Chapter One

The Strain Gauge

**Strain gauge**: it is an electrical conductor whose resistance changes as it is strained.

**Types of strain gauge**:

- **Bonded gauges** *(see Fig. 1.1)*
  1- Wrap-around wire strain gauge
      It were wound with fine copper wire on a thin paper tube, which was then flattened and stuck to a metal surface. It is used for high resistance gauges (several hundred ohms resistance).
  2- Flat-grid strain gauge
  3- Etched foil strain gauge

Generally, Flat-grid and Etched foil strain gauges have resistance of not much more than one hundred ohms.

These three types strain gauges must be fixed with a suitable adhesive to the surface whose strain they are to measure. When they are properly bonded, the electrical conductor is embedded in the bonding material, so that not only does tensile strain cause the strain gauge’s resistance to increase, but compressive strain causes it to decrease in exactly the same proportion.

- **Unbonded gauges** *(see Fig. 1.2)*

  This type is used to give an electrical output signal proportional to a very small displacement of one body relative to another body.

One of its applications is an accelerometer. The very fine wire forming the strain gauge resistance is stretched between insulating pegs on the two bodies (seismic mass) and the casing around it.
Strain calculation

The relationship between strain and electrical resistance is given by the equation:

\[
\frac{\delta R}{R} = k \varepsilon
\]

Where:

- \( \varepsilon \) is strain. That is, \( \varepsilon = \frac{\delta l}{l_{\text{original length}}} \) elongation

where \( \delta l \) is the change in length due to strain. From above equation it is clear that electrical strain is proportional to mechanical strain.

The bridge circuit (Null method) (see Fig. 1.3, 1.4)

Because of the actual change of strain gauge resistance is very small, Wheatstone bridge circuit has to be used. \( R_A \) is the active gauge, bonded to the material whose strain is to be measured. \( R_B \) is variable resistance. \( R_C \) is a fixed resistance. \( R_D \) is the dummy gauge, another strain gauge, identical to \( R_A \) but bonded to an unstrained piece of the same material as \( R_A \) is bonded to, and placed as close as possible to \( R_A \). In order to cancel out any resistance change in \( R_A \) caused by change of temperature.

To measure the resistance of \( R_A \) the bridge is balanced by adjusting \( R_B \) so that the voltages at P and Q are equal. Then:

\[
R_A = R_B \times \frac{R_D}{R_C}
\]

The advantage of this method that the results are unaffected by variations in the voltage of the power supply. The problem, it takes the time and attention of an operator and transient changes of strain may pass unnoticed.
The direct-reading bridge (see Fig. 1.6)

In industry, strain gauges are more often used to measure a load causing strain than to measure strain itself. One of advantage, it gives a continuous output signal.

In this method the bridge is left unbalanced. The calibration is done by applying known loads to the structure and noting the output voltage $V_{PQ}$ (the relation is a straight line). The main problem, the calibration will only be correct for one particular voltage of the power supply.

The output voltage may be zeroed at zero load by adjusting a low-resistance potentiometer, $R_z$.

Temperature-compensated gauges (see Fig. 1.5)

Sometimes, due to limitations of space or other constraints, dummy gauge cannot be used.

Consider the effects of a temperature increase as it acts on a strain gauge alone, and on a steel surface to which it is to be bonded. These effects are:

1- An increase in the resistance of the strain gauge.
2- A linear expansion of the metal of the strain gauge.
3- A linear expansion of the steel surface.

As expansion 2) is usually greater than expansion 3). (because of the difference in the coefficient of linear expansion of the two metals) the effect of the bond between strain gauge and steel is to put the strain gauge in compression, causing a decrease in its resistance. By a choice of suitable constituents of the strain gauge alloy, and suitable heat treatment during its manufacture, the decrease in resistance can be made to cancel out the increase in resistance from effect 1).
The twin-active-gauge bridge (see Fig. 1.7)

When the direct-reading bridge is used to measure loads (such as: bending moment, tension and compression, shear) instead of strains, it is more useful to exploit the dummy gauge measuring. The advantage it will still cancel out temperature effects in active gauge. Also, it will increase the output voltage of the bridge.

To measure bending moment, the dummy gauge is positioned on the opposite side of the neutral axis to the active gauge. For a cross-section symmetrical about the neutral axis, this double the strain sensitivity and makes the arrangement insensitive to any end load which may be present, as the resistance change in the two gauges due to end load is of the same sign, and so cancels out.

To measure end load (tension or compression), the dummy gauge is positioned where it will be acted upon by the Poisson’s ratio (is the ratio of lateral strain to longitudinal strain) effect. The two strains are always of opposite sign, and the actual value of Poisson’s ratio depends on the material which is being strained.

To measure shear force, the active and dummy gauges are positioned at 45° to the direction of the shear and 90° to each other, so that one is acted on by the tensile, and the other by compressive strain set up by the shear.

Semiconductor (piezo-resistive) strain gauges

It is made from crystalline materials in which large changes of electrical resistance occur when stress is applied.

**Advantage:**

1- Large sensitivity compared with traditional strain gauge.
2- No need for amplification of their output.
3- Can be used to measure dynamic strains

**Disadvantage:**
The main problem their gauge factors may vary considerably as strain is applied, and also as temperature changes, so they are not quite as simple to use as ‘conventional’ gauges.

Possible sources of error in strain gauge signals

1- Cross-sensitivity
Because a strain gauge has width as well as length, a small proportion of the resistance element lies at right angles to the major axis of the gauge, at the points where the conductor reverses direction at the ends of the gauge. So as well as responding to strain in the direction of its major axis, the gauge will also be somewhat responsive to any strain there may be at right angles to major axis.

2- Bonding faults
For perfect bonding, the suitable adhesives and procedures for bonding gauges to the strain surface should be complied.
If the bonding is unsatisfactory, creep may occur. Creep is a gradual relaxing of the strain on the strain gauge, and it has the effect of decreasing the gauge factor, so that the output of the bridge becomes less than it should be. Creep may also occur where gauges have been used to measure dynamic strain, and have been subjected to many thousands of cycles of strain.

3- Hysteresis(see Fig. 1.8)
If a strain gauge installation is loaded to a high value of strain and then unloaded, it may be found that the gauge element appears to have acquired a permanent set, so that resistance values are all slightly higher when unloading when loading-up. The same effect continues when the direction of loading is reversed. To manipulate this problem, repeating cycles of loading/unloading should cause the hysteresis loop to narrow to negligible
proportions. Severe hysteresis, which cannot be reduced in this way indicates faulty bonding of the gauge.

4- **Effects of moisture**
The gauges or the bonding adhesive may absorb water. This can cause dimensional changes which appear as false strain values. Another effect when moisture connections forms high resistance connected in parallel with the gauge. To prevent this, gauges should be bonded in dry condition or a suitable electrically insulating water repellent, such as a silicone rubber compound.

5- **Temperature change**
One possible source of temperature difference is the heat produced by the current through a strain gauge. When the bridge is first switched on, the gauges may warm up, so the bridge should not be used for measurement until sufficient time for temperature to stabilize.
Chapter Two

Temperature Transducers

**Temperature**: is a function of the intensity of vibration of its atoms and molecules.

**Temperature measuring unit:**

- Celsius scale (centigrade scale) uses the Celsius degree as its unit of temperature. **Celsius degree** is one-hundredth of the temperature change between the freezing and boiling points of water at standard atmospheric pressure, the freezing point being 0°C and the boiling point 100°C.

- Kelvin is the same unit of temperature at as Celsius degree. Zero kelvin is absolute zero where it is the temperature at which atoms and molecules are absolutely vibrationless (at -273.15°C). Thus the freezing and boiling points of water at standard atmospheric pressure are 273.15 K and 373.15 K respectively.

**Methods of temperature measurement**

There are four ways in which this can be done:

1. **Expansion**, temperature change can be converted into change of volume, as in a liquid-in-glass thermometer, or into change of shape, as in a bimetallic strip.
2. **Thermoelectricity**, a small voltage is generated where two different metals are joined together. The magnitude of the voltage generated depends on the temperature of the junction.
3. **Electrical resistance**, resistance of metals and of semiconductors varies with temperature.
4. **Radiation**, the heat energy radiated by a body increases in quantity and includes radiation at shorter and shorter wavelengths as temperature increases.
Time constant(first-order linear systems)(Fig. 2.1)

When thermometer is suddenly plunge into boiling water it does not instantly indicate the temperature of the water. The mercury rises very quickly at first, but slows down as it rises its final value.

