Cathode Ray Oscilloscope (CRO):

In studying the various electronic, electrical networks and systems, signals which are functions of time, are often encountered. Such signals may be periodic or non-periodic in nature. The device which allows, the amplitude of periodic or non-periodic electrical signals, to be displayed primarily as a function of time, is called Cathode Ray Oscilloscope, commonly known as CRO. A cathode ray oscilloscope contains a *cathode ray tube* and necessary power equipment to make it operate.

The CRO gives the visual representation of the time varying signals. In an oscilloscope, the electrons are emitted from a cathode accelerated to a high velocity and brought to focus on a fluorescent screen. The screen produces a visible spot where the electron beam strikes. By deflecting the electron beam over the screen in response to the electrical signal, the electrons can be made to act as an *electrical pencil of light* which produces a spot of light wherever it strikes. As electrons have negligible mass, therefore, they respond almost instantaneously when acted upon by an electrical signal and can trace almost any electrical variation no matter how rapid. The electron beam can be deflected in two directions: the horizontal or x-direction and the vertical or y-direction. Thus an electron beam producing a spot can be used to produce two dimensional displays. Thus CRO can be regarded as a **Fast x-y plotter**. The x-axis and y-axis can be used to study the variation of one voltage as a function of another. Typically the x-axis of the oscilloscope represents the time while the y-axis represents variation of the input voltage signal. Thus if the input voltage signal applied to the y-axis of CRO is sinusoidally varying and if x-axis represents the time axis, then the spot moves sinusoidally and the familiar sinusoidal waveform can be seen on the screen of the oscilloscope. The oscilloscope is so fast device that it can display the periodic signals whose time period is as small as microseconds and even nanoseconds. The CRO basically operates on voltage, but it is possible to convert current, pressure, strain, acceleration and other physical quantities into the voltage using transducers and obtain their visual representations on the CRO.

The oscilloscope has become an universal instrument and is probably most versatile tool for the development of electronic circuits and systems. It is an integral part of electronic laboratories. It is widely used for trouble shooting radio and television receivers as well as for laboratory work involving research and design. With an oscilloscope, the wave shape of a signal can be studied with respect to amplitude distortion and deviation from the normal. In addition, the oscilloscope can also be used for measuring voltage, frequency and phase shift.

Block diagram of a CRO:

A simple oscilloscope consist of a cathod ray tube, a vertical amplifier, a timebase, a horizontal amplifier and a power supply. A basic block diagram of a general purpose oscilloscope is shown in Fig.13.24

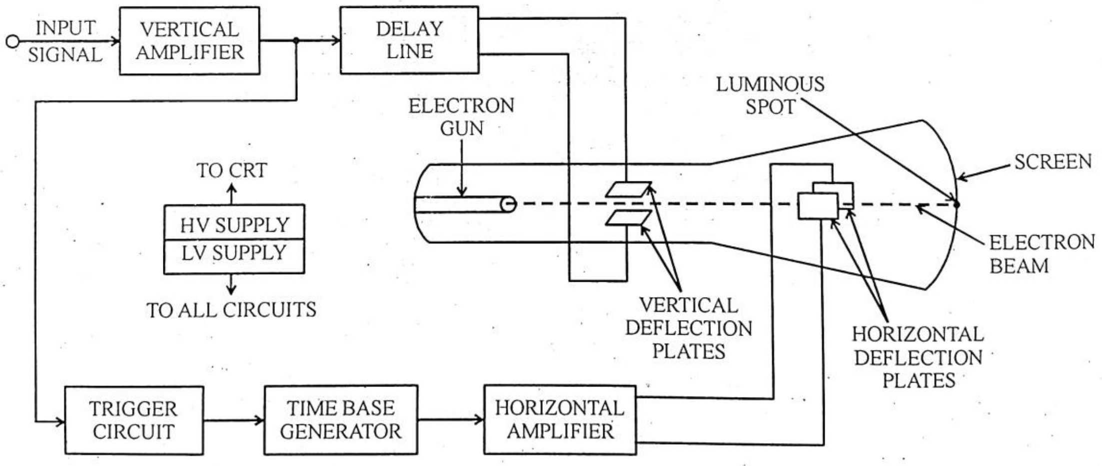

Fig.13.24. Block diagram of a CRO.

