RESTRICTED

A.P. 3188

ROYAL AIR FORCE

STANDARD NOTES

FOR

AIR SIGNALLERS

AIR MINISTRY
OCTOBER, 1953

RESTRICTED

A.P. 3188

STANDARD NOTES

FOR

AIR SIGNALLERS

Promulgated for the information and guidance of all concerned.

By Command of the Air Council,

J. H. Barnes.

AIR MINISTRY

OCTOBER, 1953

AMENDMENT RECORD SHEET

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SECTION 1

BASIC RADIO PRINCIPLES

STANDARD NOTES FOR AIR SIGNALLERS

CHAPTER 1

BASIC ELECTRICAL PRINCIPLES

The Constitution of Matter

1. All matter is said to consist of atoms ; the molecules of more complicated substances being composed of a combination of several atoms. All substances, whether solid, liquid, or gas, are made up of various combinations of these elements.

(*a*) *The Atom.* An atom consists of an equal number of positive and negative charges of electricity known respectively as protons and electrons. These charges take up a definite pattern comprising a central nucleus of one or more protons and in most cases a few electrons, and an outer ring of electrons which revolve continuously about the nucleus. The positive and negative charges have the following properties :—

(i) Like charges repel one another.

(ii) Unlike charges attract one another. Thus the negative electrons are held in place by the attraction of the positive protons, each atom being electrically neutral since it contains equal numbers of unlike charges.

(*b*) *Ionization.* In some materials the outer electrons are loosely held and, if sufficient energy is applied, some of these electrons may be detached. The nature of each atom has not changed but it is no longer electrically neutral ; if it has lost one or more electrons it is positively charged, if it has an excess of electrons it is negatively charged. Such an atom is called an "ion".

The Nature of Electrical Current

2. In certain substances internally free electrons are in continuous movement, passing from one atom to an adjacent atom, but without any definite direction of movement. If such a substance is connected between the terminals of a source of electrical supply, the free electrons move in one definite direction. The electrons always flow from a point where they are in excess to a point where there is a deficit, *i.e.* from negative to positive.

Conductors and Insulators

3. A conductor is a material in which electrons are only loosely attached to their groups, so that application of electrical pressure causes these free electrons to move through the material in the direction of the electro-motive force. In general, all metals can be classed as conductors, while some non-metallic materials such as carbon and acids also conduct electricity. Some materials allow the movement of electrons more readily than others, the measure of ease with which they do so being known as their conductance. For example, metals like copper and aluminium have a high conductivity and are generally used for electrical conductors.

4. Insulators, also known as dielectrics, are materials in which electrons are so firmly attached to their groups that little or no electron flow occurs when electrical pressure is applied. At normal pressure these materials are considered as non-conductors. If, however, the applied pressure is progressively increased, a point is reached at which the material breaks down, or punctures, and passes current. The ability of a known thickness of insulating material to prevent such a break-down is called its "dielectric strength". Although there is no perfect non-conductor, materials such as rubber, cotton, porcelain, and bakelite are termed non-conductors or insulators ; pure distilled water is also a non-conductor.

Electrical Pressure, Current, and Resistance

5. Three primary conditions exist in the simple electric circuit : electrical pressure, the flow of electric current, and the degree with which materials obstruct the flow of electricity, *i.e.* Resistance.

(*a*) *Electrical Pressure.* The electrical pressure which causes an electric current to flow in a circuit is known as the electro-motive force (E.M.F.). It may be produced in three ways :—

(i) By chemical action, as in a primary cell.

(ii) By heat, as in a thermo-couple.

(iii) Mechanically, as in a generator.

The difference in electrical pressure which exists between any two points in a circuit is known as the potential difference (P.D.), as distinct from the total E.M.F. required to drive the current through the circuit.

(*b*) *Current.* The current in a circuit is the rate of flow of electricity. The practical unit of a quantity of electricity is the *coulomb*, which is approximately equal to $10^{1}{}_{6}$ electrons passing a given point per second. Thus the current in a circuit is the number of coulombs per second flowing past a definite point in that circuit. An ampere is a rate of flow of 1 coulomb per second.

(*c*) *Resistance.* The opposition offered by a conductor to the flow of current in a circuit is known as resistance, and it is measured in *ohms*. Resistance depends on three factors :—

(i) The cross sectional area of the conductor.
(ii) The length of the conductor.
(iii) The material of the conductor.

To keep the opposition to the flow of electricity to a minimum a conductor should be used with the largest cross sectional area, the shortest length, and made up of a low resistance material such as copper. Conductors made of high resistance materials, such as eureka, which offer considerable opposition to the flow of electricity, are deliberately used as resistances to restrict the current. The resistance of a conductor is only constant at constant temperature ; the resistance of pure metals increases with rise in temperature while that of carbon decreases. The fraction by which the resistance of a conductor increases for each degree centigrade rise of temperature above a definite temperature (usually 20° C.) is called the temperature coefficient of resistance of the material. Carbon has a negative temperature coefficient of resistance.

Standard Units

6. (*a*) *Volt*. The volt is the unit of difference of electrical pressure. A potential difference of one volt exists between two points in a circuit when one coulomb of electrons per second flows past a definite point and the resistance between the two points is one ohm.

(*b*) *Ampere*. The ampere is the unit of rate of flow of electric current. A current of one ampere is the rate of flow of one coulomb per second past a definite point in a circuit.

(*c*) *Ohm*. The ohm is the unit of resistance. It is that resistance which permits a current flow of one ampere when a P.D. of one volt is applied across it.

7. **Units and Symbols.** The most common units, the symbols used for them, and their relative values are shown in the table below.

Types of Electric Current

8. There are three types of electric current :—

(*a*) *Direct Current* (*D.C.*). Direct current is current which flows in a constant direction.

(*b*) *Pulsating Current*. Varies in amplitude throughout the cycle but never reverses its direction.

(*c*) *Alternating Current* (*A.C.*). Alternating current is a current flow which is constantly changing its direction and value.

Ohm's Law

9. In a D.C. circuit the ratio between its applied electrical pressure and the current flowing is constant, at constant temperature ; that is $\frac{E}{I}$ (see para. 7) is a constant, and this constant is the resistance of a conductor. This relationship between E.M.F., current, and resistance is expressed by "Ohm's Law", which states that the current in a circuit is directly proportional to the pressure and indirectly proportional to the resistance of the circuit. Thus, other factors remaining equal, if the pressure is doubled the current is doubled ; if the resistance is doubled the current is halved. Ohm's Law can be expressed as an equation :—

$$\text{Current in Amperes} = \frac{\text{E.M.F. in Volts}}{\text{Resistance in Ohms}}$$

$$\text{in symbols} \qquad = I = \frac{E}{R}$$

If any two of these quantities are known the third can be found by transposing the symbols, *e.g.* :—

$$R = \frac{E}{I} \quad \text{or} \quad E = IR$$

Resistance of a Simple Circuit

10. **Series Connection.** Conductors joined end to end to form a single circuit are said to be in "series". In a series circuit the value of the current is the same at all points and depends on the total resistance of the circuit and the applied

CLASS	NAME	SYMBOL	VALUE
Current Flow (I) ...	Ampere Milliampere Microampere	A mA μA	1 Amp 0·001 Amp 0·000001 Amp
E.M.F. or P.D. (E) ...	Volt Kilovolt Millivolt Microvolt	V kV mV μV	1 Volt 1,000 Volts 0·001 Volt 0·000001 Volt
Resistance (R) ...	Ohm Megohm Microhm	Ω MΩ μΩ	1 Ohm 1,000,000 Ohms 0·000001 Ohm

E.M.F. The P.D. across each resistance is proportional to the value of that resistance. The total resistance of several resistances in series is equal to the sum of the individual resistances, *i.e.* :—

$$Rt = R1 + R2 + R3 + \text{etc.}$$

11. **Parallel Connection.** Conductors joined so that they offer alternative paths for the current are said to be in "parallel". In a parallel circuit the voltage is common to each path, and the current in each path is proportional to the resistance of that path. The total current equals the sum of the individual currents. If several resistances are connected in parallel, the reciprocal of their total resistance $\frac{1}{Rt}$ is equal to the sum of the reciprocals of the individual resistances, *i.e.* :—

$$\frac{1}{Rt} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \text{etc.}$$

The total resistance, calculated from this expression, is always less than the lowest value of the individual resistances.

12. **Series Parallel Combinations.** To find the total resistance of a circuit containing both parallel and series connections, first find the "equivalent value" resistance of the parallel banks (see para. 11) and then add this to the total value of the other resistances connected in series.

Heating Effect of a Current

13. When current flows in a conductor the electrical power absorbed in overcoming resistance is converted into heat, causing a rise in temperature of the conductor. A steady temperature is reached when the heat lost per second by radiation, conduction, and convection, is equal to the heat gained per second from the current.

14. The actual rise in temperature depends on the nature of the conductor, *i.e.* its dimensions and the material of which it is made. For example, the rise in temperature is greater :—

(*a*) In a thin wire than in a thick wire carrying the same current.

(*b*) In an iron wire than in a copper wire of the same gauge and carrying the same current.

15. In general, therefore, when wiring, the current capacity of a conductor must always be large enough relative to the current flowing to prevent damage to the insulation of the conductor through temperature rises. All electrical machines should be adequately ventilated or otherwise cooled to prevent overheating.

16. The heating effect of an electrical current, however, is deliberately used in lamp filaments, heater elements, hot wire connectors, electric fires, and many other devices.

Voltage Drop

17. When current flows, energy is absorbed in overcoming the resistance of the conductor and this absorption results in a drop in electrical pressure along the conductor known as "Voltage Drop". This difference in pressure between two points in a circuit is measured in volts (E). Voltage drop in a circuit is calculated by Ohm's Law, *i.e.* $E = IR$.

18. Using cables of low resistance is particularly important in circuits carrying heavy currents, as a large current (I) causes a correspondingly large voltage drop. Since voltage drop occurs in cables, the effective voltage at the terminals of the equipment connected to the ends of those cables is less than its applied voltage at the supply ends.

19. When wiring circuits, therefore, the current-carrying capacity of the cables must be large enough, to avoid excess voltage drop and overheating of the cables.

Power in Electrical Circuits

20. Power is the term used for the "rate of doing work". The electrical unit of power is the *watt*, and the power available from a source of supply is the product of the E.M.F. in volts and the current in amperes, *i.e.* watts = power = $E \times I$.

21. If the value of the voltage is not known, power can be calculated from the expression :

$$\text{Power} = I^2R \text{ watts (since } E = IR)$$

or if the current is unknown :

$$\text{Power} = \frac{E^2}{R} \left(\text{since } I = \frac{E}{R}\right)$$

The equation Power $= I^2R$ also represents the power lost in overcoming the resistance of the conductor and in producing heat.

22. The watt is too small for practical use where the power involved is large, and the unit adopted therefore is the kilowatt (1,000 watts). The mechanical unit of power, the Horse Power, is equivalent to 746 watts.

Therefore a kilowatt $= \frac{1{,}000 \text{ watts}}{746} = 1{\cdot}34$ horse power.

CHAPTER 2

SECONDARY CELLS

The Chemical Effect of a Current

1. Some substances, like salts and acids, conduct electricity when dissolved in water, and are known as electrolytes ; dilute sulphuric acid is a typical electrolyte. The conductors through which the current enters and leaves the solution are known as electrodes. The passage of the current decomposes the solution into its constituents, the process being known as electrolysis. Some of the ions are negatively charged and some positively charged ; the former are attracted to the positive electrode and the latter to the negative electrode. Gases are produced at the electrodes. Electro-plating is an application of the electrolysis process, the essentials being an electrode of the plating metal and an electrolyte suitable for the type of plating ; the article to be plated forms the other electrode. The passage of current takes metal out of the electrolyte and deposits it on the article being plated ; at the same time an equal amount of metal is dissolved from the plating metal electrode into the electrolyte. Electrolysis is used to restore *secondary cells* or *accumulators* to their original useful state after they have been discharged. Primary cells, as used in flashlamp batteries, cannot be recharged as the active material in them is consumed during use. The secondary cell is a means of storing electrical energy in chemical form.

Types of Secondary Cells

2. There are two types of accumulators in service use, Lead Acid and Nickel Alkaline. The first has the disadvantage of being very heavy and needs extra attention ; the second is lighter and will stand up to hard usage, but its voltage is low and its initial cost rather high.

Note. The term "cell" is generally used to denote a single cell ; the term "accumulator" denotes a group of two or more cells.

Lead Acid Accumulator

3. The lead acid accumulator consists of a container into which plates of lead are inserted (Fig. 1). These plates are insulated by separators which are designed to restrict the free circulation and diffusion of the electrolyte as little as possible. They are made of chemically treated cedar wood, rubber, or highly micro-porous plastic. The positive plates are pasted with lead oxide, while the negative plates are filled with a paste of litharge. The plates before use are put through a process which converts the litharge to spongy lead and the red lead to lead peroxide. This is done by immersing the pasted plates in dilute sulphuric acid (normally of a specific gravity of 1·270 for aircraft accumulators) and passing a current from an external source so that it enters by the red lead plates (positive) and leaves by the litharge plates (negative). The cell is now storing electrical energy which will be released on completion of a closed circuit across the plates. The plate by which current enters is called the *anode*, and the plate by which it leaves is called the *cathode*. Whenever hydrogen or metallic elements are produced electrolitically they always appear at the cathode—this knowledge is useful when determining the polarity of a supply at any time. When the cell has become discharged it may be re-energized by connecting it to an external source and once more passing an electric current through it. During this charging process, hydrogen and oxygen molecules are freed from the plates. As these molecules form an explosive mixture, accumulators are fitted with unspillable vents designed to allow gas to escape without leakage of electrolyte. To enable the vents to function correctly, the correct level of the electrolyte must not be exceeded. If the level is allowed to rise above the centre cone of the vent, gas pressure will eject the electrolyte.

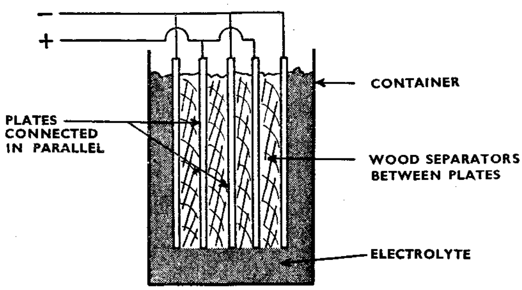

Fig. 1. Secondary Cell

4. **Voltage.** The voltage of a cell is the potential difference between its terminals either on open or closed circuit. The voltage of a fully charged cell immediately after charge may be as high as 2·3 volts owing to a film of gas bubbles clinging to the plates, but it will fall to approximately 2·1 volts when the bubbles disperse. The voltage may rise to 2·7 volts when the cell is on charge, and should never be allowed to fall below 1·8 volts on light load. The voltage of a fully charged cell falls quickly for a short period at the start, then more slowly during the greater part of the discharge period, and finally falls away quickly. The time taken to discharge a fully charged cell to its normal end point (1·8 volts on light load) is called the discharge rate. Accumulator tests are based on the *Ten Hour Rate*, when

$$\text{the Load Current} = \frac{\text{Nominal Capacity}}{\text{10 Amps}}.$$

5. **Capacity.** The amount of electricity that can be taken from a fully charged cell at a given discharge rate, to reduce its voltage to the normal end point (1·8 volts on light load), is termed the *Capacity* of the cell. It is measured in ampere-hours, *i.e.* discharge current in amperes multiplied by the duration of the discharge in hours. The capacity of an accumulator decreases if it is discharged at a higher rate, *e.g.* if a cell gives two amps for ten hours it will give less than four amps for five hours. Similarly, decreased current, or intermittent working, tends to increase the actual capacity. Accumulators deteriorate when in use, and the capacity falls until the capacity/weight ratio becomes uneconomic. Accumulators become uneconomic for service use when :—

(*a*) Enough paste has dropped from the plates as sediment to reduce the capacity below 75 per cent. (aircraft use), or 60 per cent. (ground use).
(*b*) The separators have become perforated and the accumulator fails to hold its charge.
(*c*) The plates have become sulphated.

6. **Grouping** (Fig. 2). Cells or accumulators can be grouped together to form a battery ; the capacity or voltage of the battery depends on the number of cells or accumulators and the method of connection.

(*a*) *Series Connection.* Batteries of any voltage can be built up by connecting several cells in series, *i.e.* positive to negative. The total voltage across the outside positive and negative terminals is the sum of the individual voltages. The capacity of such a battery is the same as that of a single cell.
(*b*) *Parallel Connections.* Capacity may be increased by connecting several cells in parallel, *i.e.* positive terminals to positive, and negative to negative. The total capacity will then be the sum of the individual capacities ; but the voltage across any positive and negative terminal will be that of a single cell.
(*c*) *Series/Parallel Connection.* This method is a combination of the previous two methods whereby voltage and capacity may be increased together.

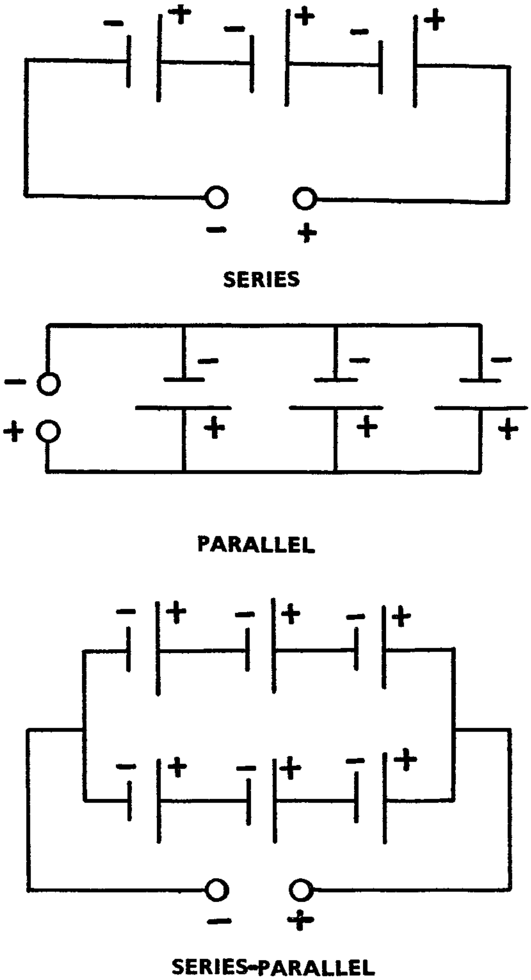

Fig. 2. Various Methods of Connecting-up Batteries

7. **Faults.** The main faults associated with lead acid accumulators are :—

(*a*) *Internal Short Circuits.* These are caused by :—
(i) Paste shed from the plates forming conducting paths between plates of opposite polarity. (Otherwise known as Shedding.)
(ii) Splits or perforations occurring in the separators.
(iii) Permeation of the separators by lead hydrate.

Faults (i) and (ii) occur with normal usage but are accelerated by overcharging. Fault (iii) occurs when overdischarged batteries are left in that condition, or when batteries are left connected to a load and forgotten. Indications of internal short circuits are no gassing on charge and little or no voltage between the cell terminals. The sediment can be removed by washing out the cells with weak acid. The cells should then be refilled with electrolyte of the correct S.G. and recharged. There is little hope of rectifying the other conditions except at a repair depot.
(*b*) *Sulphation.* Sulphation is caused by neglect or improper treatment, usually in the form of persistent undercharging or persistent discharging to too low a voltage. When a battery is discharged the lead plates sulphate, and if it is allowed to stand in a discharged condition the sulphate first formed slowly changes to a harder form which is difficult to

remove. Failure of the specific gravity to rise to the correct value after charging is an indication of slight sulphation, which, if allowed to continue, will become visible as a white deposit on the plate. When this stage is reached it is very difficult and often impossible to remove it.

Note. Batteries should never be left in a discharged condition (*i.e.* below 1·8 volts per cell on light load).

(*c*) *Alkali Contamination.* Alkali will ruin lead acid accumulators. It is therefore very necessary to ensure that hydrometers, syringes, distilled water containers, tins of grease, terminals, etc., used for lead acid accumulators, have not been in contact with alkali.

Nickel Alkali Cells

8. In this type of accumulator the positive plate consists of nickelic hydroxide held in a specially constructed grid of nickel. The electrolyte is a concentrated potassium hydroxide solution, while the negative plate is of specially prepared iron. The actual chemical changes which go on during charge and discharge are very complex, but may be generally expressed by saying that during discharge nickelic hydroxide is changed to nickelous hydroxide, while the iron is changed to ferrous hydroxide. On charging, the chemical actions are reversed. The lid of the cell has a valve which allows the escape of gas, but which prevents the entry of atmospheric carbon dioxide which would spoil the electrolyte by changing it to potassium carbonate. The E.M.F. of such a cell is about 1·3 volts and its efficiency is lower than that of the lead acid type. Its great advantages lie in its lightness and its ability to withstand not only hard physical treatment, but overcharging and overdischarging. Unlike a lead acid cell it does not deteriorate when left standing uncharged for long periods.

Type "B" Charging Board

9. The D.C. supply is fed to the accumulators via a charging board to control the flow of charging current (Fig. 3). The Type "B" Charging Board has three charging circuits, paralleled off by heavy copper bus-bars. Each circuit will supply a maximum of 10 amps at 36 volts. The current in each circuit is controlled by separate charge relating resistances, and the circuit includes a double pole switch and 10-amp fuses. A reverse current cut-out, which is simply an automatic switch, is connected in the main feed to prevent the accumulators from discharging should a fault occur. The cut-out will not complete the circuit unless the supply voltage is greater than that of the accumulators on charge. If the supply fails, or the supply voltage falls below that of the accumulators on charge, the cut-out opens, disconnecting the accumulators from the supply.