The rate of heat transfer to the thermometer is proportional to the temperature difference between the water and the thermometer; the smaller the remaining temperature difference, the more slowly does the temperature rise.

Such system are called first-order linear systems, which describe by the following equation:

\[(\text{Change which still has to be made}) = (\text{step input}) \times e^{-\frac{t}{\tau}}\]

Where

- \(e\) is 2.718
- \(t\) is time(seconds)
- \(\tau\) is time constant(seconds)

It is important to know the time constant of transducers. To estimate how long the operator wait before take reading. The time constant can be found by taking a tangent to the curve at any point or as the value of \(t\) at which the ordinate of the response curve is 63.2% of the step input.

Sinusoidally varying temperatures(Fig.2.2)

If the input to a first-order transducer such as a thermometer, varies continuously, its time constant causes the corresponding variation in its output to lag behind that of its input. If the input variation takes the form of a sinewave, the output variation is determined by the following two equations:

\[\text{Output amplitude} = \frac{\text{(input amplitude)}}{\sqrt{(\omega\tau)^2+1}}\]
And

Phase lag = arctan \( \omega t \)

Where \( \omega \) is the angular frequency of the sinewave in radians/second.

Thermocouples(Fig.2.3,2.4,2.5)

If two different metals are joined together, either mechanically or by welding, a small continuous voltage is generated at the junction. This voltage is generated by what is known as the Seebeck or thermoelectric effect. It depends on the temperature of junction and on the metals used. Therefore, the junction is converting temperature into voltage.

One of its application is in gas-fire safety devices where thermocouple projecting into the flame give enough current to energise a solenoid holding a gas valve open against the force of a weak spring – if the flame goes out, the thermocouple ceases to generate current and the spring closes the gas valve.

Thermistors(Fig. 2.6)

This device is made from materials in which a large change of electrical resistance is produced by a small change of temperature. The usual type of thermistor has a negative temperature coefficient(n.t.c.) and a resistance-temperature relationship which is defined by

\[
R = A e^{B/T}
\]

Where A and B are constants for the particular material, and T is absolute temperature of the thermistor in kelvins. Writing this equation for a particular pair of values of resistance and temperature, \( R_1 \) and \( T_1 \), we get:

\[
R_1 = A e^{B/T_1}
\]

And dividing the general equation by particular, gives:
From which the resistance $R$ can be calculated at any absolute temperature $T$, if $R_1$, $B$ and $T_1$ are known. $B$ is a temperature in kelvins, called the characteristic temperature of the thermistor.

**Application**

One of its application measure the temperature of the cooling water in a motor vehicle engine. The current meter can consist of just a bimetal strip carrying a pointer, the current being passed through a length of resistance wire wound round the bimetal strip to act as a heater. As the water temperature increases, the resistance of the thermistor decreases; thus the current passing through the heating coil increases, causing it to heat up the bimetal strip and so deflect the pointer. It is very crude, very cheap, but rugged, and immune to vibration and ‘transients’

**Positive temperature coefficient (PTC) thermistors**

In this type, increase of temperature increases its resistance, instead of decreasing it. It is usually used for over-temperature protection of industrial protection equipment, and for over-current protection of electrical circuits. Over-temperature protection type has a low resistance until the temperature reaches a specified reference temperature. Within a few degree above temperature the resistance increases about a hundred-fold, switching off a circuit. Over-current protection type is a switch-off fail-safe device, operated by the self-heating effect which occurs when too much current is passed through it. The resistance of the thermistor increases rapidly if the current limit is exceeded, thus bringing the current down to a small fraction of the specified limit. A typical application is the protection of the primary winding of a mains transformer.

**Resistance thermometers**

These devices offer a reliable, precise method of measuring temperature. Platinum is the metal usually used for the temperature-sensing resistor because it can withstand high temperatures without deterioration, and because its resistance-temperature relationship is almost perfectly linear. It can be used for temperature measurement throughout the range -260°C to +800°C. In the laboratory type of resistance thermometer, the platinum is in the form of a wire wound on a mica former and enclosed in a glass bulb which may be evacuated or filled with an inert gas to protect the platinum.
In industrial resistance thermometers, which do not have to cover such a wide range of temperature but must be more shock-proof, the platinum wire is wound on a ceramic former and enclosed within a glass or ceramic protective sheath. The winding is usually arranged to be non-inductive, by making the current travel down one helix and back up parallel helix.

**Radiation pyrometers (Fig. 2.7)**
These measure the temperature of a body from the electromagnetic radiation which it emits in the form of radiant heat, which is infra-red radiation and, if its temperature is high enough, visible light. This type is normally used to measure very high temperatures, such as furnace temperatures. An object at room temperature emits infra-red radiation from which its temperature can be determined, though we would normally use thermometer. However, one of the virtues of a radiation pyrometer is that it does not make contact with the measured object, so if we have a situation where it is necessary to measure a ‘low’ temperature without making contact, a radiation pyrometer can be used. Radiation pyrometer consists of a tube in which a temperature sensor is mounted. The internal surfaces of the tube have a matt black coating to minimize internal reflection. The tube may be open-ended, with the incoming radiation restricted to the area of the sensor by means of a disc with a central hole in it.

**Temperature sensors for radiation pyrometers (Fig. 2.8)**
The temperature sensor loses heat to its surroundings, therefore has a lower temperature than the object being measured. A compact device of low thermal capacity is required. Thermistors may be used for ‘low’ temperature measurement; thermocouples or thermopiles are used for higher temperatures. A thermopile is a number of thermocouples connected in series, the voltage generated by a single hot-junction/cold-junction pair being multiplied by the number of such pairs. The cold junctions may be kept at a stabilized temperature by installing the thermopile in a small temperature-control box—the oven. A small hole in the side facing the thermopile so that only the hot junctions are exposed to the radiation.

**Calibration**
There are two types of calibration:
Primary calibration, an instrument is calibrated by reference to values obtained from first principles under laboratory conditions.
Secondary calibration, an instrument is calibrated against values determined by a standard instrument which has itself received a primary calibration.

**The bimetallic strip**
This consists of two metals with unequal coefficients of linear expansion, bonded together to form a single piece of material. A change in temperature causes them to expand or contract unequally, and this results in a proportionate increase or decrease in the curvature of the material. Simple dial-and-pointer type thermometers are made by forming the bimetallic strip into a spiral or a helix. This is fixed at one end to the body of the instrument and carries a pointer at the other end. Temperature change causes the bimetallic strip to curl or uncurl so that the pointer indicates temperature on a circular dial.
Chapter Three

Displacement Transducers

Mechanical devices

These devices usually consist of combination of rack and pinion, gear train, cable and drum and lever. Their purpose is to amplify small displacement.

**Advantage**: it is a positive in action – that is, the amplification factor, is set fixed and cannot vary.

**Disadvantage**:

1- Input displacement must be applied with sufficient force to overcome friction in the mechanism.
2- Inertia of the components of the mechanism is magnified by the gain of the mechanism, so very large input forces are needed if the device is accurately to follow rapidly varying displacements.
3- Purely mechanical devices are not remote reading.

The potentiometer (pot) (Fig. 3.1)

It consist of a resistance element (the track) is connected across a source of voltage, and a wiper, which can be positioned anywhere along the track, picks off a corresponding proportion of the source voltage.

- **Wire-wound pot**

Figure 3.1 shows this type of pot. It is robust and wear-resistant, but their resolution is limited because their output voltage increase or decreases in steps corresponding to the successive turns of wire contracted by the wiper.
- **Slide pot**

In this type, the resistance element is straight, the wiper travelling in a straight line along its length instead of being rotated by a spindle.

- **Multiturn pot**

In this type, the resistance wire is wound on a helical former. The wiper is made to travel along a helical path with the same pitch as the resistance element, so that it is always in contact with the resistance.