5.2 Cathode Ray Tube (CRT)

The cathode ray tube (CRT) is the heart of the C.R.O. The CRT generates the electron beam, accelerates the beam, deflects the beam and also has a screen where beam becomes visible as a spot. The main parts of the CRT are :

i) Electron gun ii) Deflection system iii) Fluorescent screen

iv) Glass tube or envelope v) Base

A schematic diagram of CRT, showing its structure and main components is shown in the Fig. 5.1.

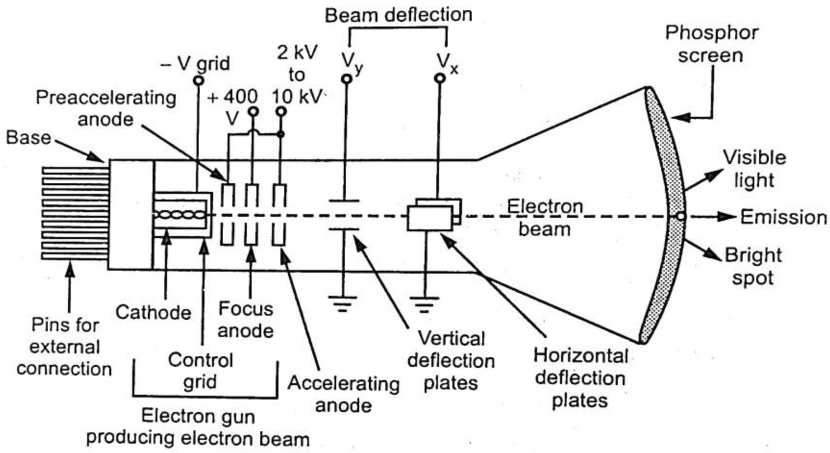

Fig. 5.1 Cathode ray tube

Electron Gun

The electron gun section of the cathode ray tube provides a sharply focused electron beam directed towards the fluorescent-coated screen. This section starts from thermally heated cathode, emitting the electrons. The control grid is given negative potential with respect to cathode. This grid controls the number of electrons in the beam, going to the screen.

The momentum of the electrons (their number × their speed) determines the intensity, or brightness, of the light emitted from the fluorescent screen due to the electron bombardment. The light emitted is usually of the green colour. Because the electrons are negatively charged, a repulsive force is created by applying a negative voltage to the control grid (in CRT, voltages applied to various grids are stated with respect to cathode, which is taken as common point). This negative control voltage can be made variable.

Key Point : *A more negative voltage results in less number of electrons in the beam and hence decreased brightness of the beam spot.*

Since the electron beam consists of many electrons, the beam tends to diverge. This is because the similar (negative) charges on the electron repel each other. To compensate for such repulsion forces, an adjustable electrostatic field is created between two cylindrical anodes, called the **focusing anodes**.

Key Point : *The variable positive voltage on the second anode is used to adjust the focus or sharpness of the bright beam spot.*

The high positive potential is also given to the preaccelerating anodes and accelerating anodes, which results into the required acceleration of the electrons.

Both focusing and accelerating anodes are cylindrical in shape having small openings located in the centre of each electrode, co-axial with the tube axis. The preaccelerating and accelerating anodes are connected to a common positive high voltage which varies between 2 kV to 10 kV. The focusing anode is connected to a lower positive voltage of about 400 V to 500 V.

5.2.2 Deflection System

When the electron beam is accelerated it passes through the deflection system, with which beam can be positioned anywhere on the screen.

The deflection system of the cathode-ray-tube consists of two pairs of parallel plates, referred to as the vertical and horizontal deflection plates. One of the plates in each set is connected to ground (0V). To the other plate of each set, the external deflection voltage is applied through an internal adjustable gain amplifier stage. To apply the deflection voltage externally, an external terminal, called the Y input or the X input, is available.

As shown in the Fig. 5.1, the electron beam passes through these plates. A positive voltage applied to the Y input terminal (V_y) causes the beam to deflect vertically upward due to the attraction forces, while a negative voltage applied to the Y input terminal will cause the electron beam to deflect vertically downward, due to the repulsion forces.

Similarly, a positive voltage applied to X-input terminal (V_x) will cause the electron beam to deflect horizontally towards the right; while a negative voltage applied to the X-input terminal will cause the electron beam to deflect horizontally towards the left of the screen. The amount of vertical or horizontal deflection is directly proportional to the correspondingly applied voltage.