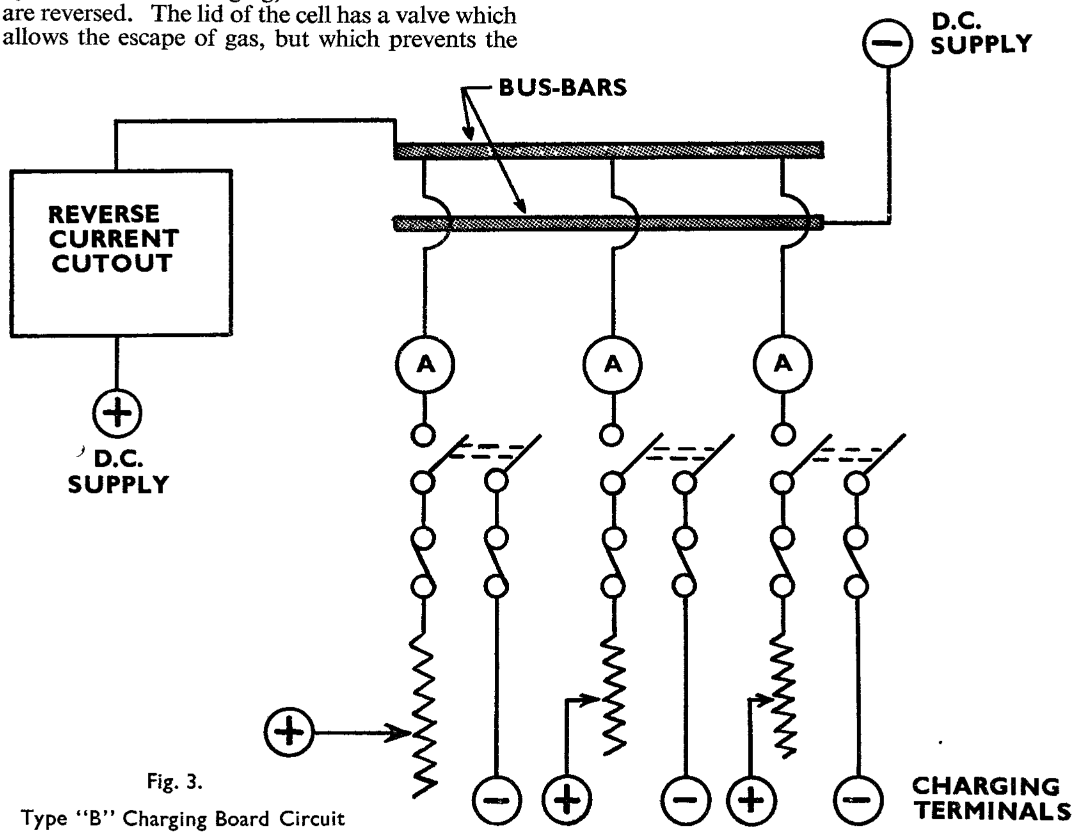

Fig. 3.
Type "B" Charging Board Circuit

Operating a Charging Board

10. The following procedure must be followed when operating a charging board :—

(*a*) Connect accumulators to the output terminals so that the accumulator positive is connected to the output positive. If not marked, the polarity may be found by using a moving coil voltmeter.

(*b*) Set charge regulating resistance to the position of maximum resistance, *i.e.* minimum current.

(*c*) Start rectifier by pressing the START push-button.

(*d*) Close the main double-pole switch.

(*e*) Adjust the regulating resistance to give required charging current, indicated by the ammeter.

The Hydrometer

11. The hydrometer is a device for measuring the specific gravity of a liquid (Fig. 4). Hydrometers must always be kept in a wooden case marked either "Lead Acid" or "Alkaline". Each hydrometer must be used for one type of electrolyte only.

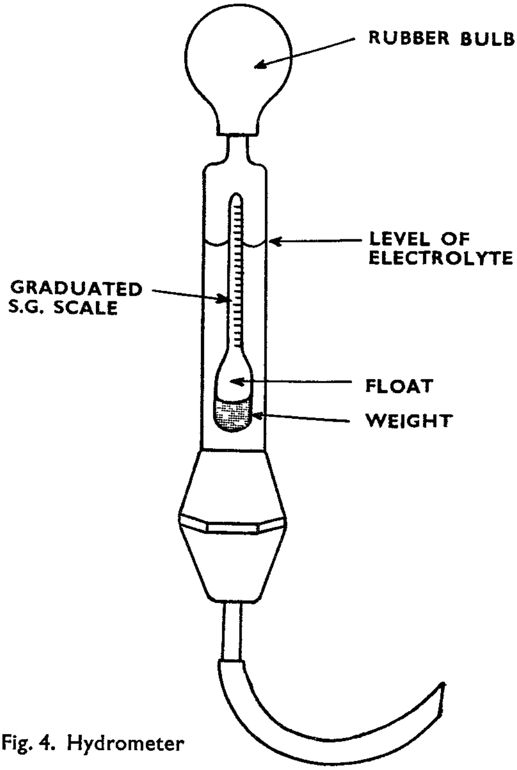

Fig. 4. Hydrometer

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CHAPTER 3

ELEMENTARY MAGNETISM

1. Iron, steel, cobalt, and nickel are metals affected by magnetic forces, and consist of millions of molecular magnets. When a bar of one of these metals is magnetized, the molecules are brought into line and produce poles at the ends of the bar—thus forming one large magnet.

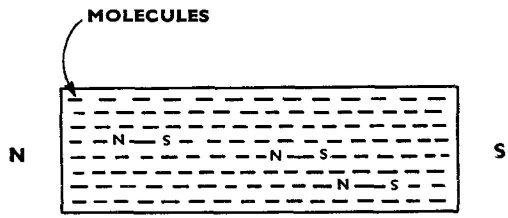

Fig. I. Bar Magnet

Properties of a Magnet

2. (*a*) (i) The force of attraction is greatest at the ends of a magnet, which are known as poles. The poles attract pieces of non-magnetized iron and steel.

(ii) If a magnetic bar is freely balanced at its centre it will always come to rest in the direction of the earth's magnetic field. The pole which seeks the North pole of the earth is known as the North-seeking pole, and the other the South-seeking pole.

(iii) Like poles repel, unlike poles attract each other. If a second magnet is brought near the suspended magnet the latter is either attracted or repelled according to the pole presented to it.

(*b*) *Magnetic Field.* A field of magnetic influence exists in the space surrounding a magnet. As the distance from the magnet increases the strength of the field decreases. The magnetic field is represented in a diagram by lines of force, which are assumed to have the following properties :—

(i) They never cross.

(ii) They are deflected by, and tend to pass through, magnetic materials placed in the magnetic field and, in doing so, they induce magnetic properties in that material.

(iii) They form a complete magnetic circuit running from North pole to South pole outside the magnet and completing the loop from South to North through the magnet.

(*c*) *Magnetic Materials.*

(i) Soft iron is easily magnetized, but loses the greater part of its magnetism when the magnetizing force is removed. It is used in electro-magnets.

(ii) Steel retains the greater part of its magnetism and is used for permanent magnets. When steel is alloyed with certain other metals, themselves almost non-magnetic, like tungsten, it gains still greater magnetic retentivity.

3. **Definitions.** The following terms and symbols are used when dealing with magnetic circuits and materials :—

(*a*) *Flux Density* (*B*). The strength of a magnetic field, *i.e.* the number of lines of force per sq. centimetre, at right angles to the field.

(*b*) *Permeability* (μ). The ability of a magnetic material to increase flux density ; it may be compared with conductivity in the electric circuit. The permeability of air is unity, while that of soft iron and steel varies between 200 and 1,000. The numbers simply indicate order of magnitude.

(*c*) *Reluctance.* Reluctance is similar to resistance in an electrical circuit. The reluctance of a magnetic circuit is greatly increased by the existence of air gaps, and in electric machines air gaps are kept as small as possible.

(*d*) *Saturation.* A magnetic material has reached saturation point when it is completely magnetized, *i.e.* when the flux density cannot be further increased.

(*e*) *Retentivity.* The property possessed by a material of retaining magnetism after the magnetizing force has been removed. The magnetism retained by the material after the magnetizing force has been removed is known as the "Residual Magnetism".

(*f*) *Hysteresis.* The lagging behind of magnetization in a material as the magnetizing force is being removed.

Magnetic Effects of an Electric Current

4. Current flowing through a conductor sets up a magnetic field. The direction of the current flow, and the direction of the lines of force around the conductor bear the same relationship to each other as do the thrust and turn of a corkscrew. Fig. 2 illustrates this.

5. If a conductor carrying current, instead of being straight, is wound in the form of a coil, a magnetic field is produced in and around the coil.

The form of the field is similar to that of a bar magnet. The method of determining the polarity is shown in Fig. 2. The polarity of the field reverses if the direction of current is reversed, and the field disappears when the current is switched off.

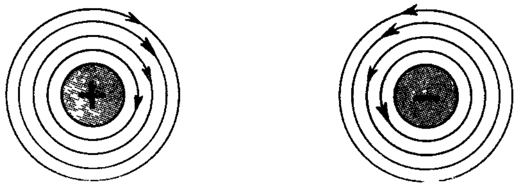

Fig. 2. Magnetic Field Round a Conductor Carrying a Current—Illustrating "Corkscrew Rule"

6. The strength of the magnetic field depends on :—

(*a*) The current (in amperes).
(*b*) The number of turns comprising the coil.
(*c*) The length of the coil.
(*d*) The permeability of the core.

Thus in an air-cored coil the flux density (B) is proportional to the magnetizing force (H) expressed in ampere turns per centimetre, *i.e.* the product of the current in amperes and the number of turns in each centimetre length of the coil. Most electro-magnets consist of a solenoid wound on a core of soft iron or similar magnetic material, which offers an easier path to the lines of force ; the flux density due to the ampere-turns per centimetre is thus increased by an amount depending on the permeability of the core. Electro-magnets are used in relay switches and motor and generator field systems, the chief advantage of this type of magnet being a stronger magnetic field, which can also be controlled by variation of the current.

Electro-Magnetic Induction

7. The principle of electro-magnetic induction is used in electric machines whenever an electric current is produced by means of a magnetic field. When a permanent magnet is inserted into a coil (see Fig. 4), lines of force cut the turns of wire at right angles. If the two ends of the coil are connected to a galvanometer the instrument pointer is deflected, indicating that an E.M.F. is being induced in the coil and that current is flowing. The pointer returns to the central position as soon as the relative motion between the magnet and coil ceases. This relative motion must always be such that the lines of force move across the conductors at an angle ; if they move parallel to the conductors no E.M.F. is induced.

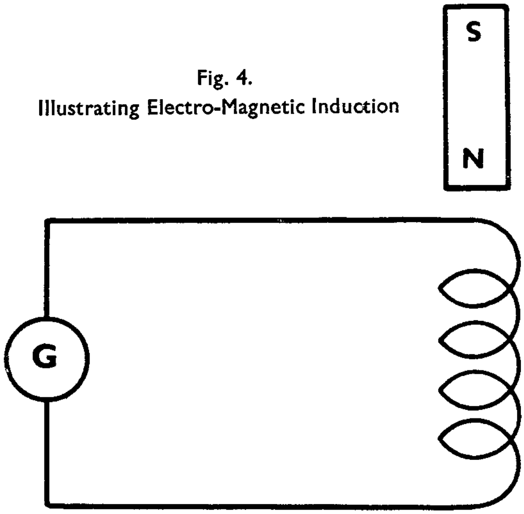

Fig. 4.
Illustrating Electro-Magnetic Induction

When the magnet is withdrawn the pointer is again deflected, but in the opposite direction. In both cases the direction of the induced current is such that the electro-magnetic field opposes the movement of the magnet.

8. The principles of electro-magnetic induction are summarized by two laws :—

(*a*) *Faraday's Law.* Faraday's Law states that the value of the induced E.M.F. is proportional to the rate of change of flux linkage, *e.g.* an E.M.F. of one volt is induced when the rate of change is 100,000,000 lines of force per second.

(*b*) *Lenz's Law.* Lenz's Law states that in electro-magnetic induction the induced currents have such a direction that their reaction tends to stop the motion which produced them.

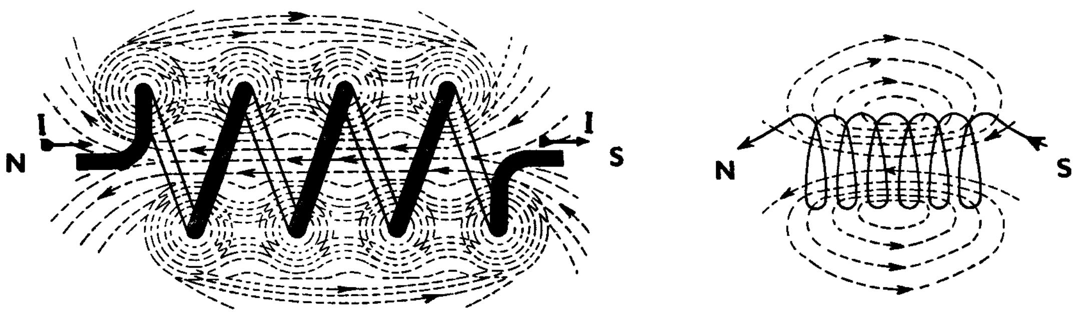

Fig. 3. Field Round Solenoid

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Inductance

9. Inductance (symbol L) is the property possessed by any circuit such as a coil, where a change of current is accompanied by a change in the strength of a magnetic field.

(*a*) *Self Inductance.* When the current through a coil is varied, the resultant movement of the surrounding lines of magnetic force induces an E.M.F. in the turns of the coil. This induced E.M.F. is in such a direction that it opposes the changing condition in the circuit (Lenz's Law). Thus on closing the switch in an inductive D.C. circuit the self-induced (or back) E.M.F. opposes the applied E.M.F. and causes a gradual rise in current to its maximum steady value, while the magnetic field surrounding the coil is being established. On opening the switch the collapse of the magnetic field tends to maintain the flow of current. The unit of inductance is the Henry (H) and a circuit has an inductance of one Henry if an E.M.F. of one volt is induced in the circuit when the current changes at the rate of one ampere per second. Iron-cored inductances are generally used in rectifier circuits for smoothing out variations in direct current obtained from an A.C. supply.

(*b*) *Mutual Inductance.* If two coils are so placed that when current is passed through one of them the resultant magnetic flux links with the other coil, any variation of the current in the first coil causes an E.M.F. to be induced in the second coil. The coils are known as the primary and secondary coils respectively, and are said to have mutual inductance. The unit of measurement is the Henry, and the mutual inductance of two coils is one Henry when an E.M.F. of one volt is induced in the secondary due to the primary current changing at the rate of one ampere per second. This principle is used in transformers, ignition coils, and magnetos.

The Transformer

10. The transformer is used for raising or lowering the voltage in an A.C. circuit. A typical transformer consists of two coils electrically separated and wound on the same laminated iron core. If one coil is connected to an A.C. supply, an alternating magnetic flux is set up in the core. This rising and falling flux links with the second coil and induces in it an E.M.F. If the second coil is connected to a load, current flows. The coil to which the supply is connected is called the primary winding, and the coil to which the output is connected, the secondary winding.

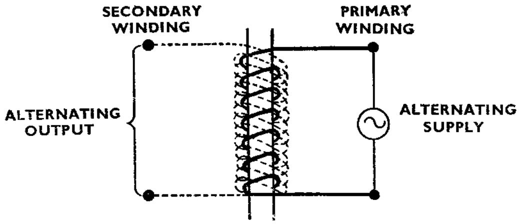

Fig. 5. Open Core Transformer

11. **Transformation Ratio.** The value of the secondary E.M.F. in a transformer depends on the number of secondary turns compared to primary turns. In Fig. 5 the secondary is wound with a large number of turns of fine wire, while the primary has only a few turns of thick wire. The E.M.F. induced in the secondary is higher than that of the primary, but the current which can be taken from the secondary is less than the current in the primary, neglecting any losses which are very small. Therefore, if the secondary winding is double the value of the primary, then the value of the secondary current is half that of the primary current. The ratio of primary E.M.F. to the secondary E.M.F. is equal to the ratio of the number of primary turns to the number of secondary turns, *i.e.* :—

$$\frac{\text{Secondary E.M.F.}}{\text{Primary E.M.F.}} = \frac{\text{Secondary turns}}{\text{Primary turns}}$$

$$= \text{Transformer ratio}$$

In a step-up transformer this ratio is greater than one, and in a step-down transformer it is less than one.

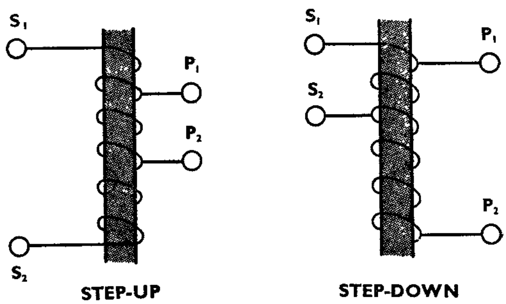

Fig. 6. Illustrating Transformer Ratios

CHAPTER 4

ELEMENTARY MOTOR AND GENERATOR PRINCIPLES

Electro-Magnetic Induction

1. A generator is a machine which converts mechanical power into electrical energy. It consists of a magnetic field in which conductors are rotated in such a manner that they cut the magnetic lines of force. This conversion is based on *Faraday's Law* of self-inductance, which states that whenever the magnetic flux through a circuit changes, an E.M.F. is induced in the circuit proportional to the rate of change of flux. If a conductor is moved in a magnetic field in such a manner that it cuts lines of force, an E.M.F. is induced in that conductor. In a similar manner, if the conductor is held stationary and the magnetic field is moved or varied in intensity an E.M.F. is induced in the conductor. A voltmeter connected across the two ends of the conductor will read the value of the E.M.F. induced, and if a closed circuit is connected across the two ends of the conductor a current will flow.

Generator Theory

2. The simplest form of generator consists of a loop of wire, known as an *armature*, rotating in a permanent magnetic field (Fig. 1). By reference to Fig. 2 and the application of *Fleming's Right-Hand Rule* (Generators), which states: "Extend the thumb, forefinger, and middle finger of the right hand in three mutually perpendicular directions; point the thumb in the direction of *motion*, the forefinger in the direction of the *field*, then the middle finger gives the direction of the *induced* E.M.F.", it will be seen that the resulting flow is not always in the same direction but alternating.

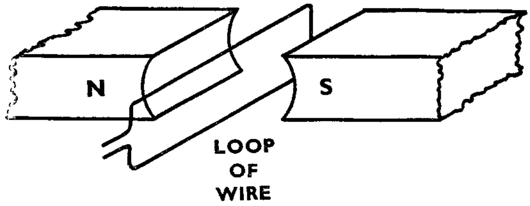

Fig. 1. Rotating Loop

3. In Fig. 2 (a) it will be seen that the sides of the loop are moving at right angles to the field, cutting the maximum number of lines of force, and the induced E.M.F. is at a maximum in one direction. As the loop rotates the induced E.M.F. falls, until the sides of the loop are moving parallel to the field (Fig. 2(b)), when, for an instant, no lines of force are cut and the E.M.F. is zero. Continued rotation causes the sides of the loop to move into the field once more and the E.M.F. rises until it again reaches a maximum (Fig. 2(c)). As the relative motion between each side of the loop and the magnetic field was reversed at the point shown in Fig. 2(b), the second maximum E.M.F. is in the opposite direction to the first maximum E.M.F. shown in Fig. 2(a). With continued rotation, the sides of the loop once again move parallel to the magnetic field and, as no lines of force are being cut, the induced E.M.F. again falls to zero as in Fig. 2(d). After one complete revolution, the loop again reaches its original position in the field and the E.M.F. is again at a maximum.

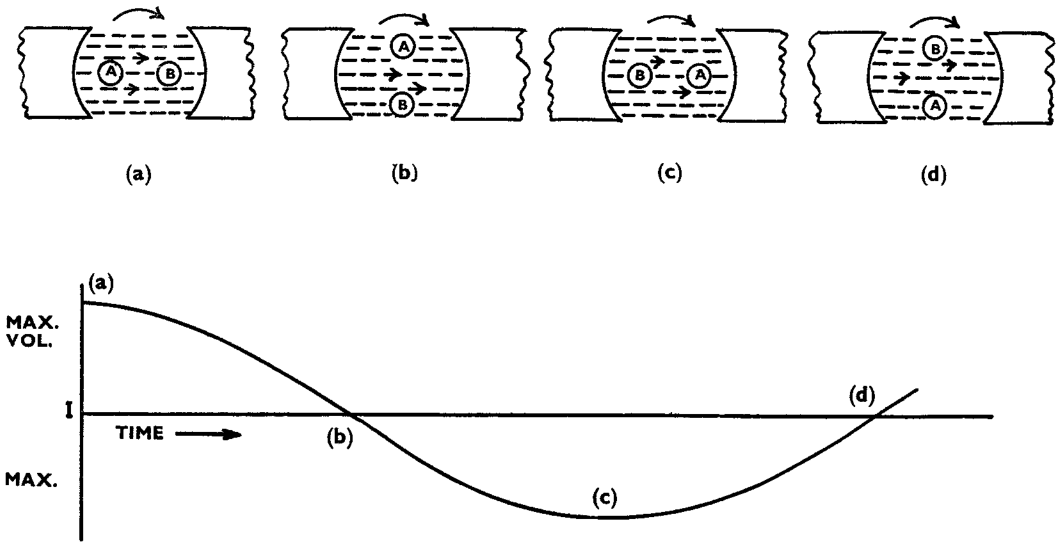

Fig. 2. Basic Generator Principle

4. To feed an external circuit the rotating coil is connected to *slip-rings* and a *brush*. Slip-rings are usually made of copper, and brushes of carbon or carbon-copper mixture (low resistance). The brush is arranged to bear on each slip-ring so as to collect the output and feed it into the external circuit (Fig. 3). The polarity of each slip-ring therefore changes with each 180 degrees rotation of the loop of wire, giving an alternating output.

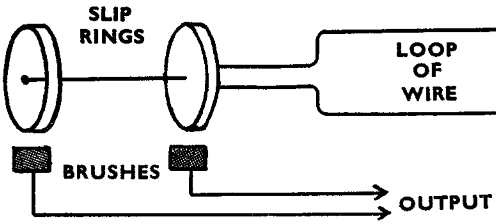

Fig. 3. Rotating Loop Connected to Output via Slip-Rings

5. The output of such a simple generator is very low indeed. It is, however, increased by the combination of the following :—

(*a*) A stronger magnetic field, created by substituting an electro-magnet for the permanent magnet (usually fed by the generator itself), consisting of a large number of turns of copper wire wound round the pole piece, which then becomes the soft iron core of a solenoid.