Some resistance elements are made deliberately non-linear, to cancel out an opposite non-linearity in the circuit such as logarithmic track pot, in which the resistance is so arranged that, at any point, the log of the resistance from one end of the track is proportional to the angle turned by the wiper. This type of pot is used as volume controls in radio receivers where they contract the fact that at the low end of the track, a small increment of resistance gives a much greater percentage increase in volume than a similar increment at the high end of the track.

**Potentiometer loading** *(Fig. 3.2, 3.3)*

For practical application, the current drawn by the wiper should not be neglected due to measure the output voltage of a pot, a voltmeter must be applied or connect it to the input of an amplifier. Therefore, the load will has a resistance.

For the circuit shown in Figure 3.2, $R_L$ is the resistance of the voltmeter or the input resistance of the amplifier. The portion of pot resistance between the wiper and its lower end will have some value $aR$, where $R$ is the total resistance of the pot and $a$ (between 0 and 1). The equivalent resistance is

$$R_e = \frac{aR \times R_L}{aR + R_L}$$

Where the voltage applied to the load is
\[ V_L = \frac{R_e}{R_e + (1-a)R} \times V_s \]

Substituting for \( R_e \) gives

\[ V_L = \frac{a}{1 + a(1-a)(R/R_L)} \times V_s \]

The curves in Figure 3.3 show how the output voltage \( V_L \) deviates from the linear relationship \( V_L = a \times V_s \) as the ratio \( R/R_L \) is increased from 0 to 1 (that is, as \( R_L \) is decreased from infinity).

**Pot noise**

In time the resistance track and the wiper of a pot acquire a coating of dirt and corrosion products. This introduces a varying resistance between the wiper and the resistance track, causing electrical ‘noise’ in the signal from the pot, as the wiper travels along the track. To reduce the noise in the design step:

1- Sealing the pot casing against dust and moisture
2- Using a multiple-contact wiper, or using a solid carbon brush as the wiper

**The linear variable differential transformer (LVDT) (Fig. 3.4, 3.5)**

The difference between this transducer and pot, there is no contact between fixed and moving parts, as result there is no friction to be overcome and negligible electrical noise in the signal.

The structure of this transducer is, the fixed part is a transformer consisting of three coils: a primary winding (supplied with AC of constant amplitude and constant frequency from an oscillator) and two matched secondary winding. The input displacement is applied as an axial displacement of the core. With the core in mid-position in the transformer, the secondaries pick up AC voltages which are equal in magnitude but opposite in phase, so they cancel out. Displacement of
the core towards one secondary causes an increase in the amplitude of the AC in that winding and a corresponding decrease in amplitude in the other winding.

The output is an AC voltage with amplitude proportional to the displacement.

LVDT limitations

1- Small displacement range (±15mm) can be measured due to practical limitation to the dimension of the core and windings.
2- There is a displacement frequency limit imposed by the smoothing circuit.
3- It is impossible to guarantee the phase shift between the primary winding for AC voltage to be 180°.

Variable inductance transducers (Fig. 3.6)

The displacement alters the air gap between the end of the E-shaped core and a mild steel plate. The alternating current through the coil sets up and alternating magnetic field. The reluctance of the magnetic flux to pass through air is a thousand times greater than its reluctance to pass through iron, so a small reduction in the air gap causes a large increase in the magnetic field strength in the flux path. Thus a reduction in the air gap causes a reduction in the reading on the AC meter and vice-versa. The change in meter reading is proportional to the change in air gap over a limited range of gap (usually about 5 mm).

Capacitive transducers (Fig. 3.7)

This is the a differential pressure transducer. The two pressure, \( P_1 \) and \( P_2 \), are applied each to an isolating diaphragm at either end of the transducer body. The diaphragms deflect and transfer the pressure through silicone oil, which also acts as the dielectric, to the opposite faces of the sensing diaphragm. Deflection of the sensing diaphragm towards one of the fixed plates reduces the thickness of dielectric on that side, increasing its capacitance, thus reducing its reactance and vice-versa.
**Application**: it can be used to measure the contents of fuel tanks in aircraft. The plates of the capacitor are two metal tubes, one inside the other, projecting from top to bottom, inside the tank. The annular space between the inner tube and the outer tube is filled partly by the fuel and partly by the air above the fuel. Since air and fuel have different relative permittivities, the capacitance depends on the quantity of fuel in the tank.

The main **advantage**, the total capacitance is made up of a number of such pairs of tubes at suitable places in the tank, the reading is largely unaffected by the attitude of the aircraft in pitch or roll.

**Binary coded disc**(Fig.3.8)

This component can be used to measure angular or linear displacement. It is a disc that divided to sectors with different colors (black and white) which represent the binary logic(‘0’,’1’).

**Overcoming ambiguity**

Binary coded disc problem is that when more than one binary digit changes the sensors do not detect the change simultaneously.

There are two methods to manipulate this problem:

1- To add an anti-ambiguity track and an extra sensor (Fig.3.9)
2- Using Gray cyclic coded pattern on the disc instead of natural binary pattern(Fig.3.10). The benefit of Gray code that only one digit at a time changes.

To measure an angle of rotation to the nearest 1/16 of a revolution, to the nearest 22.5°. Each disc has four tracks, because 16=2^4. To measure rotation with an error not greater than one degree, the disc need to have nine tracks(because 2^8<360<2^9).
Sensors

For severe environmental conditions such as high temperature or severe mechanical shock, brushes may be used, contacting on a disc in which the ‘dark’ sectors are of electrically conducting material and the ‘light’ sectors are insulating. Alternatively, optical sensors (Fig.3.11) may be used. The dark and light sectors may be formed on a transparent disc, through which beams of infra-red light may be projected on to phototransistors. Otherwise the disc may be opaque, with each track on the disc reflecting infra-red light to a photo transistor housed in the same package as the light source.

Appendix

Capacitance occurs where two electrical conductors are separated by an insulator (dielectric). Capacitance calculated in farads (F) from formula:

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]

Where

C is the capacitance in farads,
\( \varepsilon_0 \) is the permittivity of free space (8.85 \( \times 10^{-12} \) F/m)
\( \varepsilon_r \) is the relative permittivity of the dielectric
A is the area of overlap of the plates
d is the thickness of the dielectric

A capacitor prevents the passage of DC, but AC passes through. It has a resistance to AC (a reactance) given by the formula:

\[ X_C = \frac{1}{2\pi fC} \]

Where
\(X_c\) is the reactance in ohms,

\(f\) is the frequency of the AC in hertz,

\(C\) is the capacitance in farads.
Chapter Four

Force, torque and pressure transducers

**Elastic sensors**

These types of sensors use material that deflect proportionately to force, torque or pressure. The sensor may measure direct effect of load (deflection), as in a spring balance, or its side effect (strain), as in a strain gauge.

The sensor material should be perfectly elastic and free from creep.

**Hydraulic load cell (Fig 4.1)**

In this transducer, the force is applied to a diaphragm (moving part) that cover a capsule filled by oil. The resulting pressure measured by a pressure gauge graduated in units of force.

**Piezoelectricity (Fig 4.2)**

In this transducer which used quartz or other types of piezoelectricity material, this material acquires electrostatic charge proportional to the load when it is loaded in compression and a corresponding voltage appears between the electrodes. It can thus be used as a force transducer.

**Piezoelectric force transducer (Fig 4.3)**

The piezoelectric material is in the form of two quartz discs, one on either side of a metal disc which acts as one of the electrodes. Because the quartz discs cannot be loaded in tension they are given a compressive preload by tightening the nuts.
against each other. Then tension is measured as a decrease in the preload on the disc, compression as an increase.