When the voltages are applied simultaneously to vertical and horizontal deflecting plates, the electron beam is deflected due to the resultant of these two voltages.

The face of the screen can be considered as an x-y plane. The (x,y) position of the beam spot is thus directly influenced by the horizontal and the vertical voltages applied to the deflection plates V_x and V_y, respectively.

The horizontal deflection (x) produced will be proportional to the horizontal deflecting voltage, V_x, applied to X-input.

$$\therefore \quad x \propto V_x$$

$$\therefore \quad \boxed{x = K_x V_x}$$

where K_x is constant of proportionality.

The deflection produced is usually measured in cm or as number of divisions, on the scale, in the horizontal direction.

Then $K_x = \frac{x}{V_x}$ where K_x expressed as cm/volt or division/volt, is called **horizontal sensitivity** of the oscilloscope.

Similarly, the vertical deflection (y) produced will be proportional to the vertical deflecting voltage, V_y, applied to the y-input.

$$\therefore \quad y \propto V_y$$

$$\therefore \quad \boxed{y = K_y V_y}$$

$K_y = y/V_y$ and K_y, the **vertical sensitivity,** will be expressed as cm/volt, or division/volt.

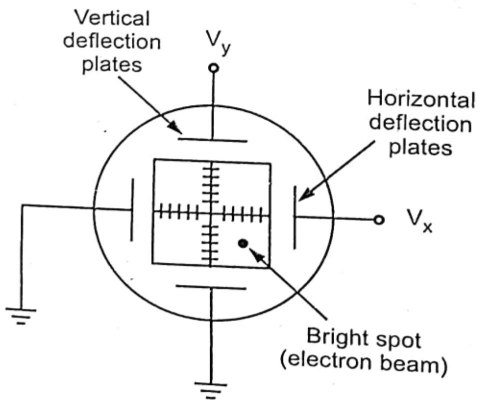

Fig. 5.2 Arrangement of plates in CRT

The values of vertical and horizontal sensitivities are selectable and adjustable through multipositional switches on the front panel that controls the gain of the corresponding internal amplifier stage. The bright spot of the electron beam can thus trace (or plot) the x-y relationship between the two voltages, V_x and V_y.

The schematic arrangement of the vertical and the horizontal plates, controlling the position of the spot on the screen is shown in the Fig. 5.2.

Fluorescent Screen

The light produced by the screen does not disappear immediately when bombardment by electrons ceases, i.e., when the signal becomes zero. The time period for which the trace remains on the screen after the signal becomes zero is known as "**persistence** or **fluorescence**". The persistence may be as short as a few microsecond, or as long as tens of seconds or even minutes.

The screen is coated with a fluorescent material called phosphor which emits light when bombarded by electrons. There are various phosphors available which differ in colour, persistence, and efficiency.

One of the common phosphor is Willemite, which is zinc, orthosilicate, $ZnO + SiO_2$, with traces of manganese. This produces the familiar greenish trace. Other useful screen materials include compounds of zinc, cadmium, magnesium and silicon.

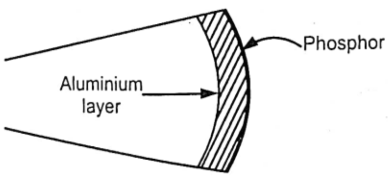

Fig. 5.3 Aluminizing

The kinetic energy of the electron beam is converted into both light and heat energy when it hits the screen. The heat so produced gives rise to "**phosphor burn**" which is damaging and sometimes destructive. This degrades the light output of phosphor and sometimes may cause complete phosphor destruction. Thus the phosphor must have high burn resistance to avoid accidental damage.

Similarly the phosphor screen is provided with an aluminium layer called **aluminizing** the cathode ray tube. This is shown in the Fig. 5.3.

Such a layer serves three functions :

1) To avoid build up of charges on the phosphor which tend to slow down the electrons and limits the brightness.
2) It serves as a light scatter. When the beam strikes the phosphor with aluminized layer, the light emitted back into the tube is reflected back towards the viewer which increases the brightness.
3) The aluminium layer acts as a heat sink for the phosphor and thus reduces the chances of the phosphor burning.