(*b*) Increasing the number of conductors.

(*c*) Attaching the conductors to a large piece of soft iron, so that the whole rotates within the magnetic field, the soft iron (armature) being inserted to concentrate the lines of force passing between the pole faces and offering them a path of low opposition.

(*d*) Laminating the armature and pole pieces, *i.e.* constructing them of soft iron insulated from each other by rust or shellac ; this decreases the losses in the generator.

(*e*) Increasing the speed of rotation of the armature.

A.C. Generator or Alternator

6. An A.C. generator or alternator is a development of the simple generator (see para. 2), and is normally run at a constant speed to maintain a constant frequency of alternation of output, the field being supplied by a separate D.C. generator.

D.C. Generator

7. A uni-directional output generator has many uses, especially in radio application, and an A.C. generator needs much constructional modification to achieve this. Some switching device is necessary (see Fig. 2(b)) to change over the contacts between coil brushes at the instant of changeover, so that the new build-up of voltage will be in the same direction in the external circuit as it was previously. This device is known as a *commutator* and consists of conducting segments and insulators arranged alternately as shown in Fig. 4.

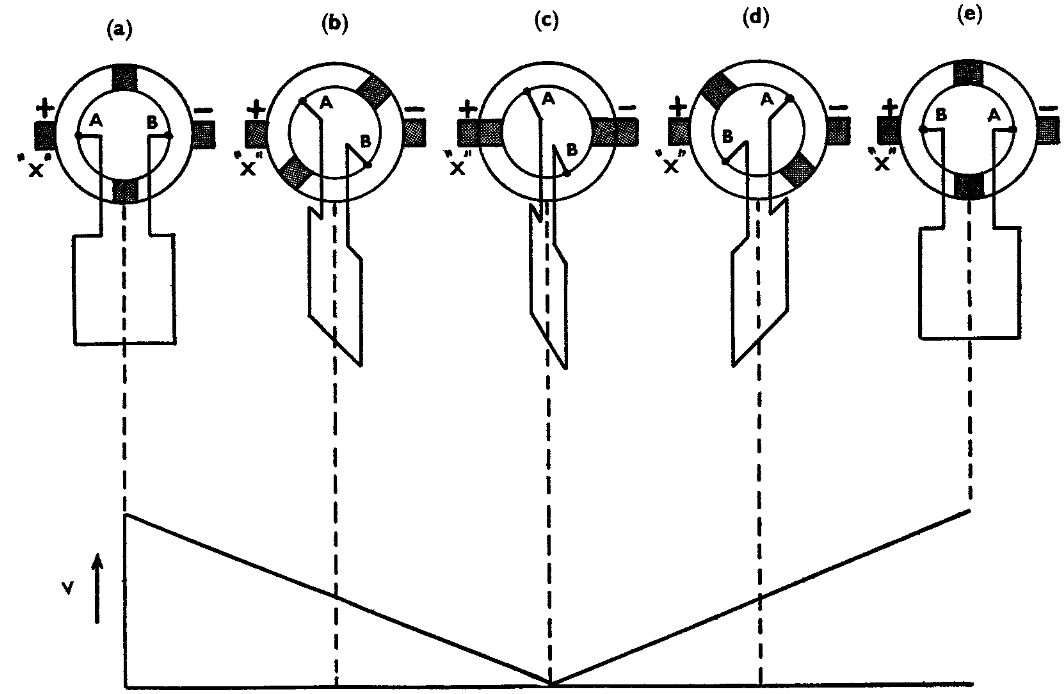

Fig. 4. Use of Commutators

8. In Fig. 4(a), brush X (in this case the positive supply to the external circuit) is bearing on segment A which is connected to one side of the coil or loop. If the coil is cutting maximum lines of force, as in Fig. 2(a), then maximum voltage is being developed at this instant. Fig. 4(b) shows the coil after approximately 60 degrees rotation in a clockwise direction where voltage developed has decreased from maximum, with brush X still bearing on segment A. Fig. 4(c) corresponds to Fig. 2(b), where no voltage is being developed, and in this position brush X is bearing on both conducting segments. In Fig. 4(d) rotation has continued and the arm of the coil connected to segment B is cutting the lines of force in the same direction as that cut by arm A, therefore the voltage being induced in arm B will be of the same polarity as that in Fig. 4(a). Fig. 4(e) shows the coil having rotated through 90 degrees in a clockwise direction with maximum voltage again being developed. Note that brush X bears on segment B.

9. Study of Fig. 4 will show that the desired switching has been accomplished and a uni-directional output is the result. In the simple generator this is by no means a steady output but is a pulsating D.C. output. To smooth out these pulsations it is necessary to increase the number of loops of wire and the corresponding segments on the commutator. The final output consists of many graphs as in Fig. 5, on the same base but displaced in time according to the position of each coil on the armature, the output being additive. A slight unevenness exists in the output, and this is known as *commutator ripple* (see Fig. 5). The output of a D.C. generator may be increased by making the physical changes described in para. 5.

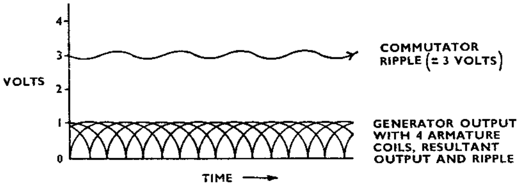

Fig. 5. Generator Output

Generator Efficiency

10. The efficiency of a generator may be as high as 75 per cent. on small generators up to 500 watts output, rising to 90 to 95 per cent. on very large power station installations. Losses can be due to:—

(*a*) *Friction.* The friction of bearings, brushes, and air resistance.

(*b*) *Ohmic Resistance.* Ohmic resistance of the conductors, brushes, and brush surface contact.

(*c*) *Hysteresis.* See Chap. 3, para. 3(f).

(*d*) *Eddy Currents.* E.M.F. induced in the armature core which causes a current to flow the magnetic field of which opposes the main field.

Motor Theory

11. The electric motor is a machine for converting electrical energy into mechanical energy. It works on the principle that if current is passed through a conductor in a magnetic field the conductor will tend to move out of the field. Several conductors in the form of windings on a cylindrical armature are usually employed and the armature, which is mounted on a spindle, then revolves in the magnetic field.

12. Fig. 6 shows the magnetic field existing between the pole pieces of a permanent magnet and the direction of the lines of force.

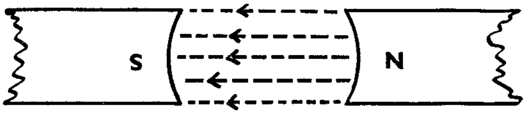

Fig. 6. Magnetic Field

13. Fig. 7 shows the magnetic field existing around a sectional representation of the current-carrying loop and direction of lines of force.

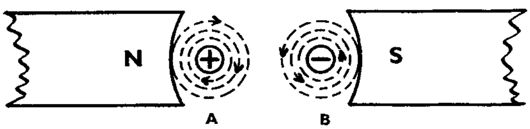

Fig. 7. Magnetic Field Round Loop

14. Fig. 8 shows the combined magnetic fields the lines of force, like elastic bands, tend to shorten along their length while remaining complete in themselves. To fulfil this property the loop is free to rotate and the lines of force cause the loop to move into such a position that the main field takes up the shortest length. One arm of the loop moves downwards in an anti-clockwise direction and the other arm upwards. This movement will continue until the loop takes up a position as in Fig. 2(b). To maintain rotation more loops must be added and a switching device (commutator) incorporated to maintain uniform direction of current within the loop (armature) windings.

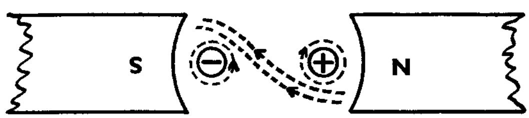

Fig. 8. Combined Magnetic Fields

15. In Fig. 7 the current in arm A is in the direction " into the paper " and the magnetic field around this arm is in a clockwise direction (Corkscrew Rule). The relative directions of force, current, and magnetic field are stated by *Fleming's Left-Hand Rule* (Motors), as follows :

> "Extend the thumb, fore, and second fingers of the *left* hand all at right angles, then the *thumb* represents the direction of *motion*, the *forefinger* points along the lines of *force*, the *second* finger points in the direction of the *current*".

Back E.M.F.

16. The resistance of the armature windings of most motors is very low, usually less than one ohm, and if this were the only opposition offered to the current, with say a 220-volt supply, the current would be extremely high. When the armature of the motor starts to rotate, however, the conductors cut the main magnetic field and an E.M.F. is induced in them ; this E.M.F. (known as "Back E.M.F.") always opposes the E.M.F. applied to the terminals of the motor. The current in the armature therefore depends on the difference between the applied E.M.F. and the back E.M.F. (known as the effective E.M.F.).

CHAPTER 5

ELECTRICAL MEASURING INSTRUMENTS

Introduction

1. In radio work the most commonly used instruments are *ammeters* and *voltmeters*, which measure current and potential difference respectively. Since an ammeter measures the amount of current in a circuit it must be connected in series with the circuit and its resistance must be very low to minimize interference with current flow. Similarly, because a voltmeter measures P.D., and is connected in parallel with the part of the circuit concerned, its resistance must be as high as possible to limit the current to a suitable value.

2. An indicating instrument consists of a pointer attached to a moving component pivoted on jewelled bearings. The pointer moves over a scale to indicate the value of current or voltage. Three forces control the movement :—

(*a*) *The Deflecting Force*. The deflecting force energizes the movement of the instrument and moves the pointer across a graduated scale.

(*b*) *The Controlling Force*. The controlling force opposes the deflecting force so that the pointer comes to rest (when the two forces are balanced) in a definite position corresponding to the value of the quantity being measured. The controlling force also returns the pointer and movement to zero when the instrument is disconnected. The force may be provided by a coiled hair spring or by gravity.

(*c*) *The Damping Force*. The damping force prevents oscillation of the pointer and brings it quickly to rest, giving a steady or "dead-beat" reading. There are two common forms of damping :—

(i) *Air Damping*. This is obtained by fixing a vane to the pointer spindle which moves in a damping chamber ; air pressure on the face of the vane slows down the motion in each direction.

(ii) *Eddy Current Damping*. This is obtained by the movement of a metal component in a magnetic field. The eddy currents thus induced in the metal set up a magnetic field which opposes and slows down the motion.

Moving Coil Measuring Instruments

3. In moving coil measuring instruments a magnetic field is provided by a horse-shoe permanent magnet. A cylindrical soft iron core is fixed between the magnet poles so that the flux passes through it across the gap. The moving coil consists of several turns of insulated wire wound on a rectangular aluminium former. The former is pivoted on bearings, sometimes jewelled, and is free to rotate, so that the sides of the coil move in the gap between the pole faces and the core. The electrical connections to the core are made by two phosphor bronze hair springs at either end of the former. The hair springs also provide the controlling force and are coiled in opposite directions to reduce the effect of temperature variations. The pointer and former are attached to the same spindle.

4. **Operation.** When a current passes through the coil an electro-magnetic field is set up, which tends to rotate the coil so that the electro-magnetic field is parallel to that of the permanent magnet. The polarity of the electro-magnetic field, and therefore the direction of torque, depends on the direction of the current in the coil. The turning movement of the coil continues until the torque produced by the current is balanced by the hair springs. Since the permanent magnetic field is constant the torque produced and the consequent deflection of the pointer are directly proportional to the amount of current, and the scale is therefore evenly divided. Eddy currents set up in the aluminium former will provide the damping force.

5. **Application.** The current required to give a full-scale deflection of a moving coil instrument may be as low as one milliamp. When used as an ammeter a low resistance bar, known as a shunt, is connected in parallel with the moving coil. The main current is carried by the shunt and a small proportional flow of the current takes the path through the moving coil. When used as a voltmeter a high resistance in series with the coil restricts the current to the value necessary to give full-scale deflection of the pointer. By using a suitable shunt or series resistance a moving coil instrument can be adapted for use on any direct current or voltage range.

6. Since the direction of torque depends on the direction of the current the instrument cannot be used for measuring A.C. without a rectifier. The rectifier is used to convert A.C. into D.C. The meter then reads the rectified A.C. as D.C. in the normal manner.

Thermo-Couple Ammeter

7. A thermo-couple or thermo junction ammeter depends on the fact that if the junction of two dissimilar metals is heated, an E.M.F. is produced. The current to be tested passes through a small heating coil ; this coil affects the two joined pieces of metal.

8. **Operation.** The hot junction is spot welded to a heating strip connected in series with the main circuit. When current passes through the heating strip the rise in temperature generates an E.M.F. in the thermo-electric couple, which is measured by the moving coil instrument. As the heating effect is proportional to the square of current, the instrument has an uneven scale.

9. **Application.** This instrument reads A.C. or D.C. values ; in A.C. circuits it indicates average effective values and is unaffected by frequency or wave form ; it is sensitive, accurate, and inductance and capacity are negligible at normal frequencies. The range is varied by the use of different heaters.

CHAPTER 6

CAPACITY AND REACTANCE

Charged Bodies

1. A charged body can be defined as a body that has gained or lost electrons. The forces of attraction and repulsion exerted by charged bodies are in a region surrounding them, which is called a field of force or electric field. When the body is deficient of electrons it is said to be positively charged; when it has a surplus of electrons it is said to be negatively charged.

2. When charged, a conductor is surrounded by an electric field having lines of force, and it behaves like a magnetic pole, repelling like charges and attracting unlike charges. Fig. 1 shows the field round a single conductor.

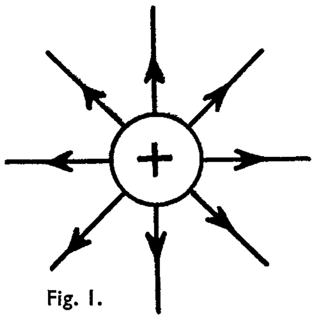

Fig. 1.
Electric Field Surrounding Conductor

3. Fig. 2 shows the effect of two conductors, one of which is charged positively and the other negatively. As they are brought closer together the lines of force link together. The closer they are brought together the greater is the linking effect. This is of importance in the construction of condensers.

Condensers

4. The simplest form of condenser consists of two parallel metal plates separated by insulating material. The insulating material (dielectric) may be: air, mica, waxed paper, oil, etc. Dry air is taken as the standard for measuring the relative strength of dielectrics and has a dialectric constant of unity; the nature of the dielectric has a considerable effect on the capacity of the condenser. When oil is used as a dielectric the capacity of the condenser is multiplied by 2·5 times, with sulphur 4 times, and with mica 6 times. The distance between the plates is also a vital factor in the design of condensers; the closer they are together the greater will be the capacity of the condenser, the further apart they are the smaller will be the capacity.

5. **Charge and Discharge of Condensers.** If the plates of a condenser are connected to a battery, one to the positive terminal and the other to the

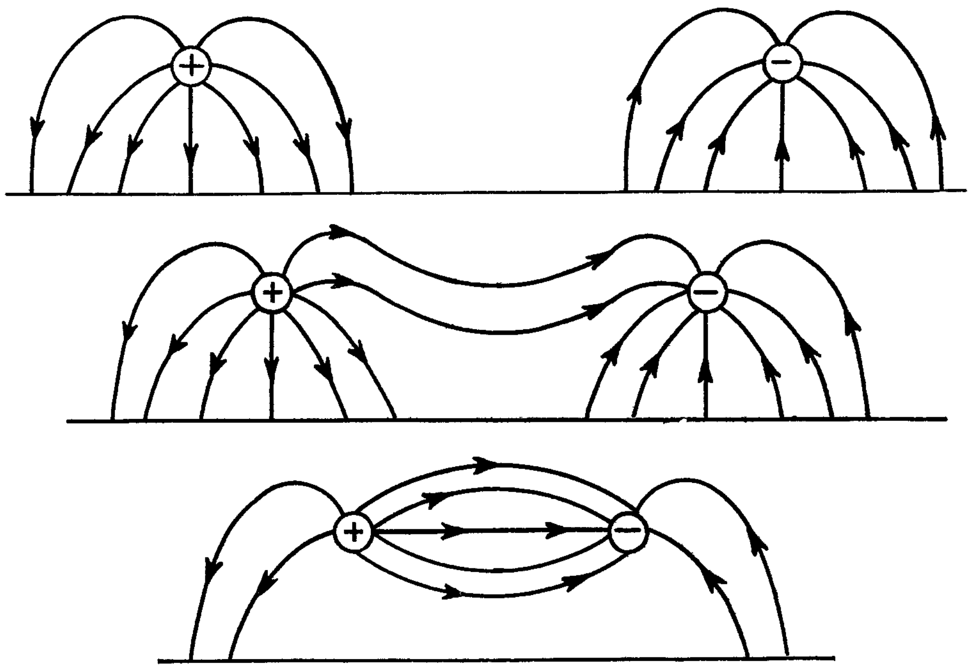

Fig. 2. Linking of Electric Fields

negative terminal, a current will flow until the P.D. between the plates equals the E.M.F. of the battery. The two plates are now oppositely charged, the positive plate having a deficit of electrons and the negative plate a surplus of electrons. At the same time an electric field is established in the medium between the plates; a displacement of electrons will occur in this medium, the electrons trying to move towards the positive plate. When the battery is disconnected each plate is left in its charged state, and if the plates are not connected to a conductor the surplus of electrons on the negative plate will flow to the positive plate until they are both reduced to an equal and neutral state. The current flow is maximum at the start of discharge and gradually falls away to zero. During discharge the electrons in the dielectric will have been released from the effect of the electric field and will have returned to their normal state. A condenser takes time to charge and discharge, and this time will be increased if resistance is present in the external circuit connecting the two plates. The greater the value of resistance the smaller will be the initial discharge current and the longer will be the time the condenser takes to discharge to a neutral state. Condensers can be made larger by placing a number of plates in parallel and interleaving them as shown in Fig. 3.

Fig. 3. Air Condenser Principle

6. **Unit of Capacity.** The unit of capacity is the *Farad*, and represents the capacity of a condenser in which one coulomb of electricity raises the P.D. by one volt. The Farad is too large for practical purposes and the Microfarad or Micro-microfarad are used. A microfarad is equal to one millionth part of a farad. A micro-microfarad is equal to one millionth of a microfarad.

Reactance

7. The opposition offered to the flow of current in an A.C. circuit by an inductance or condenser is known as its *reactance* and is measured in ohms.

(*a*) *Inductive Reactance.* The instantaneous current through an inductance of L henries when an instantaneous voltage E is applied may be calculated, after Ohms' Law, from the equation:

$$I = \frac{E}{2\pi F L} = \frac{E}{\omega L}$$

The term "ω" denotes the expression $2\pi F$. The expression ωL gives the reactance of the inductance and it will be seen that the reactance will increase as the frequency increases. In a circuit which contains only inductance the voltage is said to lead the current by 90 degrees; when the circuit also contains resistance this angle of lead is some figure less than 90. Most of the practical circuits contain resistance as it is impossible to construct an inductance which has no resistance, though by using wire of heavy gauge it is possible to construct an inductance which has a very small amount of resistance. As a result the difference in angle of lead will be nearly, but never exactly, 90 degrees.

(*b*) *Capacitive Reactance.* The instantaneous current through a condenser of capacity C farads when an instantaneous voltage E is applied, may be calculated from the equation:

$$I = \frac{E}{\frac{1}{2\pi F C}} = \frac{E}{\frac{1}{\omega C}}$$

The expression $\frac{1}{\omega C}$ gives the reactance of a condenser. As the frequency increases the reactance of the condenser decreases. In a circuit that contains only capacity the current precedes, in phase, the applied voltage by 90 degrees. If resistance is also present in the circuit, the angle is less than 90 degrees.

Impedance

8. The total opposition in an A.C. circuit containing both resistance and reactance is called the *impedance* of the circuit. Impedance is denoted by the symbol "Z" and is measured in ohms; thus Ohm's Law in A.C. circuits becomes:

$$I = \frac{E}{Z}$$

When the circuit contains resistance, inductance, and capacity, the resolution of this equation becomes rather complicated.

9. **Series Resonance.** A circuit consisting of an inductance and a condenser in series is called an *acceptor circuit*, and will have a natural or resonant frequency according to the value of L and C. If at this frequency an alternating voltage is applied, maximum current will flow through the circuit, as at the resonant frequency the voltage developed across the condenser is in opposite phase to the voltage developed across the inductance; thus the circuit behaves as if it contained only resistance, the impedance being a

minimum value, and the reactance zero. The voltage developed across either the condenser or the inductance can exceed the applied voltage by a large amount; this is most evident when the reactance of the inductance or condenser is larger than the resistance of the circuit. Advantage is continually taken of this fact in W/T circuits.

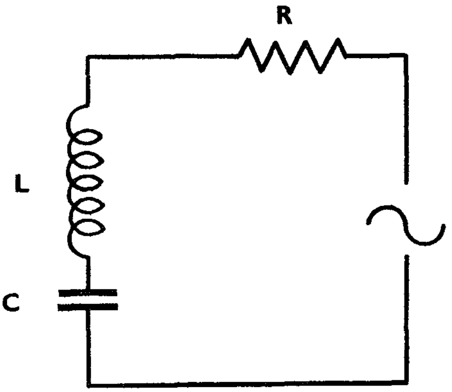

Fig. 4. Series-Resonant Acceptor Circuit

10. *Parallel Resonance.* A circuit consisting of an inductance and condenser in parallel is called a *rejector circuit*. If alternating voltages at the resonant frequency are applied across such a circuit then the currents through both branches will be equal but opposite in phase, and the current drawn from the supply will be virtually zero, but at the same time the circulating current in the rejector circuit will be high. A circuit containing L and C in parallel, whether it has resistance or not, cannot have voltage magnification, for the voltage across the inductance or condenser cannot be greater than the applied voltage. The magnification takes the form of current magnification, *i.e.* the circulating current is many times greater than the supply current. As each branch has a certain amount of resistance

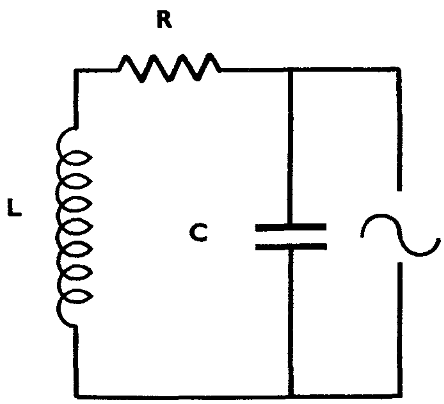

Fig. 5. Parallel-Resonant Rejector Circuit

the currents in the two branches may be equal but will not be exactly opposite in phase; there must, therefore, be a certain amount of supply current. The maximum impedance of a parallel tuned circuit is at the resonant frequency; as circuit resistance increases, therefore, the current decreases and the voltage increases.