The step response of a piezoelectric transducer

When a load is applied to a piezoelectric force transducer, the tiny amount of work done in compressing the crystal converted into electrostatic charge. This immediately begins to leak away at a rate proportional to the voltage between the electrodes. The dynamic behavior covered by following law:

\[ v = V e^{-t/\tau} \]

Where

- \( V \) is initial voltage,
- \( t \) is the elapsed time after the step
- \( \tau \) is the time constant

The charge amplifier

In Fig. 4.4, the piezoelectric crystal is represented by the capacitor \( C \) which acquires a charge \( q \) in proportion to the applied force. The relation between output amplifier and charge is

\[ V_o = -\frac{q}{C_f} \]

The advantage of a parallel resistance \( R \) with \( C_f \) is necessary to stabilize the amplifier, by providing a DC feedback path.
The electromagnetic force balance(Fig 4.6)

This type of measuring device used to measure very small force. The moment of the applied force $P$ is opposed by the torque due to the current through the moving coil, so the coil and arm are kept in equilibrium. Any movement of the arm alters the ratio of the capacitances of the differential capacitor. This alters the output voltage from the capacitance bridge and phase-sensitive detector. This output voltage is applied to one input of an operational amplifier, changing its output current, which flows through the moving coil altering the torque it exerts and so restoring the arm to its original position.

Combination of two or more transducers

In Fig. 4.7 which shows proving ring that converts force into deflection along a diameter, and this is normally measured by a dial gauge. An LVDT may be used instead of the dial gauge, converting the deflection into an electrical signal suitable for use in an automatic control system.

Torque measurement

Measurement of torque in a rotating shaft

1- Strain gauge
   The difficulty in this method, how to make electrical connection to it. This can be done by following method:
   a- Slip ring
      The main problem is the friction. Therefore, the method used to temporary measurements.
   b- Rotary transformer(Fig 4.8)
   c- Radio telemetry
These two methods (b,c) depend on excitation transformer and radio signal to transfer signal from rotating shift. Since there is no connection between surface it can be used to permanent installations.

2- **Torsional deflection**
   
a- Use the principle that one end of a shaft twists relative to the other in proportion to the torque applied. The difficulty of reading a rotating scale is overcome by illuminating it with a stroboscope flashing at the same frequency as the rotational speed of the shaft, so that the scale and pointer appear stationary(Fig 4.9).
   
b- Two radially slotted discs are attached to the shaft, a small distance apart. A non-rotating light source and photodetector are used to measure the illumination received through the slots in the discs. The slots are exactly aligned when the shaft is under no torque. As torque is applied, the shaft twists, causing one disc to rotate slightly relative to the other. The light received by the photodetector is reduced in the same proportion as the torque applied. Provide that a photodetector with a short rise time is used, its output when the slots pass through the beam of light is the same as when the shaft is stationary(Fig 4.10).

**Dynamometers**

The principles depend on applying a braking torque to machine and measure its torque output. They absorb the full mechanical power output of the engine. In the simplest types of dynamometer the braking torque is applied to a brake drum by friction, using brake blocks or a rope, and measured by means of a spring balance or a pair of spring balances.
The electrical dynamometer (Fig 4.11)

Basically, this is a DC generator driven by the engine. The generator is mounted on trunnions so that its casing free to rotate through a small angle. The Torque exerted by the engine on the armature is transmitted through the internal magnetic field to the casing, and measured by a spring balance or load cell at the end of a torque arm. The field coils are supplied with current from an external source, and braking torque is controlled by varying this current.

Because the same electrical machine is a generator when supplied with mechanical power and an electric motor when supplied with electrical power, an engine can be started by switching the field and armature windings of its dynamometer to a suitable electrical power supply. The power losses due to frictional effects also can be measured in this way, by using the dynamometer to drive a ‘dead’ engine.

Pressure measurement (Fig 4.11)

In this type, internal pressure causes the flattened cross-section to open out to a more circular form, and this causes tube itself to tend to straighten out. Change the shape of this type of measuring device gives different advantage:

a- Using a diaphragm for low pressure
b- Twisted to be more resist to shock and vibration
c- Lengthened and formed into a spiral or helix to increase sensitivity

U-tube manometers

These work on the principle that at the lower of the two levels in the U-tube, the pressures in the two limbs are equal, so the difference between the pressures acting on the two surfaces is given by

\[ p_1 - p_2 = \rho g h \]
Where

\( \rho \) is the density of the liquid

\( g \) is gravitational acceleration 9.8 m/s\(^2\)

\( h \) is the height of liquid above the lower level
Chapter five

Velocity transducers

Linear velocity measurement

To measure the speed of a body, such as a wheeled vehicle, a ship or an aircraft. For the wheeled vehicle the simplest method is to convert the linear velocity into a rotational velocity by driving a speedometer from the output shaft of the gearbox. Also, it can be measured by Doppler effect or from distance/time.

If two positions of the vehicle are known, velocity may be calculated by dividing the distance between them by the time.

In a ship or an aircraft, speed transducers measure speed through the water or the air. A pitot tube can be used to measure the speed through the air.

Doppler effect

This is the change in the frequency of a sound or radio wave reaching a receiver when there is relative velocity between the receiver and transmitter. A common example is the apparent alteration in pitch of a police siren. As the source of the wave approaches, the distance is decreasing, so each wave has a shorter distance to travel than the previous wave, and thus arrives earlier than it would if the source were stationary. The number of waves reaching the observer in a given time (the frequency) is increased. Conversely, an increasing path length gives a decrease in the received frequency. The relation between the emitted and received frequencies is:

\[ \text{frequency received} = \frac{c}{c-v} \times \text{frequency emitted} \]

Where

\( c \) is the velocity of transmission through the medium,
\[ c \approx 330 \text{ m/s for sound in air} \]

\[ c = 2.997925 \times 10^8 \frac{\text{m}}{\text{s}} \text{ for light and radio waves} \]

\( \nu \) is the relative velocity of the source towards the receiver.

\( \nu \) is positive if the distance between receiver and source is decreasing, negative if it is increasing. If the relative velocity of the source is at an angle \( \theta \) to a line joining source and receiver, then \( \nu = (\text{relative velocity}) \times \cos \theta \).

**The pitot-static tube** (Fig. 5.1)

It is open-ended and faces into the flow. Air flowing past comes to rest at the mouth of the tube, and its kinetic energy is thereby converted into pressure energy, causing a stagnation pressure which is higher than the pressure of the undisturbed air. The static tube, which surrounds the pitot tube, has a front end which is closed and rounded, to cause minimum disturbance to the flow. It sense the pressure of the static pressure through holes or slits in the wall of the tube. The velocity of the air flowing past the aircraft may be calculated from the following formula, which is derived from Bernoulli’s equation:

\[ \nu = \sqrt{2(p_1 - p_2)/\rho} \]

Where

\( \nu \) is the flow velocity

\( \rho \) is the density of the fluid

\( p_1 \) is the stagnation or total pressure

\( p_2 \) is the static pressure

The pitot tube is used to measure the speed of aircraft. Also, it is used to measure the velocity of airflow in ducts, and the velocity of the other gases and liquids in pipes. In these applications, an inclined manometer may be used to measure the pressure difference, and the flow velocity needs to be high enough to give a measureable reading. A combined pitot-static tube may be
used, as on an aircraft, or a static pressure tapping may be made in the wall of the duct or pipe.

The advantage of the pitot tube over other methods of flow measurement is that it causes minimal obstruction to the flow.

Its disadvantages are:

1- The pressure sensing orifices may become blocked if the fluid carries any particles in suspension.
2- It can only measure the velocity at one point in the cross-section of the pipe.

**The stroboscopic lamp (Fig.5.2)**

It generates flashes of light of extremely short duration, at a set frequency.

The stroboscope has the property of apparently ‘freezing’ the rotation of a shaft or the motion of a mechanism, so that a stationary image is seen when the flash frequency coincides with the frequency of rotation of the shaft or the cyclic frequency of the mechanism. The stationary image is also seen when the flash occurs exactly once every \( n \) revolutions (where \( n \) is an integer). Care must be taken when measuring rotational speed, to get true speed and not some submultiple.

To measure the speed of a rotating shaft the stroboscope flash frequency is gradually decreased from maximum until a single stationary image on end of shaft is seen. The flash frequency is then the speed of the shaft in rev/min. Stroboscope are usually graduated in flashes/min. However, a check should be made by decreasing the flash frequency further until a single stationary image is again obtained. This should be at about half the original frequency. If the second frequency is significantly greater than the half the first frequency, the true speed is above the range of stroboscope.