Key Point : *The light output of a fluorescent screen is proportional to the number of bombarding electrons, i.e. to the beam current.*

Glass Tube

All the components of a CRT are enclosed in an evacuated glass tube called **envelope**. This allows the emitted electrons to move about freely from one end of the tube to the other end.

Base

The base is provided to the CRT through which the connections are made to the various parts.

Deflection Sensitivity:

Electrostatic deflection sensitivity. *The deflection sensitivity of an electrostatic deflection cathode ray tube is defined as the amount of spot deflection on the screen in mm per volt potential difference applied between the deflecting plates.* It is expressed in mm per volt.

The *dc* or peak to peak *ac* voltage which must be applied across the deflection plates to produce a spot deflection of 1 mm on the screen is called *deflection factor.* It is expressed in volts per mm. Thus deflection sensitivity is reciprocal of deflection factor.

To calculate the expression for electrostatic deflection sensitivity let :

Length of each deflection plate $= l$

Distance between the plates $= d$

Distance between end of plates and screen $= D$

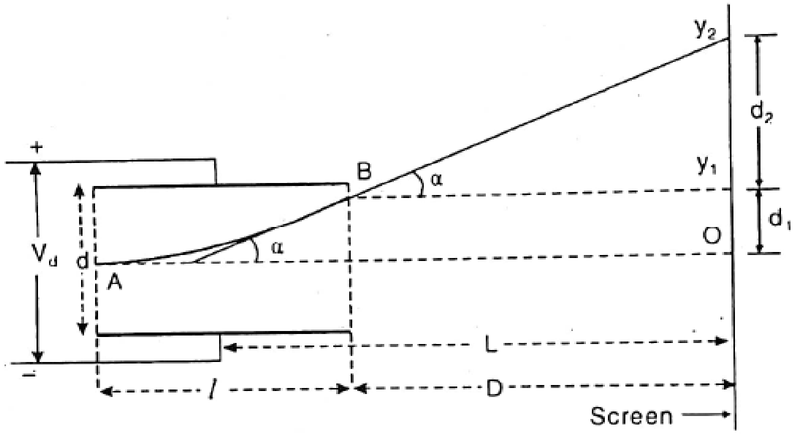

Fig. 10.5

If V_a is the final accelerating anode voltage, and v the velocity of an electron on just entering the deflection plates, then

$$\frac{1}{2}mv^2 = eV_a$$

where e is the charge and m the mass of the electron.

$$\therefore \qquad v^2 = 2\frac{e}{m}V_a \qquad \text{... }(i)$$

If V_d is the voltage applied between the plates, then

Force acting on the electron towards the upper (positive) plate is given by

$$F = \frac{eV_d}{d}$$

If a is the resulting acceleration of the electron, then

$$a = \frac{e}{m}\frac{V_d}{d}$$

Time taken by the electron to traverse through the length of deflection plates

$$t = \frac{l}{v}$$

Hence upward velocity of the electron on emerging out of the deflection plates

$$v_y = 0 + at = \frac{e}{m}\frac{V_d}{d}\frac{l}{v} \quad \text{... (ii)}$$

The electron enters the deflecting system at A and leaves at B. The path of the electron between A and B is curved.

Vertical upward displacement d_1 during the time interval t is given by

$$d_1 = 0 + \frac{1}{2}at^2 = \frac{1}{2}\frac{e}{m}\frac{V_d}{d}\frac{l^2}{v^2} = \frac{eV_d l^2}{2mv^2 d} \quad \text{... (iii)}$$

After emerging from the plates, the electron beam moves in a straight path making an angle α with the original direction and meets the screen at Y_2.

Now $\tan\alpha = \frac{d_2}{D} = \frac{v_y}{v}$

or $$d_2 = \frac{Dv_y}{v} = \frac{D}{v}\frac{e}{m}\frac{V_d}{d}\frac{l}{v} = \frac{eV_d Dl}{mv^2 d} \quad \text{... (iv)}$$

Total deflection $OY_2 = OY_1 + Y_1Y_2 = d_1 + d_2$

$$= \frac{eV_d l^2}{2mv^2 d} + \frac{eV_d lD}{mv^2 d} = \frac{eV_d l}{mv^2 d}\left[\frac{l}{2} + D\right] \quad \text{... (v)}$$