Circuit Tuning

11. An increase in value of either inductance or capacity will decrease the resonant frequency, and conversely a decrease will increase the resonant frequency, so that a circuit can be tuned to various frequencies by altering either or both. Thus a variable tuned circuit can be used to select any particular frequency in the range covered, to the exclusion of other signals on adjacent frequencies; its ability to do this is termed its selectivity.

Oscillatory Circuits

12. Oscillatory circuits are used extensively in radio work both in receivers and transmitters. There are two types, the "Open Oscillatory Circuit" and the "Closed Oscillatory Circuit".

13. **Closed Oscillatory Circuit.** The closed oscillatory circuit is used for basic oscillator circuits. The basic requirement for the circuit is a condenser and an inductance connected in parallel (see Fig. 6(a)), the circuit being broken by a switch S. In Fig. 6(a) the condenser is fully charged and its electrostatic field is shown. When switch S is closed discharge begins, and a magnetic flux is built up in and around the coil. When this flux is at a maximum, the condenser is completely discharged (see Fig. 6(b)). When the driving voltage is nil the circulating current is at a maximum. Without driving voltage the current will start to fall, and with it the flux, but due to the inductance of the coil the fall of the current is opposed and the electricity is kept on the move by the induced E.M.F. until it charges the other plate of the condenser (see Fig. 6(c)). The process is repeated in successive oscillations (see Figs. 6(d) and (e)). This cycle of operations cannot go on indefinitely as energy losses are unavoidable; the energy that is returned to the condenser becoming progressively less with each cycle of operation (Fig. 6(e)). When a condenser in an oscillatory circuit discharges without external re-energizing, the resultant diminishing oscillations are known as damped oscillations. The energy losses can be counteracted by feeding the circuit with enough electrical energy to compensate for the losses (see Chap. 8). The frequency of the oscillation in the oscillatory circuit is controlled by the values of L and C, and can be calculated from the formula:

$$f = \frac{1}{2\pi\sqrt{LC}} \text{ cycles per second}$$

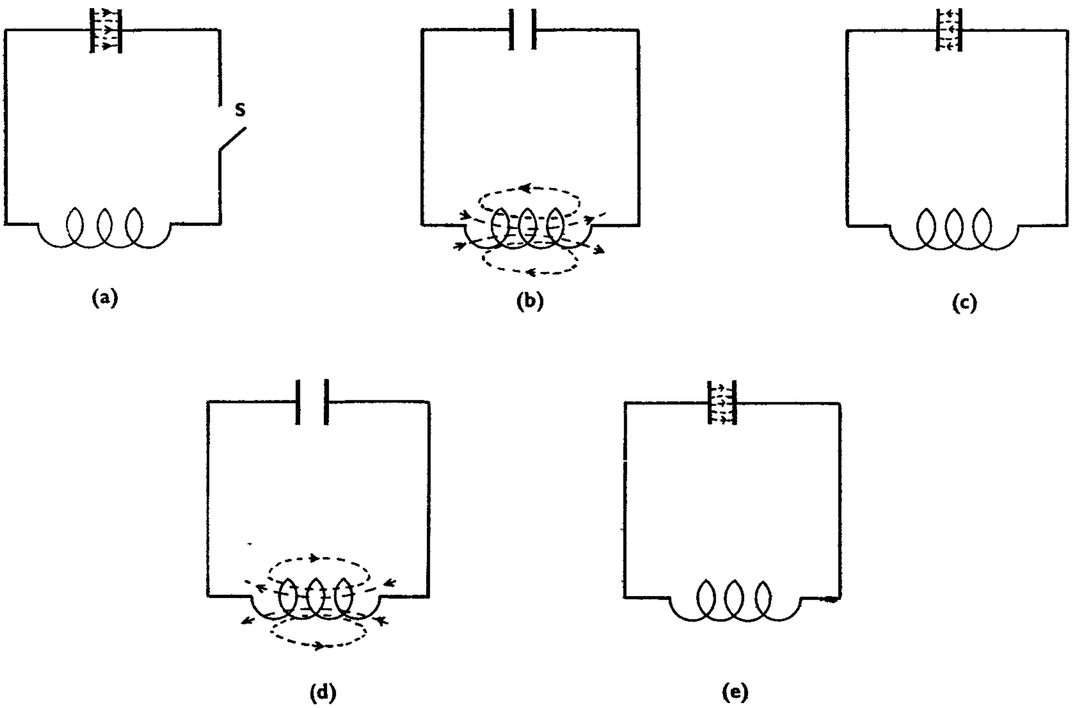

Fig. 6. The Oscillatory Circuit

14. **Open Oscillatory Circuit—Radiation.** In the closed type of oscillatory circuit the magnetic and electrical fields are concentrated. At every oscillation most of the energy associated with the field returns to the circuit. Although some of the energy is lost in the circuit, none is wasted in the fields. If the plates of the condenser are opened, however, so that the lines of force of the electric field are diffused over a wide space, the circuit becomes an open oscillatory circuit which is able to radiate electro-magnetic waves. Considerable energy is used in the radiation of these waves, and without external re-energizing the radiation will become rapidly attenuated. Therefore, at the same time as electro-magnetic radiation is taking place, it is necessary to inject energy into the circuit as quickly as it is lost so that the radiations do not become damped.

CHAPTER 7

THERMIONICS

Introduction

1. When a piece of platinum, tungsten, or other suitable wire is made red or white hot, its electrons are energized to an extent where many are able to escape and they break through the surface of the metal. An escaping electron—a thermion—leaves the hot wire positively charged. A state of equilibrium is reached when a cloud of escaped electrons around the wire causes some of the emitted electrons to return to the filament through electrostatic repulsion and attraction.

2. The simplest radio valve consists of a filament (the "hot wire" described in the previous paragraph) and a plate or anode to receive the thermions expelled by the filament. This type of valve is called a *diode*.

The Diode

3. The filament is usually made of tungsten, which is the material used in electric-light filaments. An untreated filament of tungsten wire burns brightly and is known as a "bright emitter". In practice, the tungsten filament is coated with barium or calcium oxide, which gives a greater emission of electrons at lower temperatures. This is the more usual "dull emitter".

4. If a positively charged plate is placed near the filament the escaping electrons, instead of returning to the filament, are attracted to the plate, and a flow of current results. The closely packed air molecules between the plate and the filament act as a barrier. In practice the plate and filament are mounted in a glass vacuum or in a gas filled tube.

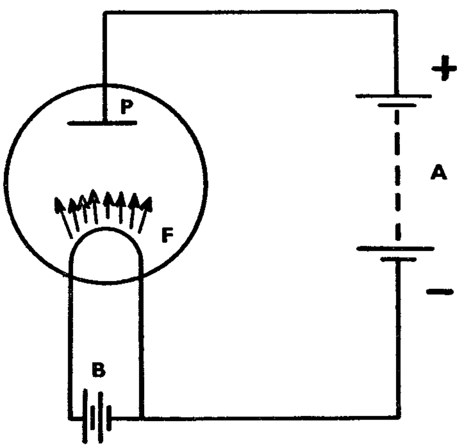

Fig. 1. Diode Valve

5. In Fig. 1, F is the filament which is heated by the battery B. The filament becomes white hot and radiates electrons. The electrons are attracted to P (the anode or plate) by the positive potential exerted by the battery A, the negative end of which is connected to the filament. Electrons can flow from the filament to the anode but not in the reverse direction, as the anode does not emit electrons.

6. Instead of heating the filament directly as shown in Fig. 1, a system of indirect heating is commonly used. The filament, in this case, takes the form of a barium-treated nickel tube into which a heating element is inserted. The tube is called the "cathode" and the heating element the "heater". There is no electrical connection between the two, and an A.C. supply may be utilized for the heater. A directly heated valve is usually heated with a D.C. supply, and if the supplied voltages were subject to variations, the efficiency of the valve would vary accordingly. Indirectly heated valves are usually to be preferred to directly heated valves because the former are not affected to the same extent by varying power supplies.

7. The only method of controlling the flow of electrons in a diode is by varying the anode voltage ; the greater the anode voltage the greater will be the flow of electrons. This method is satisfactory up to the stage where the anode potential is large enough to attract every emitted electron. At this stage the anode is said to be "saturated" and no further increase in anode current is possible.

Triodes

8. Fig. 2 shows how an electrode (which is sometimes known as a control grid) can be inserted between the filament and the plate (anode) of a diode valve. A valve so designed is known as a *triode*.

9. By inserting a control grid, which consists of wire wound spirally round two supports, between the filament and plate (cathode and anode respectively) and applying to it a positive voltage, the flow of electrons to the anode can be greatly increased and the valve made to amplify. Alternatively, if a negative voltage is applied to the control grid, electrostatic fields are set up and the flow of electrons to the anode may be retarded or accelerated. The valve can be made to stop conducting altogether, if required ; a method often used in transmitter keying. The very important position which the triode occupies in radio engineering is due to the remarkable control which the grid exerts on the anode current.

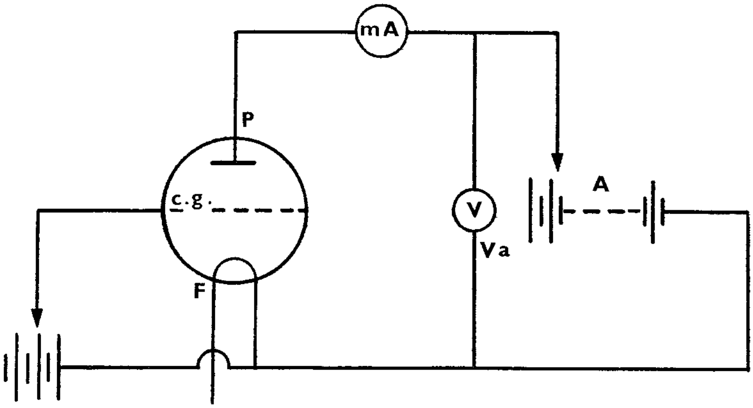

Fig. 2. Triode Valve

10. Fig. 3 shows the construction of a diode and a triode valve.

Properties of a Triode

11. In Fig. 2 a triode valve is shown connected to a voltmeter and an ammeter. Two batteries are also connected, one to supply L.T. to the grid and filament, and the other to supply H.T. to the anode. By varying the voltages applied to the grid it is possible to produce graphs as shown in Fig. 4. These graphs are known as Ia—Vg curves, Ia representing the anode current and Vg the volts applied to the grid. The Ia—Vg curves shown do not refer to any specific valve but are typical of indirectly heated triode valves. Each of the four curves shown indicates a different anode voltage. By altering the anode voltages by 20 volts with zero volts applied to the grid, a total change in anode current of slightly over one milliamp is obtained. If the anode voltage is kept constant at, for example, 180 volts with approximately 2·5 volts applied to the grid, the same change in anode current would result.

12. A triode valve has three characteristics known as :—

(*a*) Mutual conductance (gm), expressed as milliamperes per volt.

(*b*) Amplification factor (Mu).

(*c*) Anode impedance (Ra), expressed in ohms.

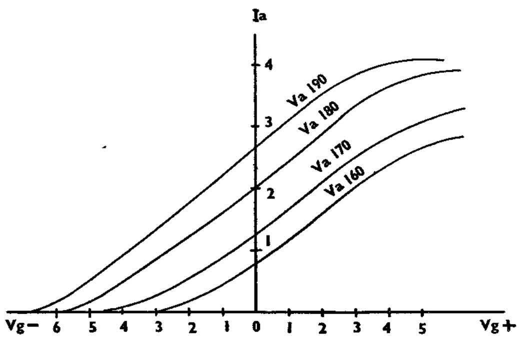

Fig. 4. Typical Ia-Vg Curves

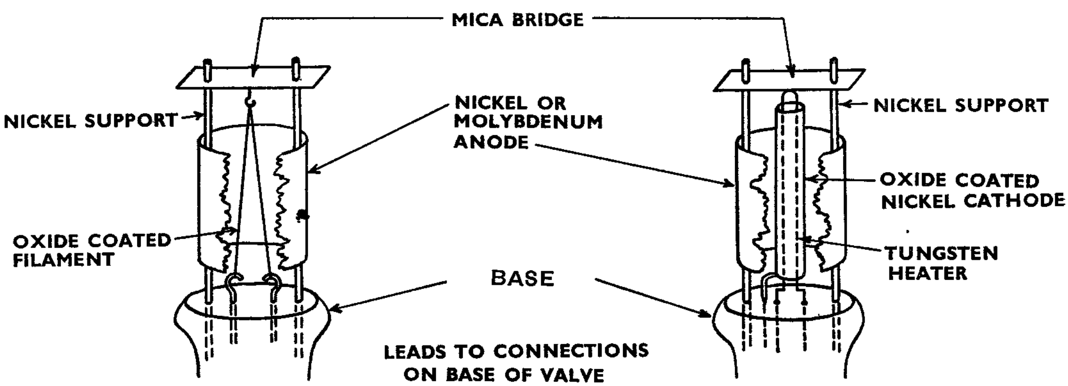

Fig. 3. Construction of a Typical Diode and Triode

13. When calculating valve characteristics the following abbreviations are used :

Anode voltage	Va
Grid voltage	Vg
Anode current	Ia

14. **Mutual Conductance.** Mutual conductance may be defined as "the rate of change of anode current with change of grid voltage, the anode voltage remaining constant". It is expressed in milliamperes per volt and is calculated from the formula :

$$gm = \frac{dIa}{dVg} \text{ ("d" means small changes in)}$$

15. **Amplification Factor.** In a triode a change of anode current resulting from a change in grid voltage is much greater than the change in anode current resulting from the same change in anode voltage. The ratio of the two is called the "amplification factor" and is expressed in the formula :

$$m = \frac{dVa}{dVg}$$

16. **Anode Impedance.** Anode impedance or, more accurately, anode resistance, may be defined as the reciprocal of the rate of change of current with anode voltage, when the grid is kept constant. It is calculated from the formula :

$$Ra = \frac{dVa}{dIa}$$

17. Graphs may be plotted showing the characteristics of a valve, using the formulæ shown in paras. 14 to 16.

18. From Fig. 4, using the 180 volt curve at zero grid volts the anode current is 2 m/a, and at 2·5 volts negative on the grid the anode current is 1 m/a ; thus for a change of 2·5 grid volts there is a change of 1 m/a anode current.

Viz. : $\underset{\text{(mutual conductance)}}{gm} = \frac{1}{2\cdot5} = \cdot4$ m/a per volt.

19. When increasing the anode voltage by 20 volts using the 160 or 180 anode volt curve, the anode current is increased by 1 m/a. To return the anode current to 1 m/a the voltage applied to the grid must be increased from zero to 2·5 volts negative.

Viz. : $\underset{\text{(amplification factor)}}{m} = \frac{20}{2\cdot5} = 8$

By increasing the anode voltage by 20, therefore, the anode current is increased by 1 m/a. *Viz.* :

$$Ra = \frac{20}{1/1{,}000} = 20{,}000 \text{ ohms.}$$

20. The valve described has a mutual conductance value of ·4 m/a's per volt, an amplification factor of 8, and an impedance of 20,000 ohms. These characteristics are all inter-related and from the figures taken for any valve the following formula is constant :

$$m = gm \times Ra$$

The Triode as a Class "A" Amplifier

21. Fig. 5 shows a triode valve connected to appropriate power supplies. The anode circuit contains a resistance R representing the anode load. Where the load is purely resistive, and the valve used as a Class "A" amplifier, its value is usually 2·5 times the Ra of the valve. If an alternating voltage is applied to the grid of the valve, the current through the valve will vary in sympathy with the grid variations. This varying current through the resistance R will cause varying voltage drops across the resistance. The end of the resistance connected to the lead A is the live end of the load, and the varying voltages registered at this point are very much greater than those applied to the grid of the valve because the voltage required on the grid to produce the same change in anode current is many times less than that obtained on the anode (see paras. 19 and 20). Thus, due to the greater control of the grid over the electron stream, and the use of an anode load to convert the changes of current to changes of voltage, the valve and its associated circuit can be made to amplify voltages. The overall gain of the output voltage over the applied voltage is known as the "stage gain" and can be obtained from the expression :

$$\frac{\text{Mu R}}{\text{R} + \text{Ra}}$$

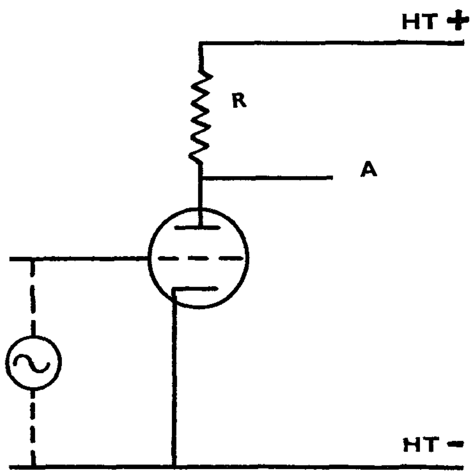

Fig. 5. Triode as an Amplifier

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Inter-Electrode Capacity

22. Each adjacent pair of electrodes in a valve act as plates of a condenser. These inter-electrode capacities, although very small, can be very troublesome, especially when the valve is working on the higher frequencies. There are three separate inter-electrode capacities in a triode valve: the capacity between anode and filament (Caf), the capacity between grid and filament (Cgf), and the capacity between anode and grid (Cag). Of these, Cag causes most trouble and acts as an external capacity between the anode circuit and grid, causing the grid circuit to oscillate; it is not possible, therefore, to use a triode for amplification at high radio frequencies. On lower frequencies the capacity will not pass as much energy to the grid circuit and the valve will operate as an amplifier.

The Tetrode Valve

23. The tetrode valve (as shown in Fig. 6) has four electrodes: a cathode, an anode, a control grid, and a screen grid. The screen grid is a fine wire mesh placed between the anode and the control grid. The screen grid minimizes the inter-electrode capacity between the anode and the control grid. It is earthed through a condenser to by-pass unwanted R.F. voltages.

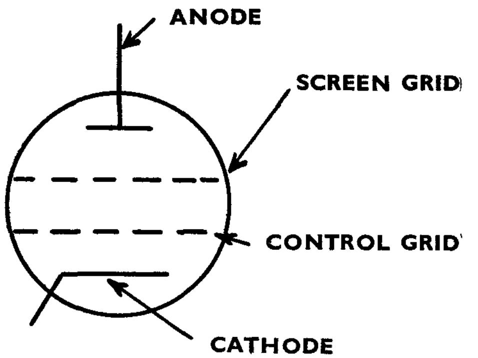


Fig. 6. Tetrode Valve

24. At the same time, the grid must be at a high potential to aid the flow of electrons to the anode. The screen grid is usually connected to H.T. positive through a dropping resistance to keep the voltage lower than that of the anode; it is then connected to earth through a condenser. The high potential on the screen grid greatly accelerates the electron flow and the electrons strike the anode with enough force to dislodge many more electrons. If the screen potential is higher than that of the anode, the electrons will be attracted to the screen and the screen current will be increased at the expense of the anode current. In a tetrode handling large current changes, therefore, there is the possibility that the anode voltage may swing below the value of the screen voltage with resultant distortion.

The Pentode Valve

25. The pentode valve (see Fig. 7) has five electrodes, the fifth being a "suppressor grid" situated between the screen grid and the anode, and connected to a point at earth potential or to a point of low negative potential. The function of the suppressor grid is to prevent electrons from being absorbed by the screen, should they become dislodged from the anode when the anode potential is near or below that of the screen grid. Owing to the effect of the suppressor grid the pentode valve has a low Cag and does not suffer from the defect of the tetrode valve. The pentode can, therefore, be used for all types of amplification and is especially useful when high power has to be handled.

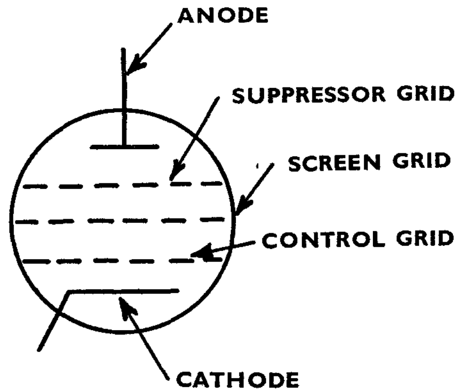


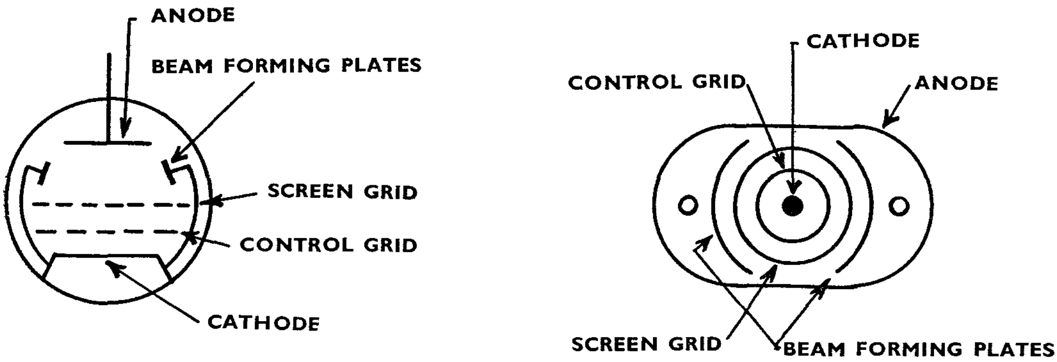
Fig. 7. Pentode Valve

The Beam Tetrode

26. The beam tetrode (Fig. 8) is a further development of the tetrode and is designed to overcome the inability of the tetrode to amplify satisfactorily. Instead of placing another grid in the valve, two plates are used to direct the flow of electrons into concentrated beams. The plates are connected internally to the cathode. Because the electron flow is concentrated into beams it becomes impossible for the electrons displaced from the anode to return to the screen grid. Beam tetrodes have similar characteristics to pentode valves, and in most cases can be used where pentodes are used.