The gradual decrease of flash frequency should be continued so that as well as the first, \( f_1 \) and \( f_2 \), further frequencies, \( f_3, f_4, \cdots, f_n \) which give single stationary images are obtained. The true speed can then be
speed = \frac{f_1f_n(n - 1)}{f_1 - f_n}

By this means speeds can be measured up to about ten times the maximum flash rate of the stroboscope.

Rotational velocity from toothed wheel and proximity pickup(Fig.5.3)

The magnetic proximity pickup - a coil wound on a bar magnet – generates a pulse of voltage each time a tooth moves past it. These pulse are fed to the pulse counter which counts them for a set period of time(usually one second), displays the result for a few seconds to enable it to be read, and the repeats the process. The toothed wheel must be made of some form of iron. It is more usual however to use a 60-tooth wheel so that the pulse counter, counting for exactly one second, automatically shows the speed in rev/min.

Disadvantage of this process, this system of measurement can only give the average speed over the time interval, and so is unsuitable for measuring rapidly varying speeds.

Hall – effect transducer(Fig.5.4)

If a magnetic field acts at right angles to the current in a conductor, a voltage, \( v \), is generated at right angles to both current and field. The voltage is due to the variation in density of the charge carriers within the cross-section, as they are deflected in accordance with Fleming’s left-hand rule for motors. A Hall-effect transducer uses semiconductor material. A constant current is passed through the chip, and \( v \) is proportional to the magnetic field, up to a limiting value of field strength.

It is used for measurement of current, magnetic field and proximity pickups. The proximity pickups sense the presence of iron from the change it cause in the field strength of a small magnet positioned so that its field passes through the chip. They are solid-state switches, switching \( v \) on and off, with advantage that they are free from contact 'bounce'.

4
The eddy current drag-cup tachometer(Fig.5.5)

The motor vehicle speedometers are drag-cup tachometers gear-driven via a flexible drive cable from the output shaft of the vehicle's gearbox.

The input rotation is applied to a magnet which rotates inside an aluminum cup carried by the spindle on which the pointer is mounted. As the magnet rotates, the magnetic field, travelling through the aluminum, generates eddy currents in it. These create their own magnetic field, which is attracted to that of the rotating magnet, and so exert a torque on the cup proportional to the speed of the input rotation. The cup and pointer assembly therefore rotate to the position at which this torque is exactly balanced by the opposing torque reaction from the torsion spring.

AC machine generator and motor can be used to substitute the flexible drive cable where the rotating part is too far away from the instrument.

DC tachogenerators

A permanent magnet field DC generator gives an output voltage approximately proportional to the speed at which it is driven.

It has permanent magnet in the form of a fixed central core surrounded by an outer steel ring, so that the magnetic field is radial in the gap between them. The armature is a non-metallic sleeve carrying the coils, which rotates in the gap.

The DC output voltage is taken from the coils through a commutator must and brushes, hence has a small ripple with small voltage 'spikes' which occur when commutator meet or leave the brushes. The ripple frequency is

$$2 \times (\text{number of coils}) \times (\text{rev/sec})$$

The ripple and spikes may be smoothed by passing the output through a low-pass filter(only in low speed). for low frequencies of ripple which still get through the filter. The polarity of the tachogenerator's output voltage reverses when the direction of rotation of the armature is reversed.
**AC tachogenerators (Fig. 5.6)**

The simple one is a small brushless alternator in which a permanent magnet rotates inside a fixed winding generating the output AC, which has amplitude proportional to the speed of rotation. The problem, the frequency of AC produced is also proportional to speed.

The AC drag-cup tachogenerator is an improvement, as its output frequency remains constant at the frequency of excitation. The stator has two windings with their axes at 90° to each other. AC is supplied at a constant voltage to one of these windings giving an alternating magnetic field of constant amplitude.

An aluminum cup in the annular gap between the stator poles and a soft iron core, is rotated at the speed to be measured. An alternating current, at right angles to both the magnetic field and the direction of motion, is generated in the metal of the cup, with amplitude proportional to the speed of rotation. This eddy current has an associated magnetic field, and this generate AC in the other winding. Thus the output signal appears as the amplitude modulation of a 'carrier wave' voltage which has the same frequency as the AC supplied to the transducer.
Chapter Six

Acceleration and vibration transducers

Seismic pickups (Fig. 6.1)

It is used to measure the motion of the surfaces to which they are fixed. They are sensitive to motion along one axis only, so if the motion is three dimensional, three seismic pickups are needed to determine the components of the motion along three mutually perpendicular axes. The essential component is the seismic mass. This is a body of metal, suspended from a resilient support. This is a support whose deflection is proportional to the force applied to it. The inertia of the seismic mass causes it to lag behind the motion of the casing when the casing is accelerated, causing a deflection in the support. This deflection forms the input to a transducer, which produces a proportional output signal. The transducer is represented by a potentiometer, but any suitable type of transducer may be used (unbounded strain gauge bridge).

Figure 6.1 The essential features of a seismic pickup.
The ‘dashpot’ represents the damping which will inevitably be present. This damping may consist only of the hysteresis of the support material, or it may be increased by filling the casing with a silicone fluid of suitable viscosity.

By choosing suitable values for the mass, the stiffness of the support and the damping, and by using an appropriate transducer, the same basic arrangement of seismic pickup can be designed as a displacement pickup, a velocity pickup or an acceleration pickup (accelerometer). The seismic pickup is essentially a damped spring-mass, and will have a natural frequency of vibration given by:

$$\omega_n = \sqrt{\frac{\lambda}{m}}$$

Where

- $\omega_n$ is natural angular frequency (rad/s)
- $\lambda$ (lambda) is spring stiffness (N/m)
- $m$ is mass (kg)

**Displacement pickups (Fig. 6.2)**

This type of pickup is used to measure the displacement of a vibrating body when there is no fixed reference point available, for example in determining the movement of the chassis of a vehicle. Therefore, the seismic mass to behave (as far as possible) as though it was fixed in space. This can be arranged by using a relatively large seismic mass and a relatively ‘floppy’ resilient support. This gives a low value of $\omega_n$ to the spring-mass system.

The damping ratio $\zeta$ (zeta).

$$\zeta = \frac{\text{Actual damping}}{\text{Critical damping}}$$

Critical damping is the value of damping which, if the mass is displaced from its equilibrium position and released, allows it to return in the shortest possible time without overshooting.
It can be shown mathematically that $\zeta = 0.707$ gives the least variation of displacement ratio for values of $(\omega/\omega_n)$ down to about 1.75 before the error in displacement measurement exceeds 5%, so displacement pickups are often designed to have a damping ratio of about 0.7.

Figure 6.2 Frequency response of a seismic displacement pickup; a) amplitude, b) phase shift
**Acceleration pickups (accelerometer) (Fig. 6.3)**

For designing the pickup system to have a low value of $\omega_n$, it can be used as displacement or a velocity pickup for angular frequencies well above $\omega_n$.

To design it as an acceleration pickup it must go to the opposite extreme. For angular frequencies well below $\omega_n$ the displacement of the seismic mass relative to the casing tends to zero. Therefore at these much lower frequencies the seismic mass must be accelerating with the same acceleration as the casing. To give it these accelerations, corresponding forces must be applied by the spring because:

$$\text{Force} = \text{mass} \times \text{acceleration}$$

Therefore, the spring used as a transducer, to measure the force applied to the mass, its acceleration, and hence the acceleration of the casing.

The curves indicate that provided the damping ratio does not exceed 1.0, a seismic accelerometer will give accurate readings of acceleration for frequencies of vibration from zero up to about 0.2 of its undamped natural frequency. For heavier damping than this, the upper frequency limit will be somewhat less. Most accelerometers, use a piezoelectric crystal as combined ‘spring’ and transducer, and the damping ratio of a crystal is assumed (0.01). The ideal damping ratio is 0.7. To obtain the wide range of usable frequency response, it is desirable, the accelerometer has the highest possible value of undamped natural frequency,
Figure 6.3 The frequency response curves of seismic accelerometers with various values of damping ratio $\zeta$

$$\omega_n = \sqrt{\frac{\lambda}{m}}$$

This can be achieved by a spring-mass system with a high value of spring stiffness, $\lambda$, and a low value of mass, $m$.