If L is the distance of the screen from the centre of the deflection plates then $L = \frac{l}{2} + D$

Substituting $\frac{l}{2} + D = L$ in relation (v), we have

Total deflection $= \frac{eV_d lL}{mv^2 d}$ ... (vi)

Substituting the value of v^2 from (i) in (vi), we get

Total deflection $= \frac{eV_d lL}{md}\cdot\frac{m}{2V_a e} = \frac{lL}{2d}\frac{V_d}{V_a}$

Hence deflection sensitivity $S = \frac{\text{Total deflection}}{\text{Voltage between the plates}}$

$$= \frac{lL}{2d}\frac{V_d}{V_a}\cdot\frac{1}{V_d} = \frac{lL}{2dV_a} \text{ m / volt}$$

$$= \frac{500\, lL}{dV_a} \text{ mm/volt} \quad \text{... (vii)}$$

From relation (vii), we find that electrostatic deflection sensitivity is directly proportional to the length of the deflecting plates and to the distance of the screen from the centre of the plates. It is inversely proportional to the distance between the deflecting plates and final anode voltage.

∴ Total spot deflection = Deflection sensitivity × Applied voltage between the plates

Thus we see that the deflection sensitivity can be increased by reducing the anode voltage but this reduces the brightness of the spot. This disadvantage can be overcome by accelerating the beam after it has passed through the deflection system. This process is known as *post acceleration* and is brought about by using an extra electrode called the *intensifier anode*.

(*ii*) **Magnetic deflection sensitivity.** *The deflection sensitivity of a magnetic deflection cathode ray tube is defined as the amount of spot deflection on the screen per unit magnetic flux density produced by the magnetic deflection coils.*

The electron beam can be deflected by applying a magnetic field perpendicular to the beam over a short distance along its path. The magnetic field will exert a force on the electrons in a direction at right angles to both; the direction of motion of the electrons and the direction of magnetic field. As a result the electron beam emerging from the magnetic field makes an angle with its original direction. This type of deflection is known as *magnetic deflection.*

To calculate the expression for magnetic deflection sensitivity consider an electron beam *AB* coming from the electron gun acted upon by a uniform magnetic field of flux density *B* over a length *l* of its path. The magnetic field is applied perpendicular to the direction of flow of electrons so that the beam describes an arc *BC* of a circle. The path of the elctrons ramains circular within the magnetic field and after leaving the magnetic field the electrons move in a direction *CD* tangential to the circular arc at *C*. Let *r* be the radius of the circular arc *BC*.

If V_a is the accelerating potential and v the velocity attained by the electrons, then

$$\frac{1}{2}mv^2 = eV_a$$

or

$$v = \sqrt{\frac{2eV_a}{m}} \qquad \ldots (i)$$

If *B* is the magnetic flux density, then Lorentz force acting on the moving electron

$$= B\,ev \qquad \ldots (ii)$$

This force acts at right angles to the direction of motion of the electron, so that the electron moves in a circular path of radius *r* and is acted upon by a centripetal force $\frac{mv^2}{r}$ ... (*iii*)

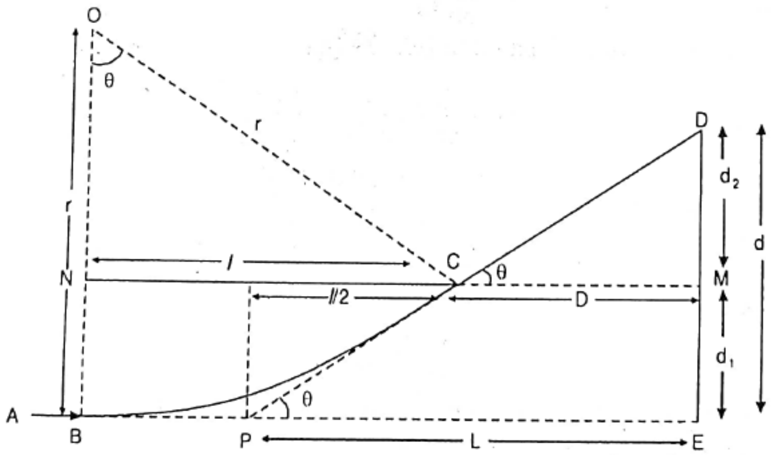

Fig. 10.6

These two forces given by relation (*ii*) and (*iii*) balance each other

$$\therefore \quad B\,e\,v = \frac{mv^2}{r}$$

or

$$r = \frac{mv}{Be}$$

Substituting the value of *v* from eq. (*i*), we get

$$r = \frac{m}{Be}\sqrt{\frac{2eV_a}{m}} = \frac{1}{B}\sqrt{\frac{2mV_a}{e}} \qquad \ldots (iv)$$

On leaving the magnetic field at the point C the electron beam moves along the straight line CD and hits the screen at the point D. The straight line CD is tangential to the circular path BC at C.