Multi-Electrode Valves

27. Several other types of valves are used in radio. All of them are combinations of the valves already described. Many of these compound valves have been produced to do special jobs; for example, the triode-hexode is used as a frequency changer in superheterodyne receivers and the double diode triode may be used as a detector for A.V.C. and as an A.F. amplifier.



DISPOSITION OF BEAM TETRODE
(PLAN VIEW)

Fig. 8. Circuit Diagram and Plan View of Beam Tetrode.

CHAPTER 8

OSCILLATORS

General

1. An oscillatory circuit must have power supplied to it at the correct frequency if the oscillations are to be maintained. The thermionic valve may be used for this purpose and valve oscillators are used extensively in transmitters, receivers, and other radio equipment.

The Triode as an Oscillator

2. The use of a triode as an amplifier was explained in a previous chapter. If some of the output of an amplifier is fed back to the grid of the valve in correct phase, enabling the valve to supply its own input, the anode circuit will receive pulses of current at the correct frequency and oscillations will be maintained. In Fig. 1, L C is a closed oscillatory circuit forming the anode load of the valve. Applying H.T. will charge up the condenser C, and the circuit will start to oscillate. The changing current through L induces voltages in I_2 between grid and cathode so that the grid becomes more positive when the anode circuit requires more current to maintain oscillation. A large condenser bypasses the oscillation from the H.T. supply.

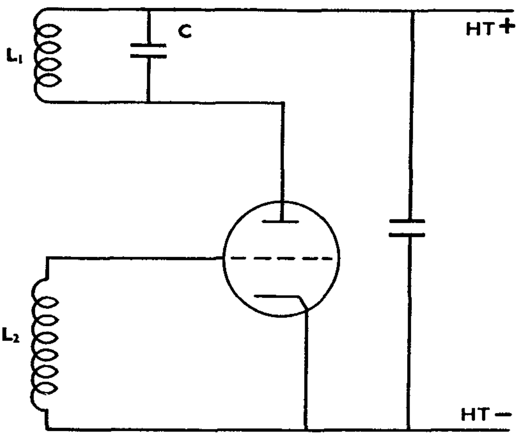


Fig. 1. Triode as an Oscillator

3. There are various types of oscillators and four of those most generally used are outlined below.

Meissner Oscillator

4. The simple oscillator described in para. 2 is the basis of the Meissner oscillator. Greater efficiency is obtained by tapping the anode lead into the coil of the anode until the load matches the valve resistance, and by applying self-bias to the grid. Output may be taken from the anode through a blocking condenser.

Hartley Oscillator

5. In the Hartley oscillator a tuned circuit between anode and grid, with a tapping from the inductance via a condenser to the cathode, ensures that the voltages fed back to the grid are in correct phase for maintaining oscillation.

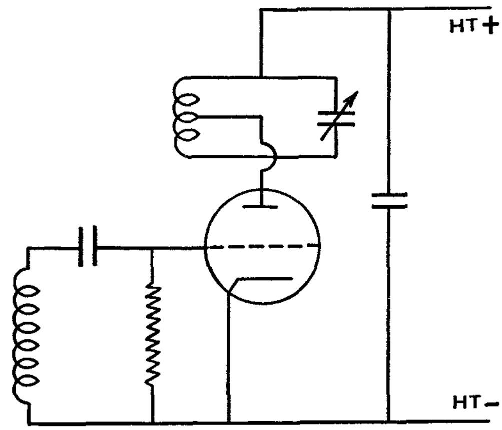


Fig. 2. Meissner Oscillator

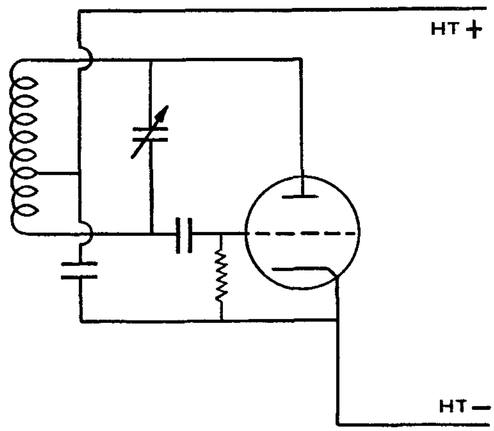


Fig. 3. Hartley Oscillator

Tuned Anode—Tuned Grid Oscillator (TA—TG)

6. In the TA–TG oscillator the capacity between anode and grid provides a coupling between the anode and grid tuned circuits. When both tuned circuits are brought into or nearly into resonance, there is enough transfer of energy from one circuit to the other to make the resulting grid-filament voltages cause variations of anode current of a phase capable of maintaining oscillations in the anode circuit.

Tuned Anode—Crystal Grid Oscillator (TA—CG)

7. TA–CG oscillators are widely used to minimize frequency drift. When a plate of suitable crystalline substance, *e.g.* quartz, is subjected to mechanical pressure, a potential difference appears between opposite faces of the plate. Conversely, if a potential difference is applied between opposite faces of the plate a mechanical strain is set up in the crystal. A crystal has a natural vibratory frequency which depends upon its thickness ; as this frequency is extremely stable the crystal is particularly useful for frequency control in transmitters. The crystal is mounted between two metal plates and may be connected as shown in Fig. 5. It behaves as an extremely stable tuned circuit and oscillations start when the anode circuit is tuned to resonance. The action is similar to that of the TA–TG oscillator.

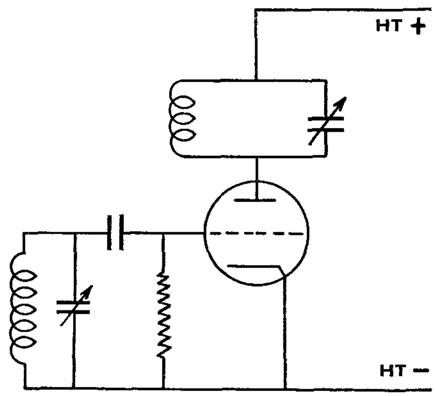


Fig. 4. Tuned Anode—Tuned Grid

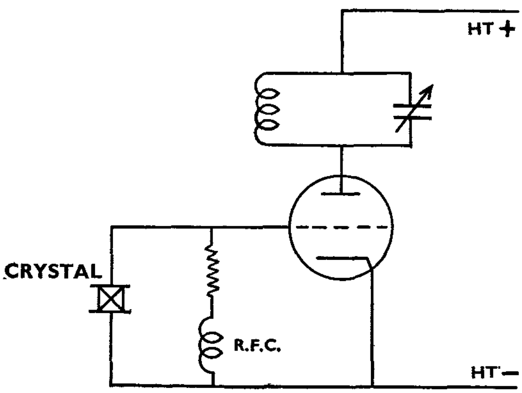


Fig. 5. Tuned Anode—Crystal Grid Oscillator

Class "A", "B", and "C" Operation

8. In general there are three ways in which a triode valve can operate. These are described in the following paragraphs.

9. **Class "A" Operation.** Class "A" amplification results when the amplitude of the grid input is insufficient to take the grid swings into the curved regions of the Ia–Vg curve. Under Class "A" conditions the output is distortionless and an exact copy of the input. Valve efficiency rarely exceeds 50 per cent., and if a "pure" symmetrical output is required efficiency may be as low as 25 per cent.

10. **Class "B" Operation.** In Class "B" operation the working point of the valve is biased back to the lower bend of the anode curve to anode current cut-off. Only positive grid swings of the input will cause anode current to flow and the output will be distorted. The mean value of anode current will therefore be less than under corresponding Class "A" conditions. In a non-oscillatory state the anode current will be almost zero. In Class "B" operation the anode current waveform is no longer sinusoidal but has a first harmonic content of roughly the same amplitude as a valve operating under Class "A" conditions. It therefore follows that, with suitable adjustment of the anode impedance, the same fundamental or first harmonic oscillatory power output may be obtained as in Class "A" operation. The D.C. input being smaller for the same oscillatory power output, however, efficiency is higher. (See Fig. 6.)

11. **Class "C" Operation.** In Class "C" operation the valve is biased to at least double cut-off and is an extreme form of Class "B". Efficiencies of the order of 85 per cent. may be achieved using this type of working ; anode current no longer flows for the whole of the positive half cycles and these are no longer faithful copies of the grid oscillatory input. To obtain peak values of anode current equal to those obtainable under Class "A" or "B" conditions the grid oscillatory input must be

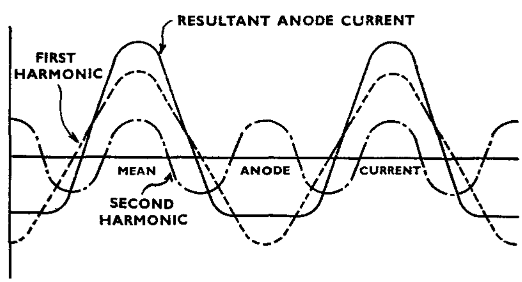


Fig. 6. Class "B" Operation—Output

much larger. Figs. 7 and 8 show the comparative values of grid input and anode current in Class "B" and "C" operations. The output of valves operated under both Class "B" and "C" contain many harmonics, and unless certain precautions are taken unwanted frequencies may be radiated. Sometimes, however, this phenomenon is useful in frequency multiplication circuits.

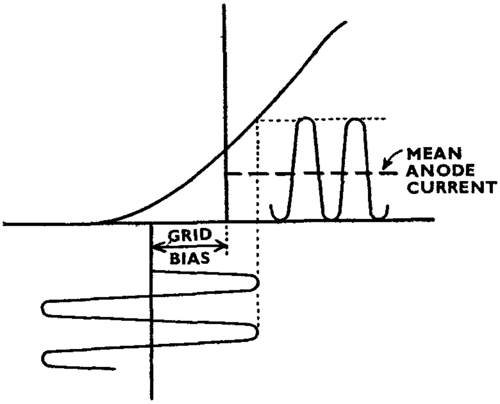


Fig. 7. Class "B" Operation

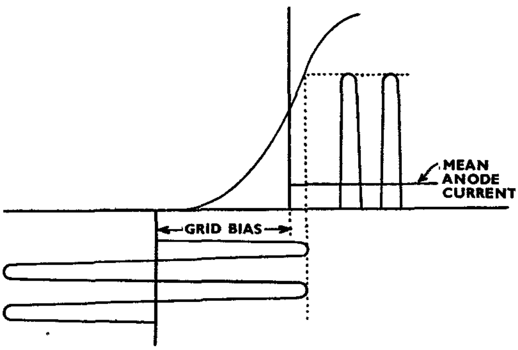


Fig. 8. Class "C" Operation

Frequency Multiplication

12. When it is required to transmit on very high frequency, a low basic frequency circuit is invariably used followed by one or more multiplying circuits. The oscillator valve in a frequency multiplying circuit is operated under Class "B" or, preferably, under Class "C" conditions. The circuits are tuned to a harmonic of the oscillator and the output harmonic is amplified and passed on to the next stage. Fig. 9 shows how a low basic frequency of 6 mc/s may be multiplied to give a final output of 108 mc/s.

13. When the multiplier is required to produce a low power signal, *e.g.* for a local oscillator in a frequency changer stage, the combination shown in Fig. 10 may be used.

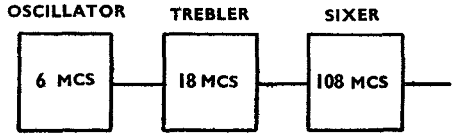


Fig. 10

Automatic Bias for Class "B" and "C" Operation

14. The required bias for moving the working point of a triode operating under Class "A" or "B" conditions may be obtained automatically by introducing a condenser and resistance into the grid circuit. Grid current flows when the grid becomes positive relative to the filament. The condenser thus acquires negative pulses and, by means of a high resistance, the charge of pulses is gradually leaked away. As a result, the mean grid potential is maintained at a steady negative value relative to the filament, and equal to the IR drop across the resistance. The more powerfully the grid swings the greater will be the grid negative potential; by adjusting the value of the resistance the correct negative potential may be obtained.

15. It is important that the values of the condenser and the resistance should be correct. If the time constant CR of the combination is too large, the grid will build up a large negative potential and oscillations will cease until enough of the charge has leaked away to permit them to start again. This is known as "Squegging" and in certain circuits is deliberately arranged.

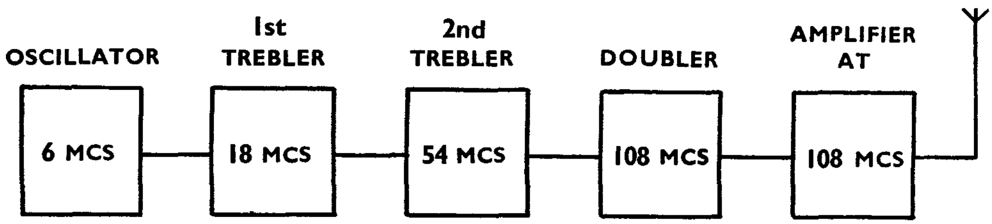


Fig. 9. Typical Frequency Multiplication Arrangement

16. The cure for squegging is to reduce the value of R. If the capacity of the condenser is too small, the charge built up on the grid will vary and thus the working point of the valve will also vary; the result will be distortion and an excess of harmonics. This form of bias is always used in oscillators, because if the valve were biased to Class "C", oscillations could never start. A circuit showing a resistor and a condenser arranged for automatic bias is shown in Fig. 11.

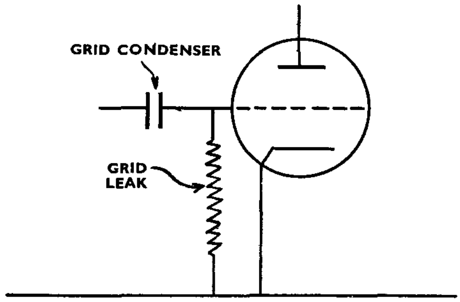


Fig. 11. Automatic Grid Bias

Detection

17. The three most common methods of detection are: anode bend, cumulative or leaky grid, and diode detection. Of these the last is normally used for reception of R/T and C.W. signals. Fig. 12 shows a circuit used for anode bend detection.

18. In Fig. 12 the grid of the triode is biased to the lower bend of the Ia–Vg curve; the current passed by the valve is small. When an amplitude modulated signal is applied to the grid, only the positive half cycles cause an increase in the anode current; as these vary in amplitude according to the modulation, so the mean value of the anode current will vary.

19. Fig. 13 shows the circuit for cumulative grid detection. It is similar to that for automatic grid bias described in para. 14. A charge is produced in the condenser by grid current flowing on the positive half cycles; this causes the negative charge to build up in the condenser which is allowed to leak slowly away through the resistance. If the incoming signal is modulated, the varying positive half cycles cause the grid bias to vary also. The variations will be a copy of the incoming modulation envelope.

20. In both types of detection described, the variations applied to the grid cause a much larger variation in anode current. The valve therefore also acts as an amplifier, and this form of detection is particularly suited to straight receivers where sensitive detectors are required. Both types of detection introduce a certain amount of distortion which is, unfortunately, also amplified. If high quality is required, therefore, another form of detection must be used.

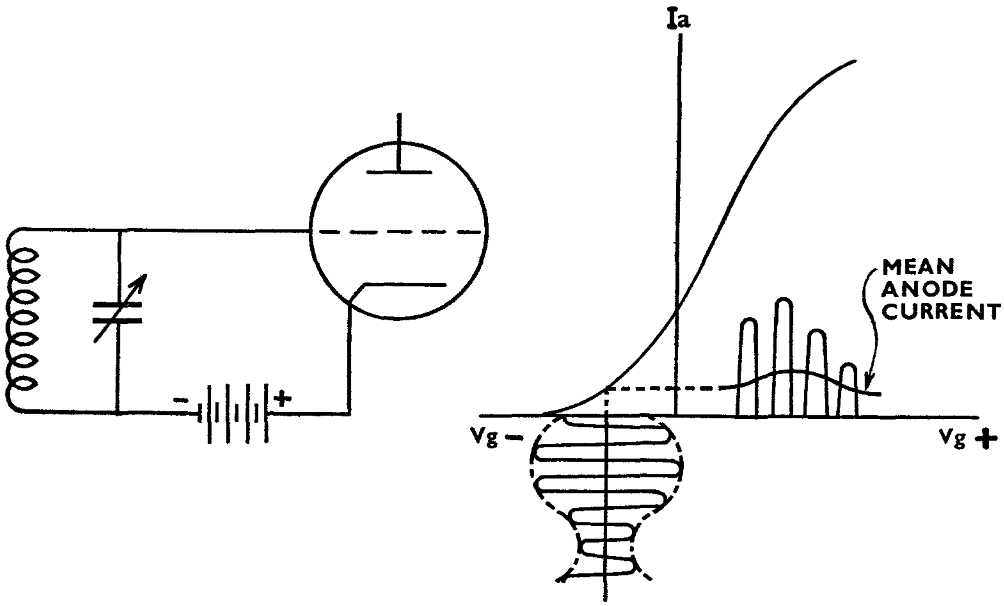


Fig. 12. Anode Bend Detection

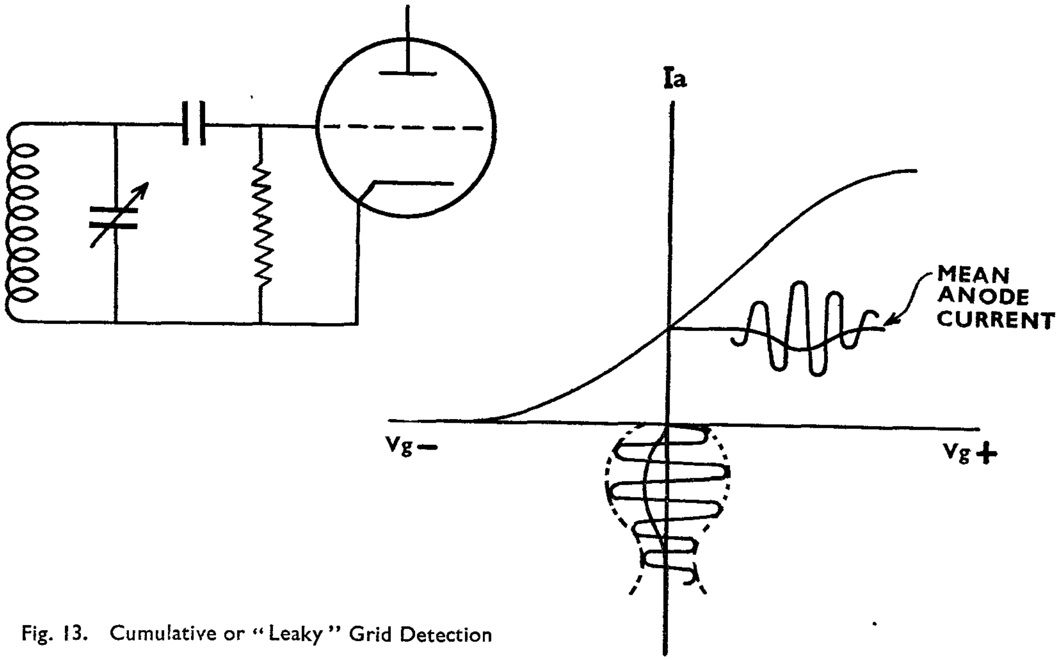


Fig. 13. Cumulative or "Leaky" Grid Detection

Diode Detection

21. Diode detection is usually used in modern superheterodyne receivers. It is rather insensitive to small signals but is free from distortion. Fig. 14 shows the circuit for a series diode detector with corresponding Ia–Vg curves. Since the diode will conduct only when a positive voltage is applied to the anode, the current flows in accordance with the value of the positive half cycles. The anode current flow causes a voltage drop across the resistance which can then be passed to an amplifier stage. The condenser passes the unwanted radio frequency component to earth. As in the previous methods of detection described, a local oscillator will be required to produce an audio component.

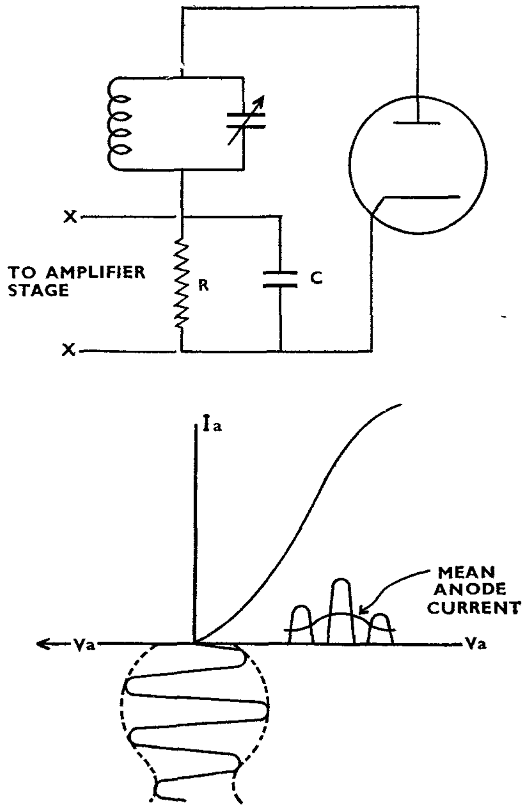


Fig. 14. Series Diode Detector

CHAPTER 9

SUPERHETERODYNE RECEIVERS

General

1. Fig. 1 is a block schematic diagram of a typical superheterodyne receiver. In the first stage the required signal is selected. Only a little amplification is possible, however, in the first stage, as it is difficult to achieve much stage gain in a high-frequency circuit and maintain good stability.