**Piezoelectric accelerometers**

Tension cannot be applied to a crystal without using some kind of adhesive to make the tensile connection, and such a connection would be unreliable, so the crystal is kept permanently compressed by the seismic mass. Thus the effect of acceleration in alternate directions is an alternating increase and decrease in the compressive force on the crystal. The compressive preload is applied by screwing the seismic mass down on to the crystal to a given torque. The electrical connections to the crystal are made by metallizing the end faces. This type of
construction gives an accelerometer which is rugged, but because the casing is part of the ‘spring’ in the spring mass system, it may be subject to spurious input. These include temperature change, acoustic noise, base bending, cross-axis motion, and magnetic fields.

Decreasing the seismic mass has the advantage of increasing the undamped natural frequency, and hence of increasing the frequency range of the accelerometer, but has the disadvantage of seriously reducing sensitivity, because the electrical output comes from the work done by the seismic mass. However, a reduced sensitivity may be acceptable if the accelerometer is only being used to find the natural frequency of vibration of a structure by finding the frequency of excitation at which the output of the accelerometer is a maximum.

**The calibration of accelerometers**

Accelerometers for the measurement of steady or slowly varying accelerations may be calibrated up to an acceleration of $\pm 1 \, g (g \text{ is } 9.80665 \, \text{m/s}^2)$ by using the earth’s gravitational attraction. The accelerometer is mounted on a tilting table from which the angle $\theta$ between the sensing axis and the vertical can be measured. At $\theta = 0$ the force of gravity on the seismic mass is the same as the inertia force due to an acceleration of $9.8 \, \text{m/s}^2$. At any other angle of $\theta$ the corresponding acceleration is $9.8 \cos \theta \, \text{m/s}^2$. For accurate calibration the true value of $g$ at the location where the calibration is taking place should be used.
Exercises on chapter 6

1. Show by means of a simple labelled diagram the essential features of a seismic pickup. List the three main types of seismic pickup.

2. For a damped spring-mass system, sketch curves showing how the ratio (displacement of mass)/(displacement of support) varies with the exciting frequency, for various values of damping ratio. Hence show the usable frequency range of a seismic displacement pickup in relation to the undamped natural frequency of the spring-mass combination.

3. State three ways in which a signal proportional to the velocity of a vibration may be obtained, listing them in order of preference (assuming that the necessary transducers are available) and giving your reasons for placing them in that order.

4. Draw a labelled diagram showing a section through a velocity pickup and explain how the signal is obtained. Is its usable frequency range above or below the undamped natural frequency of the spring-mass combination?

5. a) Describe how the seismic mass and crystal are arranged in:
   i) an accelerometer in which piezoelectric material is in compression,
   ii) an accelerometer in which piezoelectric material is in shear.

b) State the main advantage and disadvantage of each type relative to the other.

c) State an approximate value of the damping ratio of a piezoelectric accelerometer.

d) Can a piezoelectric accelerometer be used to measure accelerations which only change very slowly - if not, why not?

6. For a damped spring-mass system sketch the shape of graphs with logarithmic scales along both axes, which show how the ratio (acceleration of mass)/(acceleration of support) varies with the exciting frequency for various values of damping ratio between ζ = 0.01 and ζ = 1.0. Indicate the undamped natural frequency, and the usable frequency range of an accelerometer.

7. Describe two alternative ways in which damping may be applied to the seismic mass of an accelerometer. State the ideal value for the damping ratio of such an instrument.

8. a) Explain the principle of a servo accelerometer.

b) State three advantages which a servo accelerometer has compared with other types of accelerometer.

9. How would the following calibrations usually be carried out?
   a) The calibration of a strain-gauged accelerometer over the range +1 g to –1 g only.
   b) A primary calibration of a piezoelectric accelerometer (brief description only).
   c) A secondary calibration of a piezoelectric accelerometer.

10. Which of the accelerometer types i) to iv), listed below, would you use for which of the following applications a) to d)? Give reasons for your answers. Assume that constraints such as cost, availability and size are not applicable.

   i) piezoelectric
   ii) potentiometric
   iii) strain-gauged
   iv) servo.

a) To measure accelerations with frequencies not greater than 1 Hz. Weight must be kept to a minimum.

b) To measure accelerations with frequencies not greater than 1 Hz, where considerable electrical interference is present.

c) To measure accelerations with the maximum possible accuracy.

d) To measure accelerations with frequencies not less than 100 Hz. Weight must be kept to a minimum.
Chapter Seven

Flow measurement

The venturi meter

At the throat of the venturi meter, the pressure is reduced because the velocity of the liquid is greater in the smaller cross-section, this pressure drop is regained as the cross-section enlarges again to the original pipe diameter.

Pressure tappings at the entry to the venturi and at the throat are led to a differential pressure transducer, from which a signal proportional to the pressure difference may be obtained (see Fig. 7.1).

The pressure difference in a venturi meter is governed by Bernoulli’s law; that in any continuous body of liquid the sum of potential energy, pressure energy and kinetic energy is constant at all points. In a horizontal pipe potential energy is constant and thus cancels out from any equation.

![Figure 7.1 a venturi meter](image-url)
The sum of pressure and kinetic energy at the upstream tapping and at the throat for unit mass (1 kg) of liquid, the following equation is obtained:

\[
\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2}
\]

Where

- \( p \) is pressure (N/m\(^2\))
- \( v \) is velocity (m/s)
- \( \rho \) is the density of the liquid (kg/m\(^3\))

The volume flow rate

\[
\dot{Q} = a_1 v_1 = a_2 v_2 \frac{m^3}{s}
\]

Where

- \( a \) is the cross-sectional area of flow (m\(^2\)).

Furthermore:

\[
\dot{Q} = \frac{a_1 a_2}{\sqrt{(a_1^2 - a_2^2)}} \sqrt{\frac{2}{\rho} (p_1 - p_2)} \ m^3/s
\]

This can be simplified:

\[
\dot{Q} = a_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(1 - \beta^4)}}
\]

Where
To obtain the actual flow rate it is multiplied by a coefficient of discharge, \( C_d \), which is found in range 0.97 to 0.99.

**Reynolds number**

This number gives indication whether the flow in the pipe is laminar or turbulent. If Reynolds number (Re) is less than 2000, the flow in a pipe is laminar vice versa it is turbulent. Reynolds number may be calculated as:

\[
Re = \frac{vd\rho}{\eta} = \frac{vd}{\nu}
\]

Where

\( v \) is velocity of the liquid (m/s)

\( d \) is the inside diameter of the pipe (m)

\( \rho \) is the density of the liquid (kg/m\(^3\))

\( \eta \) (eta) is the dynamic viscosity of the liquid (Ns/m\(^2\))

\( \nu \) (nu) is the kinematic viscosity of the liquid (m\(^2\)/s)

The Reynolds number of the flow in the throat of a venture is always greater than that in the pipe because, for a given flow rate of a given liquid, Reynolds number is inversely proportional to diameter, because:

\[
Re \propto v \times d \propto \frac{1}{a} \times d \propto \frac{1}{a^2} \times d \propto \frac{1}{d}
\]
So we need only consider the Reynolds number of the flow in the pipe itself. The coefficient of discharge of a venturi meter is only constant for Reynolds numbers greater than $2 \times 10^5$ (see Fig 7.2).

![Figure 7.2](image)

Figure 7.2 coefficient of discharge versus Reynolds number for a typical venturi meter

**The orifice plate**

In this method, the flow is measured from the pressure difference it causes. It is a flat plate with a sharp-edged hole in it, through which the fluid has to pass. The fluid adjacent to the plate is stationary which serves to transmit the pressures from the moving fluid to the pressure transducer.

The formula to measure flow in venturi meter, also, can be used in this type with difference the coefficient of discharge is about 0.63 for completely turbulent flow, the coefficient of discharge depends on the Reynolds number of the flow in the pipe. Advantage of an orifice plate.

1- It gives a larger pressure difference than a venturi meter.
2- It is cheap and very compact.

The disadvantage of this type compared with venturi meter:

1- Greater power loss in pumping through an orifice plate than through a venturi meter.
2- Its lower initial cost may be cancelled out by higher running costs.
3- The calibration is changed when the liquids containing solids in suspension.
4- Also, the calibration is changed because of rounding-off the sharp edge of the orifice. Such wear may be caused by long use or by abrasive particles in the fluid.