Now, total deflection $\quad d = ED = EM + MD = d_1 + d_2 \quad \ldots (v)$

If O is the centre of the circular arc, θ the angle subtended by the arc at O and r its radius, then

$$d_1 = EM = BN = OB - ON = r - r\cos\theta = r(1-\cos\theta) \quad \ldots (vi)$$

Also $\quad \angle DCM = \angle DPE = \theta.$

$$\therefore \quad \tan\theta = \frac{d_2}{D}$$

or $\quad d_2 = D\tan\theta = D\theta$ when θ is small

Also when θ is small $\quad \theta = \sin\theta = \frac{l}{r}$

$$\therefore \quad d_2 = D\frac{l}{r} \quad \ldots (vii)$$

and $\quad \cos\theta = (1-\sin^2\theta)^{\frac{1}{2}} = 1 - \frac{1}{2}\sin^2\theta = 1 - \frac{\theta^2}{2} = 1 - \frac{l^2}{2r^2}$

$\therefore$ From Eq. (vi), $\quad d_1 = r(1-\cos\theta) = r\left(1 - 1 + \frac{l^2}{2r^2}\right) = r\frac{l^2}{2r^2} = \frac{l^2}{2r}$

Hence total deflection $\quad d = d_1 + d_2 = \frac{l^2}{2r} + D\frac{l}{r} = \frac{l}{r}\left(\frac{l}{2} + D\right)$

But $\frac{l}{2} + D = L$, the distance of the screen from the mid point of the field.

$\therefore$ Total deflection $\quad d = \frac{lL}{r}$

Substituting the value of r from Eq. (iv), we have

$$d = l\,L\,B\sqrt{\frac{e}{2mV_a}}$$

$\therefore$ Magnetic deflection sensitivity $S_m = \frac{d}{B} = l\,L\sqrt{\frac{e}{2mV_a}} \quad \ldots (viii)$

Importance of magnetic deflection sensitivity. The magnetic deflection sensitivity is inversely proportional to $\sqrt{V_a}$, where as electrostatic deflection sensitivity is inversely proportional to V_a. Therefore, electric deflection sensitivity decreases more rapidly with increasing anode voltage than magnetic deflection sensitivity. As the loss of magnetic sensitivity is smaller as V_a is increased for greater spot brightness, it is customary to use magnetic deflection in T.V system and Radar indicator, where high spot brightness is required.

The electric deflection suffers larger *deflection defocussing i.e.*, as the angle of deflection is increased the spot on the screen tends to be distorted and enlarged but this is much less in the case of magnetic deflection even for large deflection angles. The greater allowable deflection angle decreases the tube length for a given diameter. Hence magnetic deflection is desirable in cathode ray tubes used in television.

Importance of electric deflection sensitivity. The electrostatic deflection requires little power for deflection while large power is consumed in the electromagnets required for magnetic deflection. Hence electrostatic deflection is used in common purpose oscilloscopes.

Electrostatic deflection can be conveniently used for high frequencies.

Time Base

A time base is a circuit which generates a *saw-tooth waveform*. It causes the spot to move in a horizontal or vertical direction *linearly with time*. The voltage so generated is often called "saw-tooth voltage" (Fig. 50.4). The voltage during each cycle increases linearly with time upto t_i and then falls to zero in a shorter time t_f, called the *flyback* or *retrace time*.