2. The output of the R.F. amplifier is then fed to the mixer stage. In this stage the R.F. signal is mixed with a locally produced signal and all incoming frequencies are reduced to a common frequency known as the "intermediate frequency". At this frequency it is much easier to produce a large stage gain under stable conditions.

3. With the exception of the preset tuned circuits, the intermediate frequency amplifiers are very similar to the R.F. amplifier. Two stages of I.F. amplification are normal but three stages are used occasionally ; the greater part of signal amplification is effected in these stages.

4. In the next stage the audio component of the R.F. signal is extracted and passed on to the audio frequency amplifying stage, and the signal is amplified further. Also, at this stage, a portion of the signal may be used to provide a varying bias in accordance with the incoming signal strength. This bias is applied to the previous stages and a constant signal strength is maintained, as the stronger the incoming signal the stronger the bias applied. This is called automatic volume control (A.V.C.) or automatic gain control (A.G.C.).

5. The signal is then passed to the output stage, which converts the signal from high voltage/low current into low voltage/high current for the purpose of operating a loudspeaker or telephones. For maximum efficiency, the output stage should be matched to the impedance of the loudspeaker or telephones.

6. The remaining stage is known as the Beat Frequency Oscillator, a stage necessary for the reception of C.W. signals. This stage provides a locally produced oscillation differing from the intermediate frequency by roughly 1 to 2 kc/s which, when mixed with the intermediate frequency, produces an audible note when detected. It is normal for the B.F.O. to oscillate at a frequency about half that of the intermediate frequency plus the audio difference. To obtain this the second harmonic of the intermediate frequency is used. For example, if the intermediate frequency is 460 kc/s and the audio note required is 2 kc/s, the B.F.O. signal required will be 462 kc/s. For a second harmonic of 462 kc/s, the B.F.O. frequency will be 231 kc/s. The second harmonic is chosen in the interests of frequency stability for, if the B.F.O. oscillated at 462 kc/s and a strong signal were received, the signal, when converted to the I.F. of 460 kc/s, would tend to control the B.F.O. at 460 kc/s instead of 462 kc/s. There would thus be no difference in frequency and therefore no audible note.

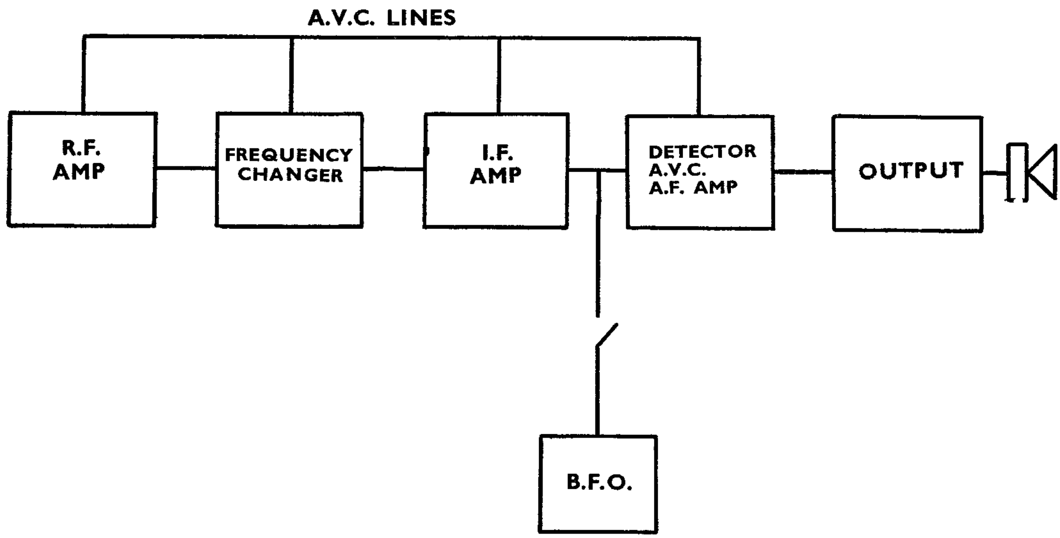


Fig. 1. Block Schematic Diagram of Superheterodyne Receiver

7. The incoming signal is developed across the tuned circuit L_1–C_1 (Fig. 2) which is tuned to the frequency of the required signal. The selected signal is applied between the grid and cathode of the valve and amplified. The load for the valve is provided by the inductance L_3, which is mutually coupled to the tuned circuit L_2–C_5, the grid circuit of the mixer stage. The resistance R_2 together with the capacity C_2 provides decoupling for the anode circuit, necessary to prevent the superimposing of R.F. on the H.T. supply to the screen ; this also acts as a decoupler in conjunction with C_3. Grid bias is provided by the resistance R_3 and a voltage difference exists between the cathode end and the grid because of the potential drop across the resistor, the grid being connected to the negative end. The condenser C_4 decouples the cathode bias resistor, preventing the steady bias produced by the anode current from being affected by the R.F. component in the anode current.

8. In Fig. 3 the mixer stage converts the incoming signal to the intermediate frequency. The incoming signal is developed across the circuit C_1–L_1 which is mutually coupled to the R.F. amplifier. The signal selected is applied between grid and cathode and amplified by the valve. The circuit formed by C_2–L_2 is a parallel-fed grid-tuned Meissner oscillator, which oscillates at a frequency higher than that of L_1–C_1 by the amount of the intermediate frequency ; its output is injected into the main anode electron stream by the injector grid which is connected to the grid of the triode portion of the valve. This signal also appears in the anode circuit, where the mixing of it with the oscillation produced by the circuit C_2–L_2 produces a third frequency which is the difference between the two. This third frequency is called the intermediate frequency. In the anode circuit, the third frequency is developed and the unwanted signals are bypassed to earth via the decoupling provided by R_2–C_7. R_1–C_8 provides voltage dropping for the screens. C_9 and R_6 provide automatic bias for the triode portion of the valve, and R_4 drops the H.T. voltage as the triode does not require the full H.T. voltage. R_5 and C_6 provide normal cathode bias for the hexode portion.

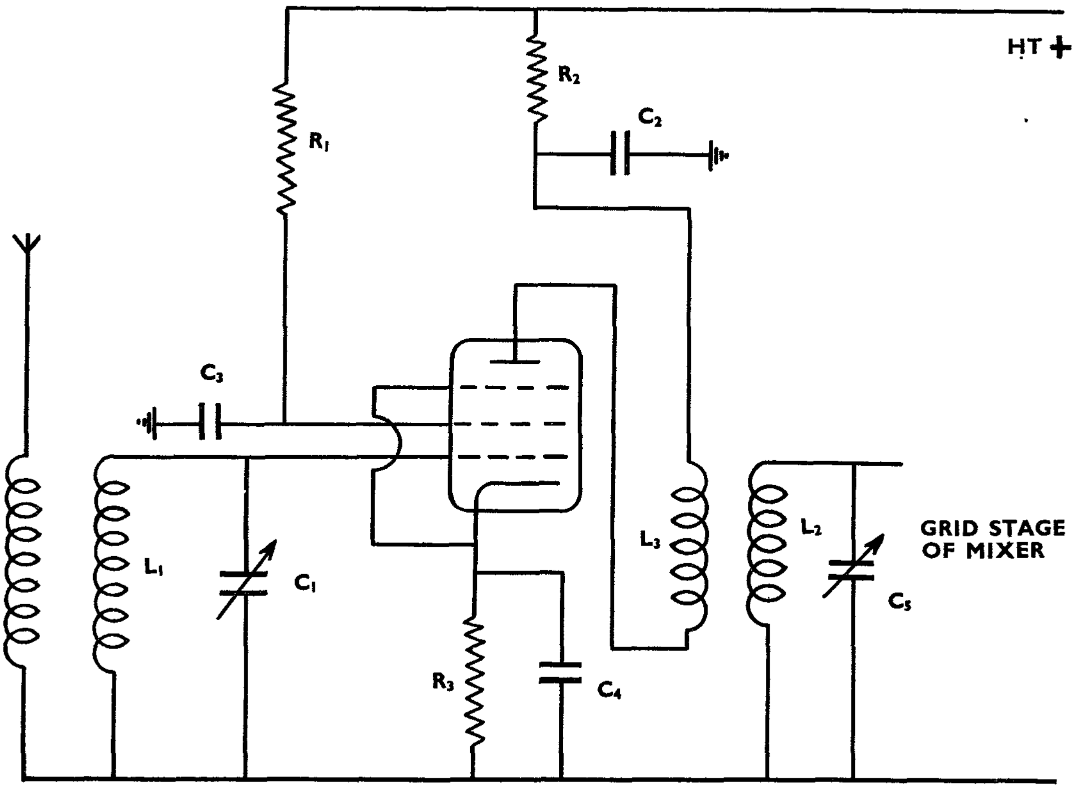


Fig. 2. Radio Frequency Amplifier

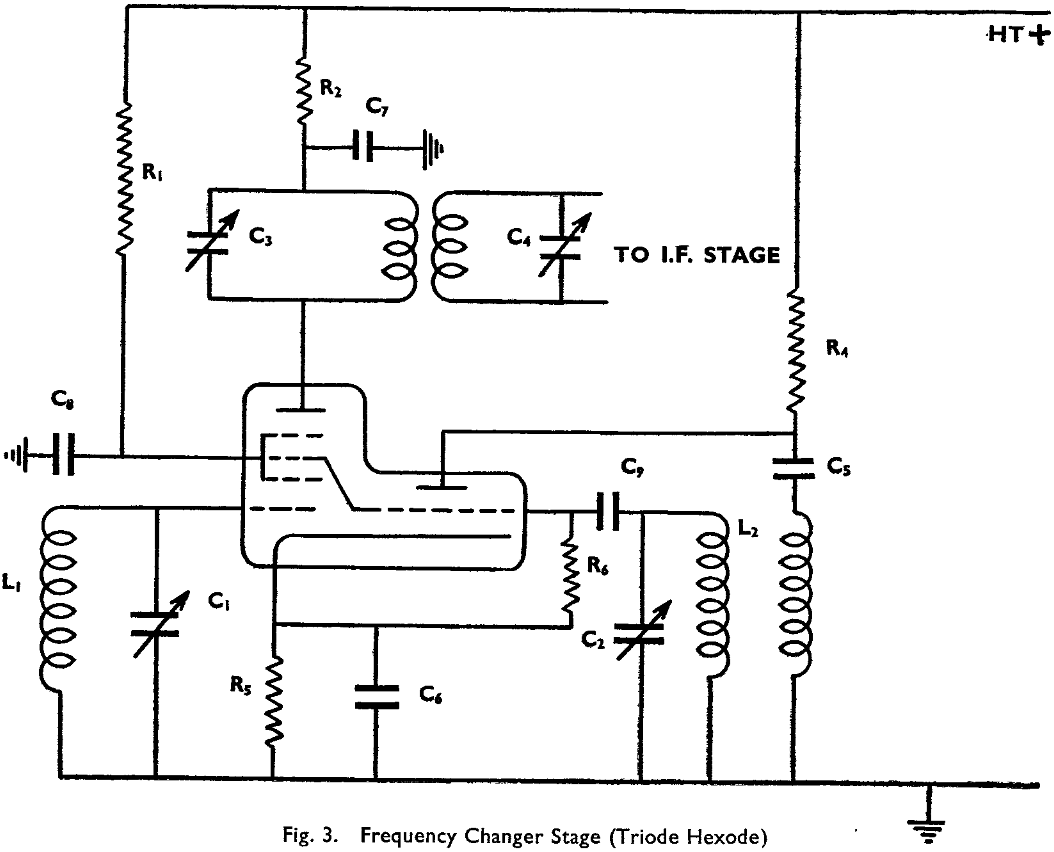


Fig. 3. Frequency Changer Stage (Triode Hexode)

I.F. Amplifier Stage

9. The I.F. amplifier stage is used for further amplification of the signal. Intermediate frequencies normally used are between 400 and 600 kc/s. In V.H.F. receivers the intermediate frequencies are usually between 9 and 10 mc/s.

10. In the I.F. stage the signal from the previous stage is applied between the grid and cathode. The valve, working in Class "A" conditions, amplifies. In the anode circuit, a tuned circuit resonant at the intermediate frequency helps to isolate further the required signal, and to increase further the ratio between the wanted and unwanted signals. A second tuned circuit, coupled inductively to the anode circuit, still further aids frequency isolation and passes the selected signal to the next stage ; this may be either another I.F. amplification stage or the detector stage. In most communications receivers, two I.F. stages are used and stage gain is of a very high order. Only in receivers working on ultra high frequencies is it usual to use more than two stages of I.F. amplification, as at these high frequencies the stage gain is not very great.

11. The circuit coupled to the control grid in Fig. 4 is the secondary circuit shown in Fig. 3. The resistance R_1 provides reduced H.T. for the screen of the valve, and the condenser C_1, in conjunction with R_1, decouples the circuit, effectively preventing R.F. from returning to the H.T. supply. R_3 and C_5 provide the normal cathode bias.

12. The tuned circuits L_1–C_3 and L_2–C_4 are together known as the intermediate frequency transformers. They are situated in the anode circuits of the mixer and I.F. stages and are fully screened. Screening is normally achieved by placing the components in cans, which eliminates pick-up of other signals and prevents re-radiation of the wanted signal.

Detector Stage

13. There are many variations of the detector stage and the version shown in Fig. 5, using a double-diode triode for detection of the I.F. and amplification of the rectified audio signal, is frequently encountered. A negative bias is also derived from this circuit for controlling the amplification of the previous stages. This is known as A.V.C.

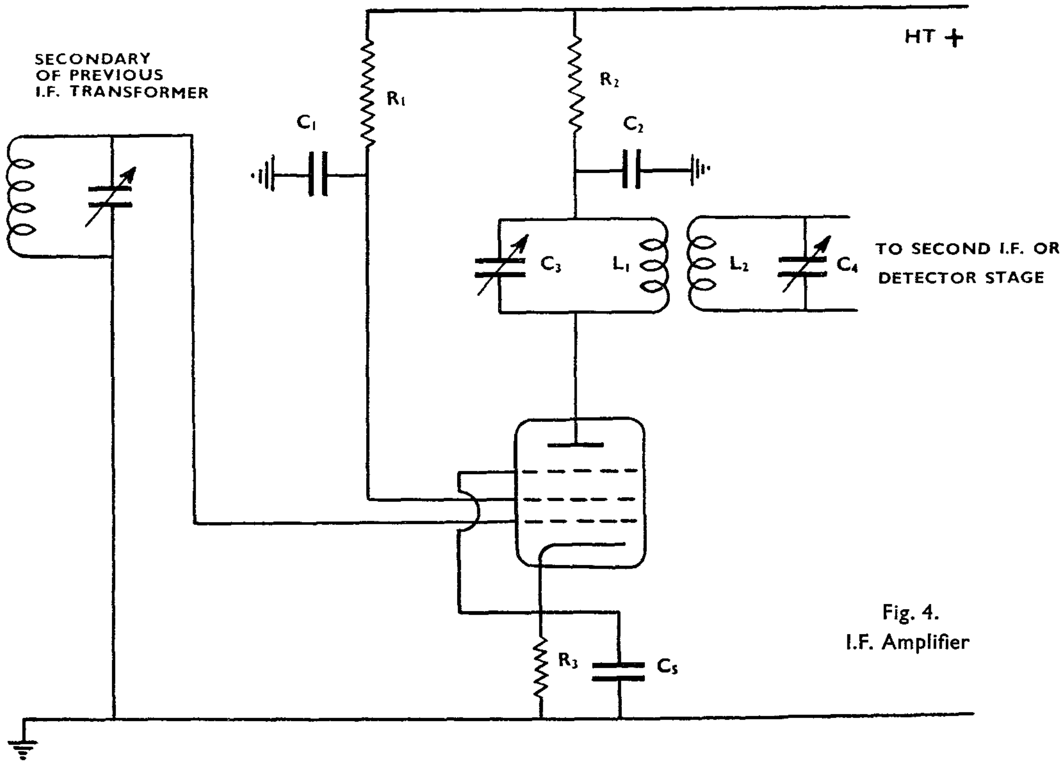


Fig. 4.
I.F. Amplifier

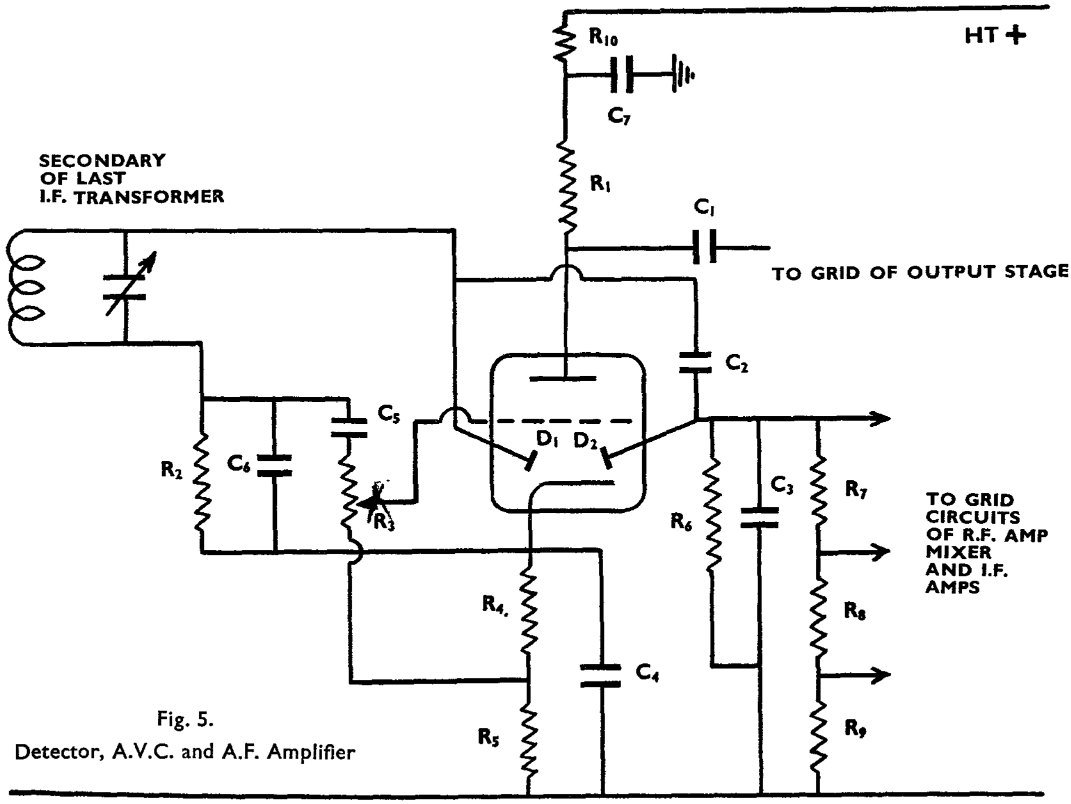


Fig. 5.
Detector, A.V.C. and A.F. Amplifier

14. The signal from the last I.F. transformer is applied to the detector diode (D_1); the resistance R_2 and the condenser C_6 are in series with the transformer secondary, and the detector operates in the normal manner. The audio component is developed across R_2 as a voltage, and the condenser C_6 bypasses R.F. to earth via C_4, which also acts as the cathode bypass condenser. The lower end of R_2 is returned to the top end of R_4 (cathode proper) as no voltage difference is required between anode and cathode, except that of the incoming signal.

15. Signals developed across R_2 are applied to the grid of the triode portion (A.F. amplifier) via the condenser C_5 and the resistor R_3. The lower end of R_3 is connected to the junction of R_4 and R_5; thus, between the grid and cathode of the triode portion there is a potential difference equal to the voltage drop across R_4. The condenser C_5 prevents this bias from being applied to the anode of the detector diode (D_1), and its value, about 0·1 mfd. or greater, offers little impedance to A.F. Volume control is achieved by the moving tap on R_3: when the tap is at the top, maximum signal is applied to the grid; when the tap is at the bottom, minimum signal is applied. In the anode circuit of the triode circuit there are two resistances and two condensers; R_1 is the anode load for the valve and its optimum value is usually 2·5 times Ra. C_1 is the coupling condenser to the grid of the next stage. The condenser C_7 and R_{10} provide decoupling for the anode H.T. supply.

A.V.C.

16. The diode D_2 is used to supply A.V.C. The anode is fed with the incoming signal direct from the I.F. transformer, via condenser C_2. This prevents the bias on D_2 being applied to D_1. Diode D_2 works in a similar manner to D_1—varying voltages across R_6 are applied to the grids of the previous stages. The lower end of R_6 is connected to the earth line and there is thus a potential difference between the anode and cathode of D_2 equal to the voltage drops across R_4 and R_5. This is known as the "delay voltage" and D_2 will not conduct until the incoming signal strength exceeds the delay bias. Weak signals are amplified considerably, and not until the incoming signal reaches the delay bias will the signal strength be checked. When the incoming signal strength exceeds the delay voltage, the excess is applied to the grids of the previous valves and as a result their amplification will be lowered: the stronger the incoming signal the stronger the bias applied and an output signal strength of constant power is maintained.

17. An important factor to consider with regard to A.V.C. is that the voltages developed across R_6 will vary according to the strength of the incoming signal and also according to the amount of modulation; both produce varying voltages across the resistance network. As only the varying voltage produced by the incoming signal is required, the modulation voltages across R_6 require to be filtered out. When considering what frequencies should be filtered out, the deciding factors are the lowest note required to be heard and the highest variation of signal strength required for the operation of the variable amplification valves. The lowest note the human ear can normally detect is about 30 c.p.s. Variations in signal strength rarely exceed more than 3 or 4 c.p.s., and the dividing frequency is somewhere between the two. A frequency of 10 c.p.s. is commonly used in broadcast receivers.

18. Fig. 6 shows an A.V.C. divider network with associated valve circuits. In each A.V.C. line there is a resistance and a condenser: C_1 and R_1, C_2 and R_2, and C_3 and R_3. The time constants of these combinations are so arranged, by careful choice of components, that variations in voltage arising from varying signal strength are passed to the grid of the valve and vary its amplification. This occurs with changes of 10 c.p.s. or less. Variations above 10 c.p.s., caused in the normal way by modulation of the signal, are passed to earth via the condenser and do not affect the amplification of the valves.