Figure 7.3 The orifice plate flowmeter a) orifice and pressure tappings  b) detail of edge of orifice c) pressure distribution adjacent to the orifice
**Mechanical flowmeters**

In meters of this type the fluid is made to do work on some kind of machine, the quantity of fluid passing through the machine being proportional to the number of oscillations or rotations of the mechanism, as indicated by a counter.

**The turbine flowmeter**

In this method, the fluid spinning the rotor at a speed proportional to the flow rate. To ensure consistent readings, the flow upstream of the rotor is straightened by stationary radial vanes, which also act as spacers to centralize the rotor bearings. The rotor may drive a mechanical counter through reduction gearing or it may generate a digital signal by means of a magnetic transducer, one cycle of AC being generated each time a rotor blade passes the pick-off coil (See Fig 7.4).

Because of friction in the bearings, the actual speed of the rotor is always slightly less than the speed at which it should theoretically be rotating.

*Fig 7.4 Turbine meter unit.*
The rotameter

It is a variable area flowmeter, consists of a ‘float’ in a tapered tube. The tube is arranged with its axis vertical so that the fluid enters the narrow end of the tube and rises to exit at the wide end. The float is affected by three forces, its weight force acting downwards, and the drag of the fluid plus buoyancy force acting upwards. The upward drag of the fluid is mainly due to this pressure drop acting on the cross float to rise until the increased annular space between float and wall of tube reduces the pressure drop to its equilibrium value again (See Fig. 7.5).

Advantage:

This type of measurement has an accurate range of about 10:1 – much better than flowmeters in which the reading depends on the square root of a pressure drop.

Disadvantage:

The calibration of a rotameter applies to only one particular density of fluid. Rotameters may be used to measure the flow rates of gases or liquids. They are limited to fairly small rates of flow.
The electromagnetic flowmeter

It using the Fleming’s right-hand rule for generators as shown in the figure.

The voltage obtained is directly proportional to the rate of flow of the liquid.

Magnetic field is produced by coils near pipe. The pipe is non-magnetic material, so that the field can pass through it. This type of measurement is used to liquid that is conduct electricity such as solution of acids, alkalis and even water while petroleum cannot be used.

With most liquids a constant magnetic field would cause polarization of the electrodes that is the formation, by electrolytic action, of an insulating layer of neutral molecules on one or both of the electrodes, causing a falling-off of the output voltage. To eliminate these errors the electromagnets are supplied either with AC at 50 or 60 Hz or with interrupted DC.(See Fig. 7.6).

Fig. 7.6 Principle of the electromagnetic flowmeter
Advantage

1- The flowmeter causes no pumping losses-this can make a considerable saving in running costs.
2- The calibration is unaffected by changes in viscosity.
3- There is a wide linear range of measurement.
4- They are able to measure reverse flows.
5- The flow rates of corrosive liquids and liquids carrying abrasive solids in suspension can be measured.

The hot-wire anemometer

It consists of a fine tungsten wire stretched between the tips of streamlined support. It measures velocity from the effect, on the wire’s electrical resistance, of the cooling caused by the flow of the fluid past the wire. It is mainly used to measure the flow velocities of gases but it can also be applied to the measurement of liquid velocities. Because of small thermal capacity it is particularly useful for the measurement of rapid fluctuations in velocity.

The heat transfer from the wire to the fluid is determined by the following equation:

\[ \text{Heat transfer rate}(\text{watts}) = A + B \sqrt{v} \]

\( v \) is the velocity of flow while

\( A \) and \( B \) are constants

Equating heat power output to electrical power input gives

\[ I^2R = A + B \sqrt{v} \]

Where

\( I \) is the current through the wire and

\( R \) is its resistance.
The hot wire anemometer is used with a bridge circuit. The best method is to keep the resistance of the hot wire constant, by adjusting the bridge power supply voltage to keep the bridge balanced.

There are two practical difficulties which could occur with a hot-wire anemometer:

1- It may vibrate in high flow velocities, causing it to break.
2- It may become coated with dirt, which will alter the calibration, or it may even be broken by impact with large dirt particles.

**Fig. 7.7 Hot-wire anemometer**

**Doppler flowmeters**

It is used to measure the flow velocity in pipes either by a beam of ultrasonic vibrations or by a beam of laser light projected through a transparent section of pipe. The laser method is equally applicable to liquids and gases. The ultrasonic method is mainly used for the measurement of liquids, through it can be applied to gases.
To use a Doppler flowmeter for measuring, the fluid should not be absolutely pure (fluids carrying particles or air bubbles in suspension). The reason, the Doppler effect acts on reflections from the particles or bubbles.

**Ultrasonic Doppler flowmeters**

It consists of a piezoelectric transmitter and a piezoelectric receiver, similar to those forming the ultrasonic sensing device in the vortex flowmeter. The transmitter applies a narrow beam of vibration to a wedge block; they pass through the wedge block and the wall of the pipe, and echoes are reflected in all direction from the particles that lie in their path through the fluid. The receiver, mounted on another wedge block, can pick up echoes only from particles which are in the narrow cylindrical volume corresponding to that through which the transmitter’s vibrations are propagated. The received echoes are very weak and have to be amplified. Their frequency has been decreased by the Doppler effect (See Fig. 7.9).

![Fig. 7.9 Doppler ultrasonic flowmeter with separate receiver and transmitter](image)
The decrease is given by:

\[ f_t - f_r = \frac{2f_t \cos \theta}{c} \times v \]

- \( f_t \) and \( f_r \) are transmitted and received frequency
- \( \theta \) is angle of deflection
- \( c \) is speed of sound in the fluid
- \( v \) is the velocity of the particles

**Laser Doppler flowmeter**

A laser enables light to be used for Doppler velocity measurements because it produces light at frequencies which are precisely known and very stable. The beam of light from the laser enters an optical system which splits it into an intense main beam and a much weaker reference beam. Both beams are focused on to the point in the fluid at which they cross. The particles in the fluid reflected the light of the main beam in all directions. A very small proportion of this reflected light will be in the direction of a photodetector which is on the receiving end of the reference beam, and so the photodetector will produce a beat frequency which is the difference between the laser light frequency and the Doppler-shifted frequency of the reflections from the moving particles.
The calibration of flowmeters

In industry application, the fluid flow is always avoided because the calibration of a flowmeter can be affected by variations in the density and viscosity of the fluid as its temperature and pressure change and by flow disturbances due to elbows, tees or valves immediately upstream or downstream of the flowmeter. Accurate calibration is important because the cost control of plant operation depends largely on flow measurement.

The primary calibration of a flowmeter for a liquid is done by setting a steady rate of flow and measuring the time taken to collect a given volume of the outflow in a tank.

For a gas, it is collected over water in a gasometer, a counterbalanced inverted cylindrical container which rises as the gas is accumulated. The temperature and pressure of the gas must be measured so that the calibration can be corrected for variation in gas density (See Fig. 7.11).

Secondary calibration of a flowmeter may be carried out by connecting it in series with another flowmeter which has already been calibrated, and using the flow rates measured by the calibrated flowmeter to calibrate the uncalibrated one.
Fig. 7.11 Calibration of a gas flowmeter
Chapter Nine

Digital Instrumentation Principles

Analogue-to-digital conversion

The sample voltages from sample-and-hold amplifier are converted into binary number by an analogue-to-digital converter (A/D). The main types of A/D converter are:

1. single slope.
2. dual slope.
3. successive approximation.
4. flash.

Figure: 1 Block diagram of a single-slope A/D converter.

Single-slope or single-ramp A/D converter (Fig.1)

At the start of the conversion operation the control circuit sets both the ramp voltage and the binary counter to zero. Any positive analogue voltage on the non-inverting input of the op-
amp sends its output ‘high’. This switches-on the ramp generator and at the same time enables the AND gate to pass cycles of square wave from the clock input to the binary counter. At the instant the ramp voltage exceeds the analogue input voltage, the op-amp output goes ‘low’. This switches off the clock input to the binary counter and it latches(hold constant in a memory) the binary number it has counted to. The ramp generator and counter are the reset to zero, ready to convert the next sample.

