In practice, the best response is slightly obtained when the damping is below the critical value *i.e.*, the instrument is slightly under damped.

The damping torque is produced by the following methods:

Air Friction Damping

In this type of damping a light vane or vane having considerable area is attached to the moving system to develop a frictional force opposing the motion by reason of the air they displace. Two methods of damping by air friction are depicted in figure

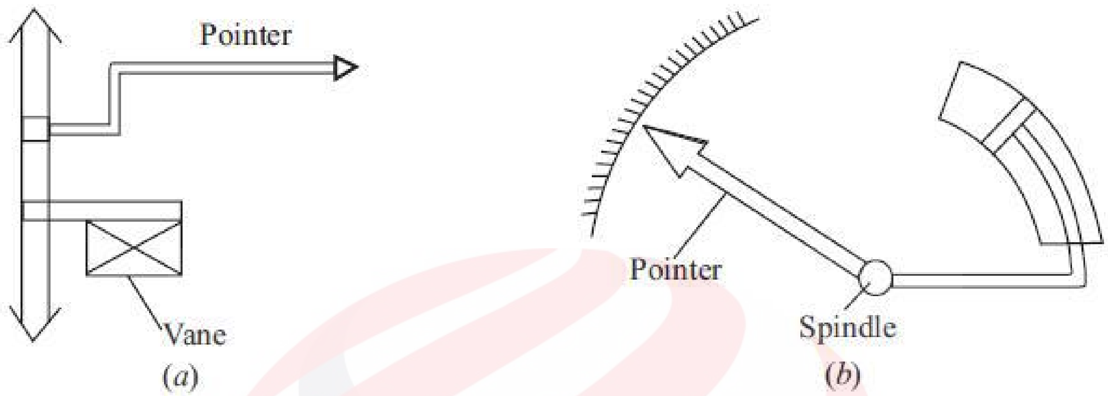


Figure: *Air-friction damping*

• The arrangement shown in Figure (a) consists of a light aluminium vane which moves in a quadrant (sector) shaped air chamber. The chamber also carries a cover plate at the top. The vane is mounted on the spindle of the moving system. The aluminium vane should not touch the air-chamber walls otherwise a serious error in the deflection of the instrument will be introduced. Now, with the motion, the vane displaces air and thereby a damping force is created on the vane that produces a torque (damping) on the spindle. When the movement is quicker the damping force is greater; when the spindle is at rest, the damping force is zero.

• The arrangement of Figure (*b*) consists of a light aluminium piston which is attached to the moving system. This piston moves in a fixed chamber which is closed at one end. Either circular or rectangular chamber may be used. The clearance (or gap) between the piston and chamber walls should be uniform thoroughout and as small as possible. When the piston moves rapidly into the chamber the air in the closed space is compressed and the pressure of air thus developed opposes the motion of the piston and thereby the whole moving system. If the piston is moving out of the chamber, rapidly, the pressure in the closed space falls and the pressure on the open side of the piston is greater than that on the opposite side. Motion is thus again opposed. With this damping system care must be taken to ensure that the arm carrying the piston should not touch the sides of the chamber during its movement. The friction which otherwise would occur may introduce a serious error in the deflection.

The air friction damping is very simple and cheap. But care must be taken to ensure that the piston is not bent or twisted. This method is used in moving iron and hot wire instruments.

Fluid Friction Damping

• This form is damping is similar to air friction damping. The action is the same as in the air friction damping. Mineral oil is used in place of air and as the viscosity of oil is greater, the damping force is also much greater. The vane attached to the spindle is arranged to move in the damping oil.

• It is rarely used in commercial type instruments.

• The oil used must fulfill the following requirements.

* It should not evaporate quickly
* It should not have any corrosive effect on metals.
* Its viscosity should not change appreciably with temperature.
* It should be good insulator.

Two arrangements of fluid damping are shown in figure below.