19. The figure 10 c.p.s. was selected as an example; any figure between 3 and 30 c.p.s. may be used.

20. To obtain the time constant of the circuit shown, it is necessary to multiply the value of C by that of R. In the example chosen, C is 0·1 mfd. in value and R is 1 megohm. These values multiplied together produce a constant of 20.

21. The divider network shown in Fig. 5 (R_7, R_8, and R_9) is used, as the same value of A.V.C. is not required at all stages. Normally, half is applied to the R.F. stage, full to the mixer stage and to the first I.F. stage, and a small proportion to the I.F. stage preceding the detector stage. The reason for applying full A.V.C. to the mixer and first I.F. stages is to keep the gain as low as possible, thereby reducing the effect of noises in the mixing valve. The R.F. amplifier is kept at a fairly high value of A.V.C. to maintain stability. The remaining valves are allowed to amplify as much as possible since the A.V.C. applied is seldom above $^1/_{10}$.

22. The A.F. amplifier is the final stage concerned with the amplification of the signal. Voltages are developed across the load of the first A.F. amplifier and are applied to the grid of the output valve via C_1, a condenser provided to prevent HT + being applied to the grid resistance R_1. The resistance R_1 places the grid at earth potential and ensures that the valve is biased by the voltage drop across the resistor R_2. The

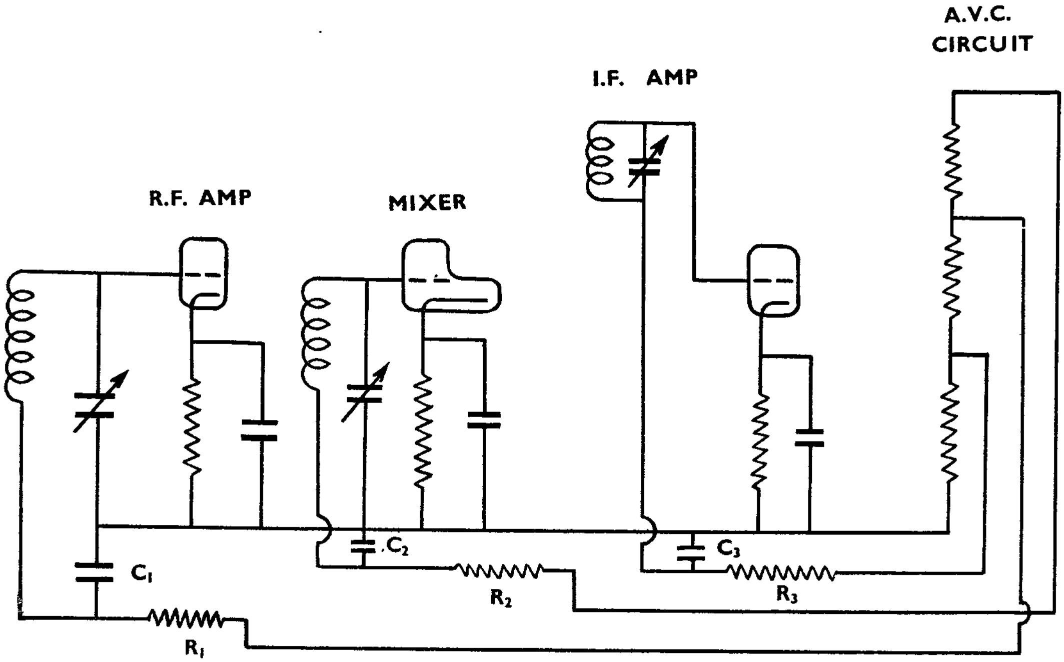


Fig. 6. Distribution of A.V.C. and A.V.C. Filters

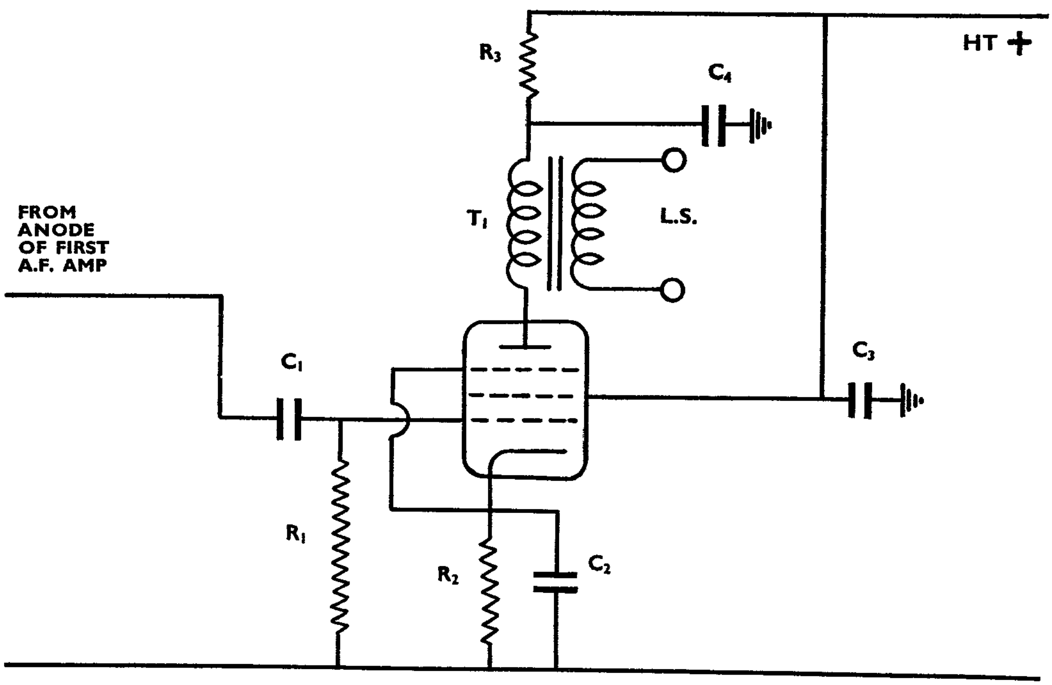


Fig. 7. Output Stage

resistor R_3 and condenser C_4 provide decoupling of the anode circuit. The H.T. supply to the screen is taken directly from the H.T. line and no dropping resistance is used; the circuit is decoupled by the condenser C_3. This follows the modern practice in output valves of having the screen at a higher potential than the anode. The transformer T_1 is of step-down ratio, the primary circuit being wound to match the impedance of the valve and the secondary to match the impedance of the speaker or earphones. The signal passed to the speaker, therefore, is of a low voltage characteristic with high current. The matching of this transformer is critical; a mismatched transformer would result in distortion and loss of power.

Beat Frequency Oscillator

23. This is the final component of the receiver and is required only when it is desired to receive C.W. signals. At the detection stage a C.W. signal possesses no audio component; a further oscillation is required, mixed with the incoming signal, before detection may take place. The local oscillator may be any one of the common types in use. The oscillator shown in Fig. 8 is a series-fed Hartley. It is controlled by an ON/OFF switch in the H.T. circuit, and R_1 is used to drop the H.T. supply to ensure that the valve operates under stable conditions. The oscillation is passed via C_2 to the secondary of the last I.F. transformer, where it mixes with the incoming signal. The resistance R_3 and the condenser C_3 provide automatic grid bias; C_1 is an H.T. blocking condenser; the tuned circuit is formed by L_1 and C_4; C_5 is a small preset condenser for adjustment of the note to be received in the speaker.

24. It is normal for the type of circuit shown in Fig. 8 to work on a frequency half that required for mixing with the incoming signal. The second harmonic of the local signal is used, and this prevents a strong signal in the I.F. stage from pulling the oscillator in step with it. If it is impracticable to use the harmonic in this manner and the fundamental oscillation is used, some precaution must be taken such as a "buffer" stage between the oscillator and the I.F. stage.

25. Fig. 9 shows a complete superheterodyne receiver constructed by joining all the previous circuits together. Although without many of the refinements incorporated in modern receivers, this receiver, if carefully constructed, would be capable of high quality reception.

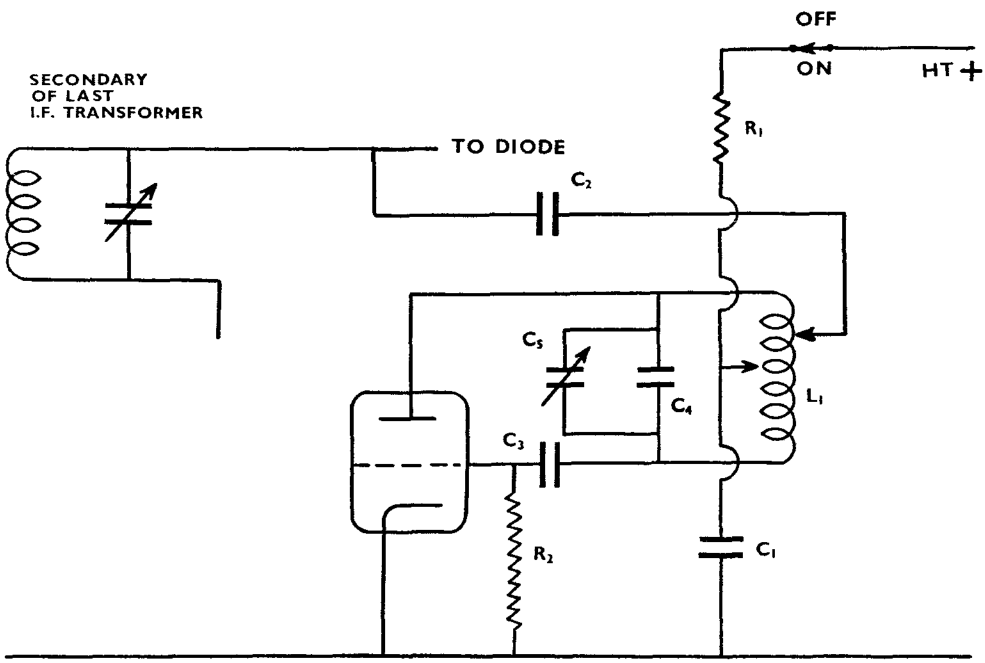


Fig. 8. Beat Frequency Oscillator

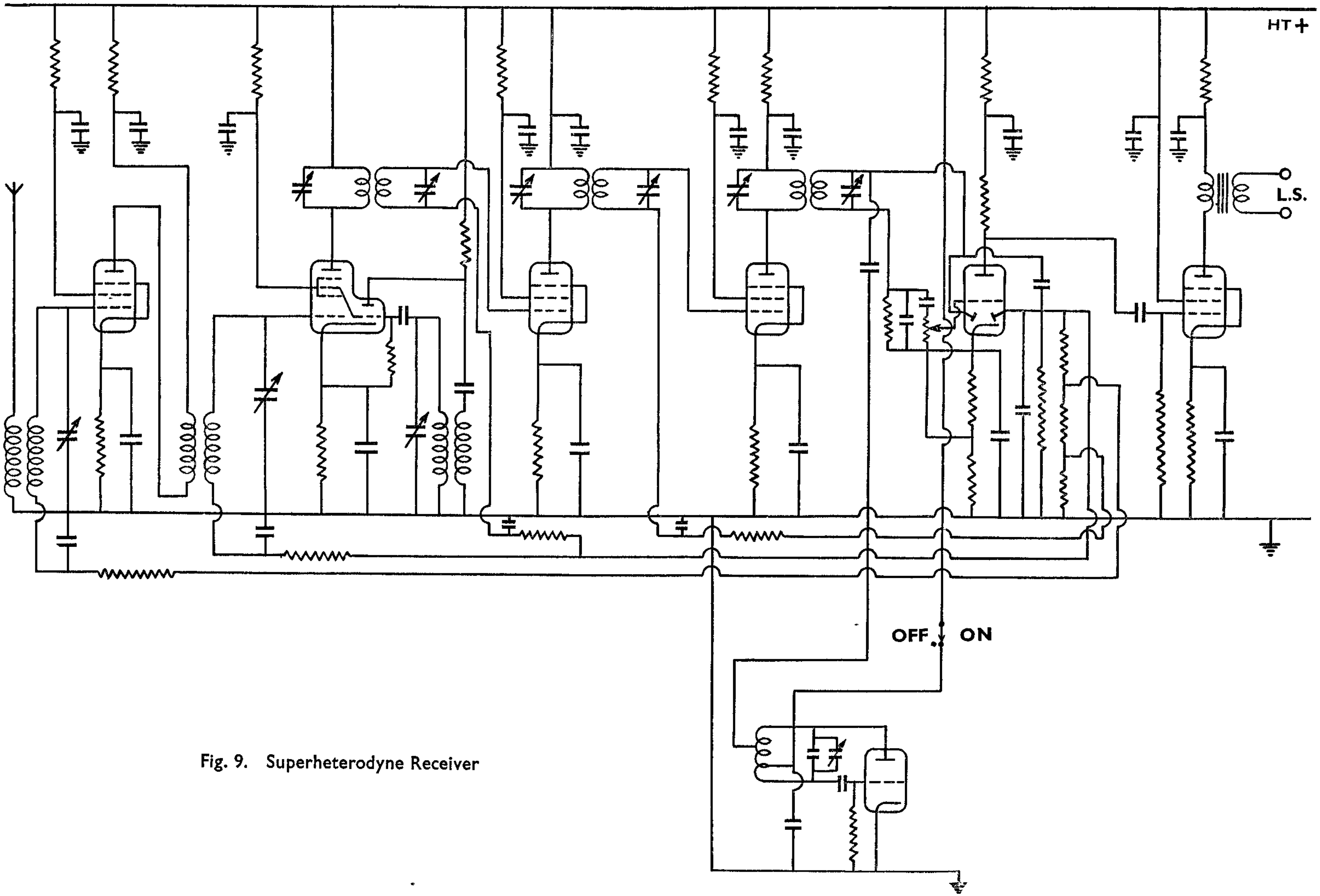


Fig. 9. Superheterodyne Receiver

TRANSMITTERS

General

1. Rapid strides have been made in the development of transmitters over the past decade, particularly in the production of miniature components. Fig. 1 is a circuit diagram of a very simple form of transmitter, incorporating a series-fed Hartley oscillator modified to transmit C.W. signals. Keying is effected by making and breaking the H.T. negative line, and the keyed C.W. signals are radiated through an aerial coupled to the oscillatory circuit.

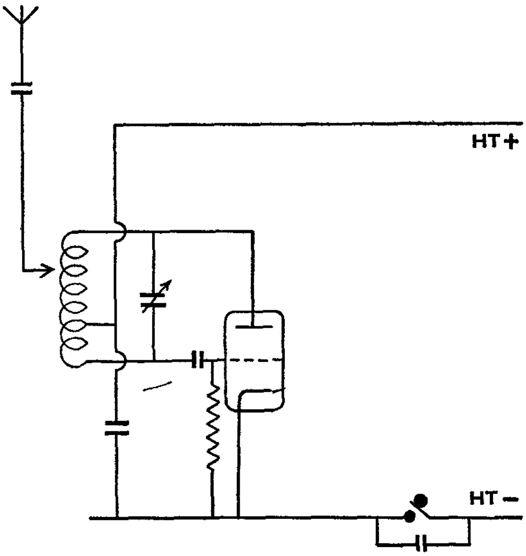


Fig. 1. Simple Transmitter Incorporating Series-Fed Hartley Oscillator

2. The simple transmitter, however, suffers from poor frequency stability, low output, and poor quality of the transmitted signal.

3. To overcome the disadvantage of low power output, modern transmitters incorporate one or more stages of *power amplification*. Further refinements help to stabilize the frequency. These refinements have resulted in the development of the Master Oscillator/Power Amplifier (M.O./P.A.) type of transmitter.

Master Oscillator/Power Amplifier Transmitter

4. In the M.O./P.A. type of transmitter the oscillator is operated at low power and its output is considerably amplified in the P.A. stages. The P.A. stages may also be used for frequency multiplication if the final frequency required cannot be produced by the M.O.; this applies particularly in V.H.F. transmitters, whose fundamental frequencies are usually controlled by crystals. It is physically impossible to cut a crystal small enough to vibrate at frequencies in the 100 mc/s range, and crystals are made to vibrate or oscillate at a much lower frequency. The final frequency is then produced by a series of frequency multiplying circuits.

5. In Fig. 2, the oscillator circuit has been completely screened to prevent external interference. A resistance, R_1, is used to limit the H.T. supply to the valve and ensures low power operation. Precautions may also be taken in the layout and design of a transmitter to further reduce frequency instability and external interference.

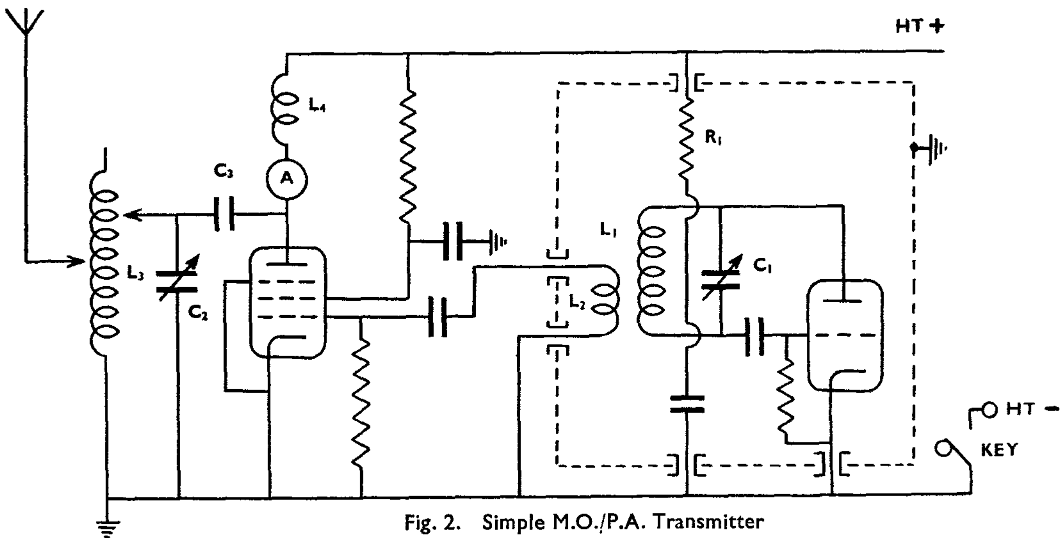


Fig. 2. Simple M.O./P.A. Transmitter

6. The oscillations produced by the master oscillator are passed through the inductive coupling L_2 to the P.A. stage, where they are amplified by the P.A. valve and developed across the anode load L_3 and C_2. From here the power is tapped off to the aerial. The condenser C_3 is an H.T. blocking condenser, and the ammeter shown in the circuit gives an indication of P.A. tuning as power will reach the aerial circuit only when the P.A. is correctly tuned to the master oscillator. In Fig. 2, automatic grid bias, produced by a condenser and grid leak in each case, is used for both valves. The screen voltage for the P.A. is produced by the voltage drop across the resistance and is decoupled by the condenser. The Radio Frequency Choke, C_4, in the P.A. anode circuit acts as a barrier to radio frequencies, preventing them from reaching the H.T. supply and thereby causing instability.

Neutralizing

7. Most of the refinements incorporated in a transmitter are found in the P.A. stages. In Fig. 2 a pentode valve is used to eliminate the need for "neutralization", which is the effect that large inter-electrode capacities have on triode valves. These capacities cause the valve to self-oscillate through energy being fed back from the anode circuit. This feed-back lags in phase with the primary oscillation and neutralization is achieved by feeding energy back to the grid in opposite phase. Using a beam tetrode or pentode, however, this trouble is avoided, as the inter-electrode capacity is too small for energy to be fed back to the grid circuit.

Control of the Power Amplifier

8. Tuning the P.A. to the master oscillator at full power causes overloading and may damage the P.A. valve. Further, much interference to other receivers would result as the transmitter would be operating at full power. One method of limiting power to the P.A. stages is to bias the P.A. suppressor grid ; a negative bias of 30 volts may reduce the transmitter output by as much as 50 per cent. Conversely, a positive voltage applied to the suppressor grid will increase output ; care, however, must be taken to ensure that the safe maximum anode current for the valve is not exceeded.

9. The P.A. valve in Fig. 3 is the same as that in Fig. 2 ; the anode load and aerial circuit being omitted for clarity. The switch in the suppressor grid circuit has three positions : "¼", "½", and "Full". In the "¼" position the circuit from the suppressor grid to the H.T. negative lead passes through a resistor ; this makes the suppressor grid negative in relation to the cathode and, depending on the extent of the voltage drop across the resistor R_1, the power is reduced. In the "½" position, the suppressor grid is connected direct to earth giving more power than in the "¼" position. In the "Full" position, the suppressor grid is connected to the positive end of a potential divider network between H.T. positive and earth, and the resistors R_2, and R_3 provide the necessary positive bias for full transmission. In practice, for example, the first position would probably be used for tuning purposes and for low power transmission over short ranges. The other two positions would be used when greater power was needed.