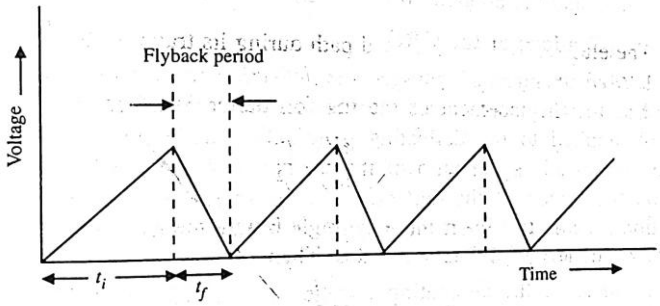

Fig. 50.4

Necessity of time-base voltage. If a d.c. voltage is applied across X-plates, the spot of light will move in a horizontal line on the screen. Similarly, if an a.c. voltage alone is applied to Y-deflection plates, the spot of light will move on the screen vertically up and down in a straight line. This line, however, does not reveal the nature of the applied voltage waveform. To get the actual waveform, it is necessary that it appears as plotted against time as an axis. Hence, a time base voltage is applied to the X-plates of C.R.O. Under this voltage, the spot sweeps linearly across the screen from left to right and then flies back quickly to the starting position for the next sweep. This horizontal sweep, however, appears as a stationary line on the screen due to persistence of vision. When vertical motion of the spot produced by the a.c. voltage applied on Y-plates is superimposed on the horizontal sweep produced by X-plates, the actual waveform of the a.c. voltage is traced on the screen. The circuit connections for such an arrangement are shown in Fig. 50.5. An exact and

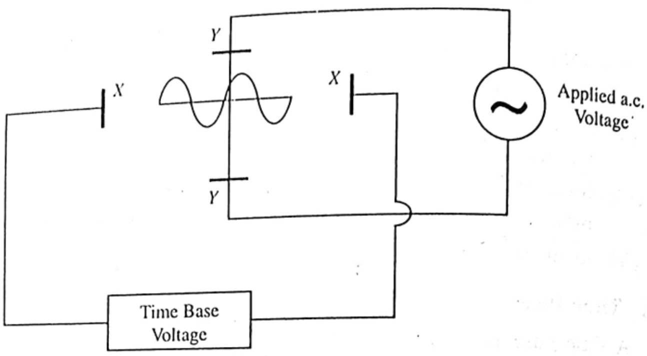

Fig. 50.5

stationary trace of the applied a.c. voltage waveform is obtained on the screen when the frequency of time base equals the frequency of the applied sinusoidal voltage. The process of matching the frequencies of the time base voltage and the applied voltage is called *synchronization*.

Applications of the CRO

1. **Measurement of voltage.** The *deflection sensitivity* of a CRO is defined as the displacement of the spot on the screen for a potential of one volt applied to the deflecting plates. This deflection sensitivity is usually expressed as the ratio of the input voltage to the length of the trace on the screen. If the deflection on the screen is multiplied by the deflection sensitivity we get the magnitude of the applied voltage. This is in the case of a d.c.

To measure the alternating voltage of sinusoidal wave form, it is applied across the Y plates. A straight line trace will be obtained on the screen. The length of this trace is measured. If this length is multiplied by the deflection sensitivity we get the peak to peak value of the ac voltage. Half this value gives the peak value of the dc. Dividing the peak value by $\sqrt{2}$ we get the rms value of the applied ac voltage.

Thus, *CRO acts as an ideal voltmeter* due to its high input impedance.

2. **Measurement of direct or alternating current.** The current to be measured is passed through a known resistance. Then the voltage developed across the resistance is applied across the vertical deflecting plates, the horizontal plates being kept short-circuited. Voltage is measured from the deflection on the screen. The corresponding current is calculated by the relation $I = \frac{V}{R}$.

3. **Study of waveforms.** The ac voltage whose waveform is to be studied is applied to the Y plates. A linear time base is applied to the X plates. The frequency of the time base is then adjusted to some exact submultiple of the frequency of the applied a.c. voltage till a steady pattern of the actual waveform is obtained on the screen. Then the ratio of frequency of a.c. voltage to the frequency of time base voltage will be equal to the number of complete a.c. voltage waves.

4. **Measurement of frequency.** When two sinusoidal voltages are applied simultaneously to the two sets of deflecting plates, a Lissajous pattern is obtained on the screen.

Let v_x and v_y be the two instantaneous voltages applied to the X and Y plates.

$$v_x = V_x \sin \omega_x t \qquad ...(1)$$

and

$$v_y = V_y \sin (\omega_y t + \phi) \qquad ...(2)$$

Here, V_x and V_y are the voltage amplitudes, ω_x and ω_y are the angular frequencies of the voltages and ϕ is the phase angle for voltage v_y.