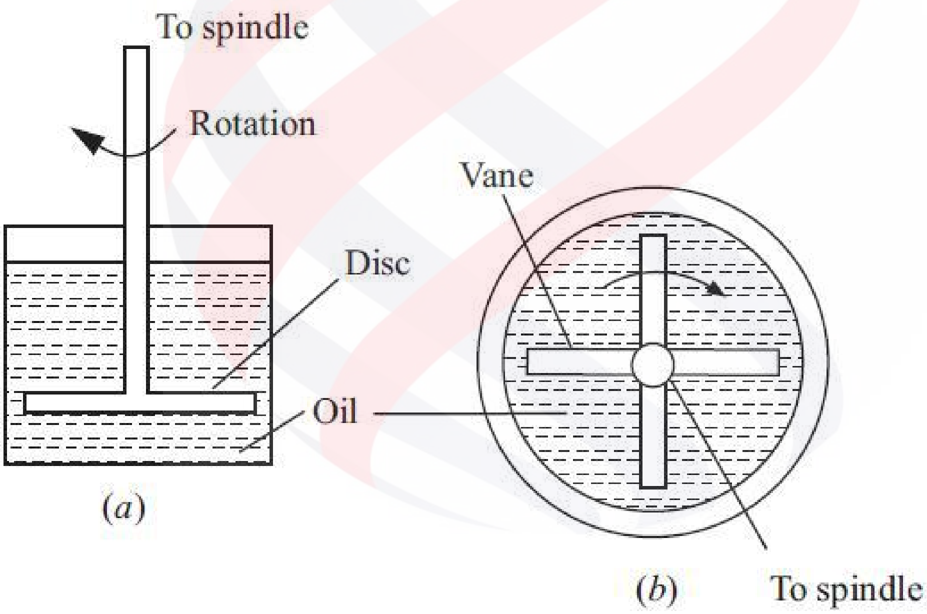


Figure: *Fluid friction damping devices*

(a) In figure (a) a disc attached to the moving system is immersed in the fluid (damping oil). When the moving system moves the disc moves in oil and a frictional drag is produced. For minimizing the surface tension affect, the suspension stem of the disc should be cylindrical and of small diameter.

(*b*) In the arrangement of figure (*b*) a number of vanes are attached to the spindle. These vanes are submerged in oil and moves in a vertical plane. This arrangement provides greater damping torque.

Advantages of Fluid Friction Damping

1. The oil used for damping can also be used for insulation purpose in some forms of instruments which are submerged in oil.
2. The clearance between the vanes and oil chamber is not as critical as with the air friction clamping system.
3. This method is suitable for use with instruments such as electrostatic type where the movement is suspended rather than pivoted.
4. Due to the up thrust of oil, the loads on bearings or suspension system is reduced thereby the reducing the frictional errors.

Disadvantages of Fluid Friction Damping

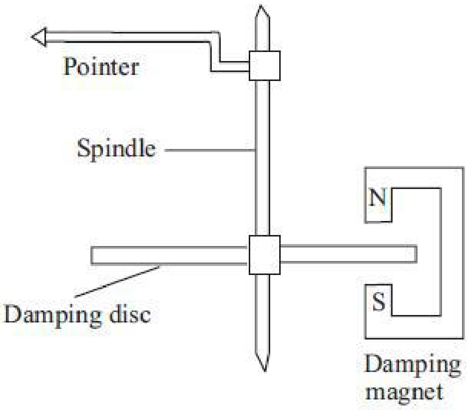
1. The instruments with this type of damping must be kept always in a vertical position.
2. It is difficult to keep the instrument clean due to leakage of oil.
3. It is not suitable for portable instruments.

The fluid friction damping can be used for laboratory type electrostatic instruments.

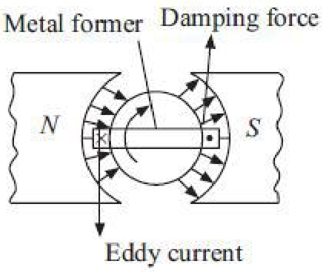
Eddy Current Damping

Eddy current damping is the most efficient form of damping. The essential components in this type of damping are a permanent magnet; and a light conducting disc usually of alumninum. When a sheet of conducting material moves in a magnetic field so as to cut through lines of force, eddy currents are set up in it and a force exists between these currents and the magnetic field, which is always in the direction opposing the motion. This force is proportional to the magnitude of the current, and to the strength of field. The former is proportional to the velocity of movement of the conductor, and thus, if the magnetic field is constant, the damping force is proportional to the velocity of the moving system and is zero when there is no movement of the system.

Figure shows two methods of applying this method of damping. In Figure (*a*) a thin disc of conducting, but non-magnetic material-usually copper or aluminium is mounted on the spindle which carries the pointer of the instrument. When the spindle rotates, the edge of the disc cuts through the lines of force in the gap of a permanent magnet, and eddy currents, with consequent damping, are produced. An arrangement similar to this is often used in hotwire instruments.



(*a*) Eddy current damping



(*b*) Electromagnetic damping

Figure (*b*) shows the essential parts of a permanent-magnet, moving coil, instrument. The coil is wound on a light metal former in which eddy currents are induced when the coil moves in the permanent-magnet field. The directions of the eddy-current which in turn produce the damping torque due to the motion of the coil (clockwise) are as shown in Figure (*b*) and this will produce damping forces as indicated in the figure.

Electromagnetic Damping

• The movement of a coil in a magnetic field produces a current in the coil which interacts with the magnetic field to produce a torque. This torque opposes the movement of the coil and shows the response.

• The magnitude of the current and hence the damping torque is dependent upon the resistance of the circuit which the instrument is connected.

• This damping method is used in galvanometers.