**Advantage:** it is simple and cheap.

**Disadvantage:**

1- It is slow.

2- It is Inaccuracy if the clock frequency or the slope of the voltage/time ramp alter due to ageing or temperature-sensitivity or components.
Figure: 2 Dual-slope A/D converter: a- block diagram b- integrator output voltage/time graphs

**Dual-slope A/D converter (Fig.2)**

This cancels out any inaccuracy due to variations in clock frequency or ramp slope by using two ramps in a count-up, count-down process.

1. The binary counter is set to zero and the analogue voltage is connected to the inverting input of the first op-amp, the integrator, which generates the ramps; its output is already at zero volts.
2- The positive analogue voltage applied to the inverting input of the first op-amp causes it to start generating a steadily increasing negative voltage at a rate proportional to the input voltage (negative ramp with slope proportional to input).

3- The output of the second op-amp (the comparator) instantly goes ‘high’, enabling the AND gate to admit clock pulses to the binary counter.

4- Counting proceeds until the counter is full. The overflow causes the counter to be reset to zero and start counting again, and the inverting input of the first op-amp is switched to the negative reference voltage.

5- This causes it to generate a positive ramp with slope proportional to the reference voltage. The negative output voltage of the first op-amp therefore starts to decrease; when it reaches zero the comparator output goes ‘low’, blocking the clock input, and the binary number in the counter is latched by the control circuit. This number is the digital equivalent of the analogue input voltage.

Advantage:
1- The accuracy of a dual-slope A/D converter is unaffected by drift in the clock frequency or in the values of the resistance or capacitance in the integrator circuit, since the upward and downward ramps are affected equally.

2- High-frequency noise disappears in the integration out.

Disadvantage
It is slow speed. Therefore, it is used in many digital voltmeters.

Successive-approximation A/D converter (Fig.3)

This type is much faster than the ramp types. The operation is as follows:

1- Starting with the most significant bit (MSB) set to 1 and the remaining bits set to 0, it generates the equivalent analogue voltage to that number, by means of a built-in digital-to-analogue converter. That voltage is compared with the input voltage, in the comparator. If it is less than the input voltage the 1 is retained, otherwise it is altered to 0.

2- The next most significant bit is then changed from 0 to 1, the equivalent voltage is again generated, and the comparison repeated. Again, this latest 1 is either retained or
changed to 0, depending on whether the generated voltage is less than or greater than the input voltage.

3- The process continues until, finally, the effect of a 1 as the least significant bit (LSB) has been tested. The digital conversion of the analogue input is then complete and the number is latched for output.

4- The D/A converter output voltages are biased to increase them by the equivalent of 0.5 LSB, so that the maximum error in conversion can only be 0.5 LSB. Each comparison is operated by one clock pulse, and the complete conversion takes place in a few microseconds.

**Parallel, simultaneous or ‘flash’ A/D converter (Fig.4)**

It is the fastest converter. It consists of 4 volt power supply. By means of series resistor forming a potential divider across the power supply, a number of equal voltage steps is
obtained. Each of these steps is applied to the inverting input of its own op-amp. The analogue input voltage is applied to the non-inverting input of all those op-amps. Where the analogue input voltage is higher than the voltage on the inverting input of an op-amp, the output voltage of the op-amp is ‘high’ (binary 1), otherwise it is ‘low’ (binary 0). These two strings of 0s and 1s are then turned into a corresponding binary number by means of encoding gates.

The 2-bit converter requires three op-amp comparators; an n-bit converter requires \(2^n - 1\) comparators. Thus each additional bit virtually doubles the number of comparators required.

Figure: 4 A simple example of a ‘flash’ A/D converter: a- circuit diagram, b- output table
Digital-to-analogue (D/A) conversion (Fig. 5)
The D/A converter circuit, known as an R-2R ladder. It has as many inputs as there are digits in the binary numbers which represent the voltage values. Each input operates its own electronic switch (a logic gate) which connects that particular leg of the ladder to the reference voltage if the binary digit is a 1, or to earth if it is a 0. If all the legs but one are connected to earth, the one connected to the reference voltage produces a current which flows towards the inverting input of the op-amp and is halved by the resistance network at each junction through which it passes. Thus the current contribution of each leg is weighted to correspond to the position of that particular digit in the complete binary number for example, in a 4-bit D/A converter the current produced by the (MSB) will be eight times \(2^{(4-1)}=8\) the current produced by the (LSB). The op-amp produces an output voltage proportional to the sum of the currents.

Pulse code modulation (Fig. 6)
This is the modulation of a digital signal on to a carrier wave, magnetic tape or disc. The digits 1 and 0 are represented by opposite voltage levels, or by opposite magnetization in the case magnetic recording. RZ (return to zero level) and NRZ (non-return to zero level). NRZ is the usual format; RZ enables individual bits to be distinguished but needs
twice as much bandwidth because each transition between 1 and 0 entails two changes of level instead of one.

For NRZ, the upper limit of the frequency range of the digital signal is determined by assuming the worst case: 0s and 1s alternating continuously at the bit-stream frequency. With NRZ the theoretical lower limit of the frequency range is 0 Hz- that is DC, due to long streams of 1s or of 0s. DC is difficult to record properly, so special NRZ codes may be used.

Figure: 6 Pulse code modulation formats
Exercises on chapter 9

1. Compare the TTL and CMOS versions of a given type of integrated circuit by stating which of the two versions is the better in respect of each of the following considerations:
   a) high input impedance
   b) low power consumption
   c) ease of handling during circuit construction.

2. A logic circuit consisting of an inverter, a two-input NAND gate and a two-input OR gate receives three digital signals, A, B and C. Signal A passes through the inverter to one of the inputs of the NAND gate; signal B is connected directly to the other input. The output of the NAND gate is connected to one of the inputs of the OR gate; signal C is connected directly to the other input.
   a) Draw a diagram of the logic circuit, showing the inputs A, B, and C.
   b) Allot any other identifying letters necessary, and draw up a truth table showing the output of the OR gate for any combination of A, B and C.

3. Which of the following statements about serial data transfer is/are true?
   a) ‘It is faster than parallel data transfer.’
   b) ‘It needs only one wire.’
   c) ‘It is unsuitable for BCD.’
   Explain the error in any untrue statements.

4. The logic gate shown in Figure 9.26 on the next page has input waveforms A, B and C. Which of the waveforms $X_1$, $X_2$ or $X_3$ represents its output? Explain why the waveform you have chosen is the correct one.

5. Which of the following arrangements will enable a three-input NAND gate to be function as an inverter?
   a) All inputs connected together to form a single input.
   b) A permanent ‘high’ on the two unused inputs.
   c) A permanent ‘low’ on the two unused inputs.

6. A particular Schmitt trigger circuit gives an output voltage corresponding to binary 1 when the input voltage reaches $+1.6$ V while rising, and an output voltage corresponding to binary 0 when the input voltage reaches $+0.8$ V while falling. If the input is a sinusoidal voltage with amplitude $\pm 7.5$ V, for how many electrical degrees of this input will the output be 1 and for how many degrees will it be 0?

7. A binary counter’s output pins are denoted $Q_1$ to $Q_{10}$.
   a) Write down in binary digits the logic levels at the pins when 189 pulses have reached the clock input since it was reset, taking the pins in order from $Q_1$ (LSB) on the right to $Q_{10}$ (MSB) on the left.
   b) Write down the binary digits of the BCD code for this number.
   c) Sketch a seven segment digit, labelling the segments a to g in the standard notation.
d) For each of the digits 1, 8 and 9, show as a 1 or a 0 the logic level required on each of the segments a to g.

8 a) Explain how a counter-timer measures
   i) the frequency
   ii) the period of a waveform.

b) List the possible sources of error in a reading obtained using a counter-timer.

9 a) The timebase of a counter-timer has a 10 MHz oscillator. The instrument, which has an 8-digit display, is to be used to measure a frequency of 5 kHz
   i) in the frequency mode with a gate time of 1 s
   ii) in the period mode. What will the display show in each case?

b) Considering only the normal display error of ± 1, what is the corresponding percentage error in the displayed value, in each case?

c) What is the ‘break-even’ frequency at which the two modes would give equal percentage errors?