By adjusting the values of ω_x, ω_y, V_x, V_y and ϕ, various Lissajous figure patterns are obtained on the screen.

Case 1. When $\omega_x = \omega_y$ and $\phi = 0$, *i.e.*, the signals have the same frequency and are in the same phase. From Eqs. (1) and (2),

$$v_y = \frac{V_y}{V_x} \cdot v_x \qquad ...(3)$$

This is the equation of a straight line passing through the origin and making an angle of $\tan^{-1} \frac{V_y}{V_x}$, with the horizontal [Fig. 50.6 (*a*)].

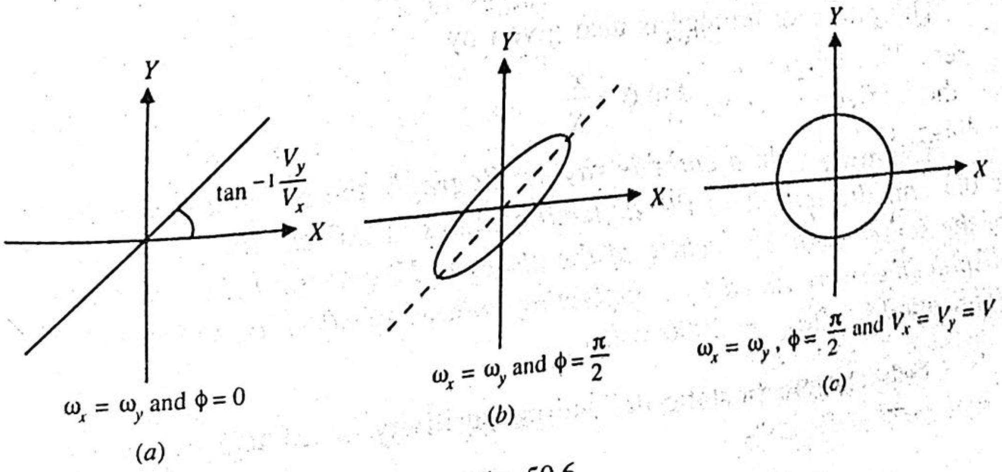

Fig. 50.6

Case 2. Let $\omega_x = \omega_y$ and $\phi = \frac{\pi}{2}$. Then,

$$\frac{v_x^2}{V_x^2} + \frac{v_y^2}{V_x^2} = 1 \qquad ...(4)$$

This is the equation of an ellipse [Fig. 50.6 (*b*)].

Case 3. Let $\omega_x = \omega_y$, $\phi = \frac{\pi}{2}$ and $V_x = V_y = V$. Then,

$$v_x^2 + v_y^2 = V^2 \qquad ...(5)$$

This is the equation of a circle [Fig. 50.6 (*c*)].

To measure the unknown frequency of a sinusoidal ac voltage, it is applied to the Y- plates. To the X plates is applied the sinusoidal voltage obtained from a standard variable frequency oscillator. The frequency of standard oscillator is now varied until a single loop stationary pattern is obtained. The frequency of the signal is then the same as that of the oscillator, which may be noted from the calibrated dial of the oscillator.

5. **Measurement of phase difference.** Lissajous figures can be used to measure the relative phase angle of two alternating voltages of equal amplitude and same frequency. They are applied to the X and Y-plates of a CRO. Usually an ellipse is obtained on the screen, the orientation of which with respect to coordinate axes depends upon the phase difference between the two voltages. The maximum vertical deflection Y and the intercept y on the Y-axis are measured (Fig. 50.7). Then if ϕ is the phase differece between the two voltages, it can be shown that

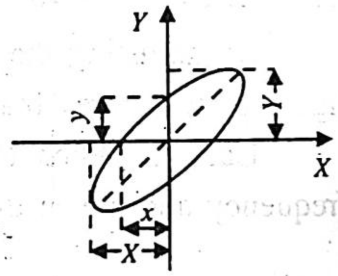

Fig. 50.7

$$\sin \phi = \frac{y}{Y} \quad ...(1)$$

The phase difference is also given by

$$\sin \phi = \frac{x}{X} \quad ...(2)$$

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