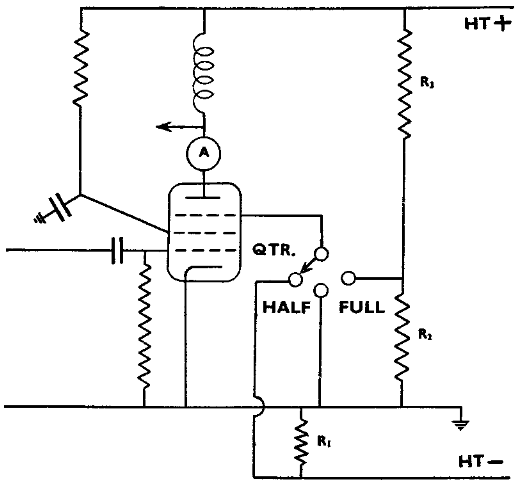


Fig. 3. Control of P.A. by Suppressor Grid Voltage

Transmitter Keying

10. In early transmitter development the normal method of keying a transmitter was to make and break the H.T. negative lead. This method was replaced by "electronic" keying, which is now the usual method of keying transmitters. In electronic keying a large negative voltage is applied to the control grid of the P.A. valve, preventing it from operating (see Fig. 4). The resistance R_1 causes

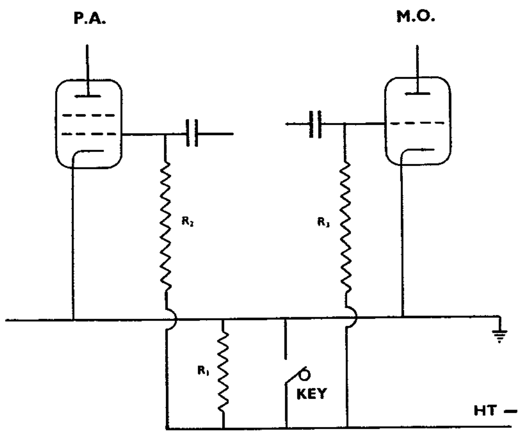


Fig. 4. Method of Keying

a large voltage drop between H.T. negative and earth, and the lower ends of the grid leak condensers R_2 and R_3 are taken to the negative end of R_1. A large negative bias is thus placed on the grids of the master oscillator and power amplifier valves causing them to stop operating. As soon as the key is pressed the resistor R_1 is shorted out and the bias is removed, the grid leaks returning to earth. The M.O. and P.A. valves then operate normally. This method of keying is very satisfactory and can be used for high morse speeds.

Modulation

11. Modulation is necessary for the transmission of M.C.W. and for R/T. There are three types of modulation : the anode choke, the control grid, and the suppressor grid.

12. **Anode Choke Modulation.** This is shown in Fig. 5, where the triode valve acts as the A.F. modulator and the L.F. choke as the anode load. Voltages are developed across the choke, in series with the H.T. supply, and are fed to the power amplifier ; thus the H.T. to the P.A. will vary according to the A.F. output. This is known as amplitude modulation. The main disadvantage of this method of modulation is that the power required for 100 per cent. modulation is roughly 50 per cent. of the P.A. output.

13. **Control Grid Modulation,** Control grid modulation requires less power but this method is generally unacceptable as distortion is very bad when the depth of modulation exceeds 30 per cent.

14. **Suppressor Grid Modulation.** Suppressor grid modulation is the most satisfactory method of modulation. Fig. 5 shows that it is possible to control the amplitude of the P.A. power by applying voltages to the suppressor grids. With this form of modulation the optimum working point is found by applying negative bias to the grid, usually at the point where the anode current is half the total value. This is the normal safe maximum current. Little audio frequency power is absorbed and a good depth of modulation may be achieved without distortion.

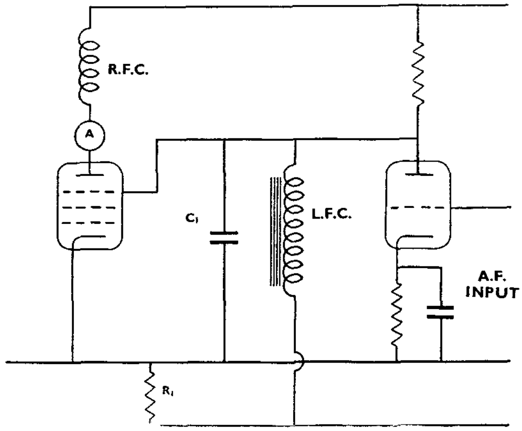


Fig. 6. Typical Transmitter Circuit Using Suppressor Grid Modulation

Frequency Doublers and Treblers

15. Fig. 6 shows a typical transmitter circuit, the anode acting as the A.F. amplifier and the L.F.C. acting as the load. The resistor R_1 provides the negative bias at the correct working point. Voltages developed across the L.F.C. are in series with the negative bias and cause corresponding changes of potential on the suppressor grid. This in turn causes the amplitude of the carrier wave to vary in sympathy with the voltages developed across the L.F.C. The condenser C_1 is small in value and its purpose is to keep the suppressor grid at earth potential so far as R.F. is concerned.

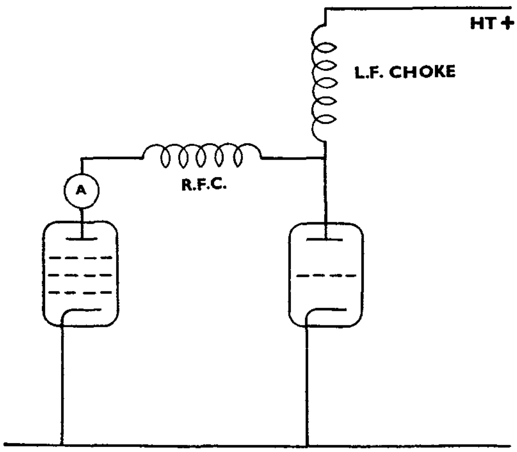


Fig. 5. Anode Choke Modulation

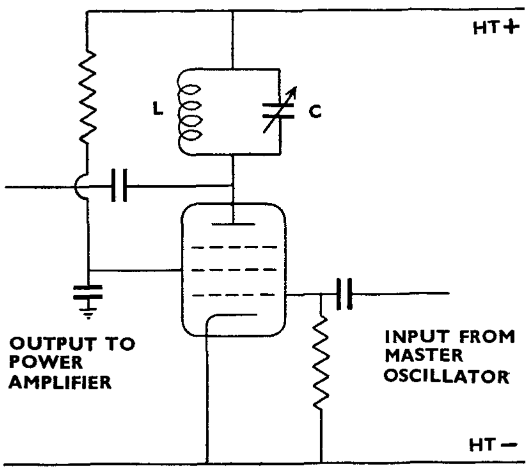


Fig. 7. Intermediate Frequency Power Amplifier

16. For V.H.F. transmitters, the output frequency is much higher than the master oscillator frequency, and the final frequency required is obtained by a series of intermediate amplification, or doubler/trebler, stages. Fig. 7 shows a typical circuit for an intermediate frequency power amplifier ; the output from the master oscillator is fed to the grid, the valve amplifying the applied oscillations. If the circuit, L and C, is tuned to the same frequency as the M.O., the voltages will be developed across this circuit to a maximum. These voltages are then applied to the grid of the P.A. stage.

17. This type of circuit may be used when one P.A. stage is insufficient to produce the power output required. When frequency multiplication is required, the circuit L C is tuned to the second or third harmonic of the master oscillator frequency, and the frequency of the oscillations developed across the circuit will be two or three times that of the M.O. The gain in power will be less, of course, as the harmonics are weaker then the fundamental frequency. Two or more doublers or treblers may be coupled together, multiplying the original frequency many times. Using this method it is possible to produce an output frequency of as high as 150 mc/s from an original oscillation of 5 to 10 mc/s. This makes it possible to use crystals with their rigid stable frequency characteristics. The grid bias point for frequency multiplication circuits is usually the lower anode bend or even beyond cut-off point ; this produces a wave form rich in harmonics.

CHAPTER 11

TELEPHONES AND MICROPHONES

Introduction

1. Telephones and microphones are devices for converting electrical impulses into sound and vice versa. They are used with land lines or wireless to receive and transmit spoken messages over great distances.

Telephone Receiver

2. The telephone receiver is the device which converts electrical current variations into sound waves. It normally consists of a permanent magnet with two soft iron pole pieces, each carrying a magnetizing winding or bobbin. The two windings are connected in series, so that current passing through them in one direction weakens both poles, while current passing through in the other direction strengthens both poles. Both pole pieces exert a pull on the centre of a thin metal diaphragm which is so mounted that it almost touches them.

3. **Example.** Suppose a telephone receiver is to be used to listen to signals from a wireless receiver. In the absence of any signal, either a steady current or no current (depending on the method of connection in circuit) will flow round the coils of the receiver, and the pole pieces will exert a steady pull on the diaphragm. When a signal is received, current varying at A.F. will flow through the coils causing corresponding changes in the magnetic flux so that the diaphragm will start vibrating in a manner corresponding to the changes of current. These vibrations of the diaphragm cause sound waves to be radiated in the vicinity of the diaphragm and the signal becomes audible.

Microphone

4. The microphone converts sound waves into electrical impulses. These impulses either travel along telephone lines to a distant telephone receiver or are amplified and used to modulate the comparatively high-frequency carrier wave of an R/T or broadcast transmitter. The microphone commonly used in the Service is the electro-magnetic type.

5. **Electro-Magnetic Microphone.** The electro-magnetic microphone is an inversion of the principle of the telephone receiver. In the telephone receiver, magnetic flux changes, caused by current flowing through the coil windings, set up vibrations in the diaphragm. In the electro-magnetic microphone, sound waves cause vibration of the diaphragm and the resultant changes of magnetic flux induce E.M.Fs. in the coil windings. These E.M.Fs. are very small and are usually amplified by means of a step-up transformer and two or three valve amplifiers.

CHAPTER 12

AERIALS AND FEEDER SYSTEMS

Introduction

1. If two conductors are placed one above the other and are electrically energized, an electric field will extend around them in the manner shown in Fig. 1.

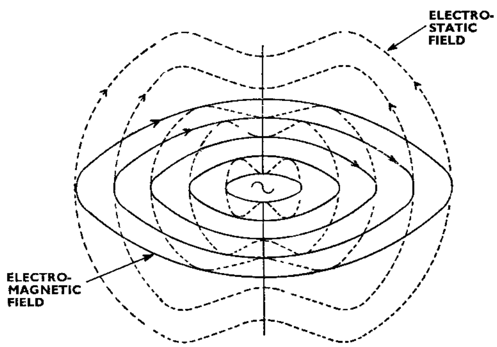


Fig. 1. Electro-Magnetic and Electrostatic Fields about a Conductor

2. If an alternating voltage is applied between the conductors, the electric field will be at its maximum when the conductors are fully charged. As the applied voltage changes in polarity, forces opposing the change cause a current to flow, and an electro-magnetic field is set up which reaches its maximum when the current flow is at its highest. The heavy lines in Fig. 1 show the magnetic lines of force. Both the electrostatic and magnetic fields reverse in direction and reach maximum intensity in each direction at each full cycle of the applied voltage.

3. When the charge between the conductors is at its highest the electric field is at its maximum intensity. When the charge changes its value the field strength in the immediate vicinity of the conductors changes, and the change is communicated from point to point outwards into space. The electro-magnetic field undergoes a similar change when the current flow varies.

4. This effect is analogous to that of a stone dropped into water, which causes ripples to expand in concentric circles from the point of impact; the amplitudes of the ripples diminish as the distance from the point of impact increases, until they fade away completely. It should be noted that the movement of the water is in an up-and-down direction only; a cork floating in the path of the ripples only bobs up and down and does not change its position.

5. Similarly, the electrostatic and electro-magnetic fields become weaker as the distance from the source of transmission increases. In passing through solids or liquids, energy is lost in the production of eddy currents and hysteresis.

6. Electro-magnetic waves travel at the speed of light, some 3×10^8 metres per second (or about 186,000 miles per second). The distance that an electro-magnetic wave travels depends to a great extent on frequency, power at source, physical construction of the transmitting system, and the type of terrain over which the wave travels.

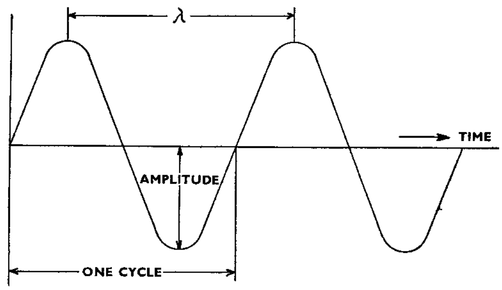


Fig. 2. Illustrating Relationship between Wavelength and Frequency

7. Fig. 2 shows the relationship between wavelength and frequency. The number of complete cycles per second gives the frequency, and the distance between corresponding points in each separate cycle gives the wavelength. A definite relationship therefore exists between the two terms. This relationship may be expressed as follows:

Speed of E.M. waves is 3×10^8 metres per second;

$$\text{Frequency (F)} = \frac{\text{Speed}}{\text{Wavelength}}; \text{ and Wavelength } (\lambda) = \frac{\text{Speed}}{\text{Frequency}}.$$

$$\text{Therefore } 3 \times 10^8 = \text{Frequency} \times \text{Wavelength}$$

$$\text{Frequency (F)} = \frac{3 \times 10^8 \text{ (V)}}{\text{Wavelength } (\lambda)}$$

$$\text{Wavelength } (\lambda) = \frac{3 \times 10^8 \text{ (V)}}{\text{Frequency (F)}}$$

(Frequency is calculated in cycles per second (c.p.s.) and wavelength is calculated in metres per second.)

Characteristics of Radio Waves

8. Fig. 3 shows the manner in which radio waves radiate from a transmitting source. Waves travelling towards the earth at a shallow angle are, in the main, reflected upwards.

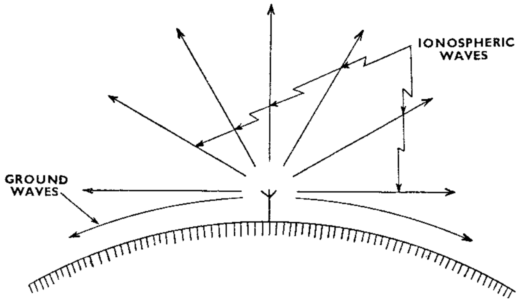


Fig. 3. Radio Waves Leaving Transmitter

9. Waves radiated horizontally from an aerial travel along the surface of the earth and are known as ground waves. Waves travelling skywards are known as ionospheric waves as they depend on the ionosphere for reflection back to earth.

Ground Waves

10. The strength of radio waves diminishes as the distance from the transmitter increases, the amount of dissipation depending on the frequency of the waves as well as on the factors referred to in para. 6. Ground waves, noted for their constancy and freedom from fading, are used when communication on low frequencies over moderate distances is required.

Ionospheric Waves

11. Ionospheric waves are those which are refracted back to earth by various layers of ionized gases in the upper atmosphere. These gases depend on radiation from the sun, and their refracting and absorbing properties vary diurnally, seasonally, and with latitude.

12. **Heavyside and Appleton Layers.** These layers were first discovered by Sir Oliver Heavyside. Subsequently Dr. E. Appleton proved that the layers were of various densities and at differing heights. In the main, these layers lie between 50 and 250 miles above the earth's surface. As air pressure at this level is lower than on the ground, the molecules of gas are less restricted in their movement and are able, under the influence of the sun, to leave their parent atoms, forming an electrified layer which refracts radio waves back to earth.

Wave Refraction

13. The bending of a radio wave in an ionized layer is gradual and not a sharp refraction. When the wave front reaches the layer, the top of the front speeds up and a gradual bending results which returns the wave to earth. The process is repeated until the wave fades completely (see Figs. 4 and 5).

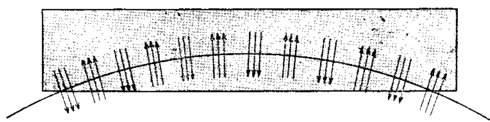


Fig. 5. Refraction

14. It is evident that a wave arriving at a small angle will easily be refracted to earth. The returned wave will, of course, strike the earth some distance from the transmitter; some refracted waves will miss the earth entirely, and it is clear that the selection of an optimum working frequency is largely determined by the prevailing ionospheric conditions.

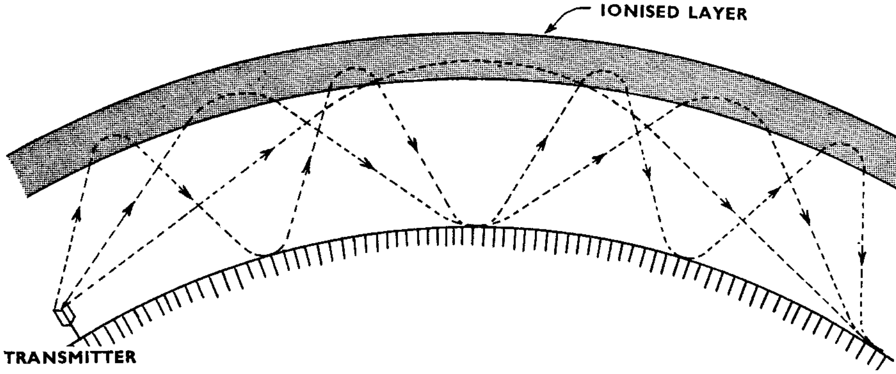


Fig. 4. Action of Ionized Layer

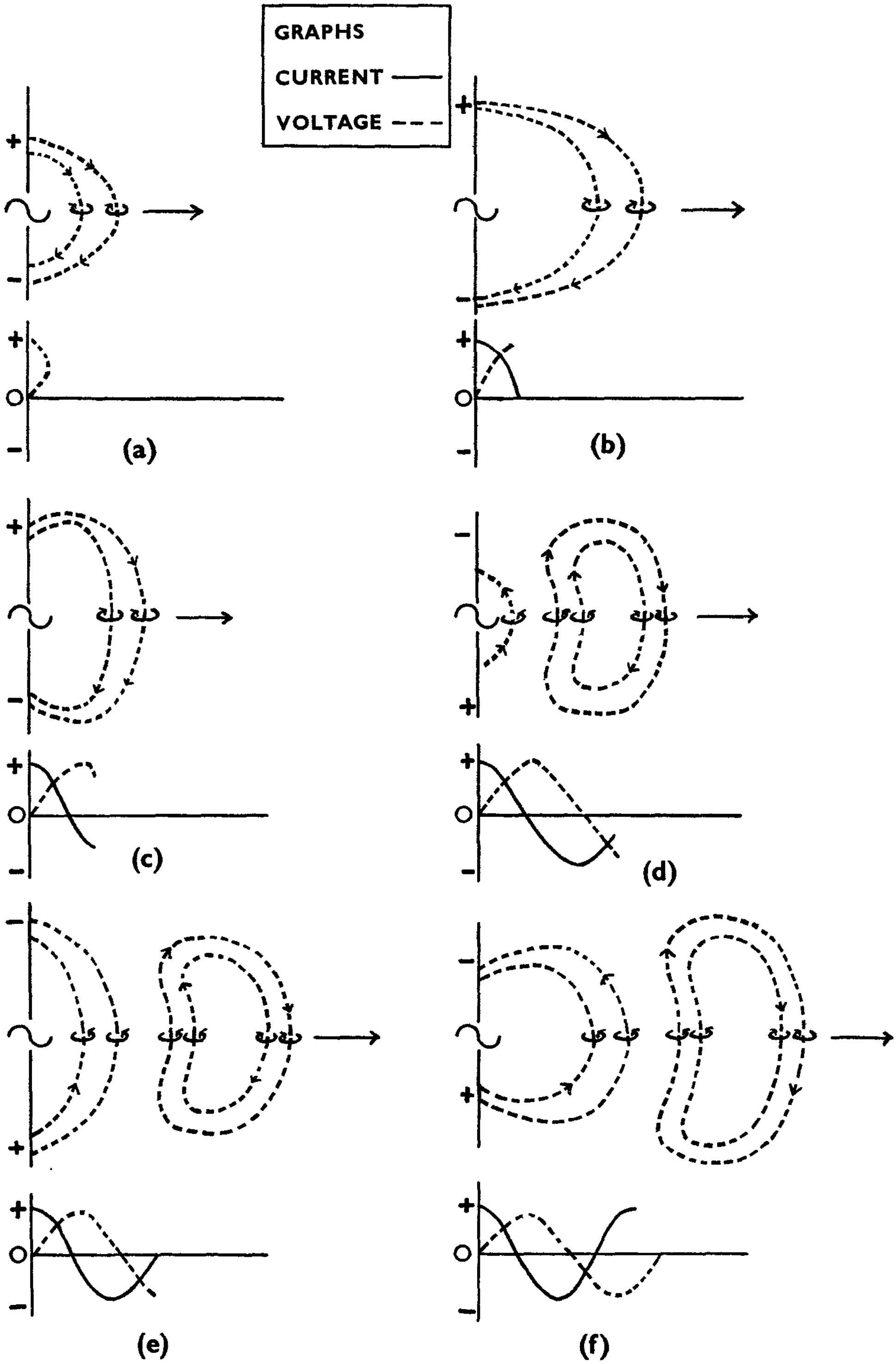


Fig. 6. Radiation

Wave Radiation

15. In Fig. 6(a) the E.M.F. supplied by the high frequency oscillator has just been applied to the aerial and the capacity of the system is being charged. The P.D. between the ends of the aerial is approximately zero, as maximum charging current is flowing. The electric field produced is of the open type, in contrast with that produced between the plates of a charged condenser. The relationship between the charging current and the potential difference between the two ends of the aerial is similar to that which exists with a capacitor.

16. In Fig. 6(b) the charging current has ceased since the capacitance of the aerial is fully charged and maximum P.D. exists between the ends of the aerial. The electric field with its accompanying magnetic field is extended all round the aerial, each line on the diagram being shown as surrounded by its own magnetic field.

17. In Fig. 6(c) the current is flowing in the opposite direction. The capacitance of the aerial is undergoing discharge, causing the P.D. to be reduced and the electric field to start to collapse.

18. In Fig. 6(d) the aerial capacitance is receiving a charge of opposite polarity and the electric field in this new direction is building up before the previous field has had time to collapse completely. Further collapse of the initial field is therefore prevented, and the remaining lines of electric strain form into *closed loops.*

19. In Fig. 6(e) the closed loops of the electric field with their associated magnetic fields are forced outwards from the aerial because the inner lines of the initial field and the outer lines of the new field are in the same direction. The strength of the new field is now at a maximum because the maximum potential difference exists between the ends of the aerial.

20. In Fig. 6(f) the initial field has been forced further outwards from the aerial and will continue to be so affected as more loops of electromagnetic strain are produced. The second field is shown partially collapsed with the potential difference approaching zero.

Relationship between Frequency and Energy Radiated

21. The amount of energy radiated by a transmitting aerial increases considerably with frequency. This is because as the frequency of a transmission becomes higher the electric field has less time in which to collapse and less energy is able to return to the transmitting aerial.

Propagation of Electro-Magnetic Waves

22. The propagation of E.M. waves through space is made possible by a medium known as the ether. That this medium exists throughout space is exemplified by the fact that radar echoes have been received from the moon.

23. E.M. waves, once released from the transmitting aerial, become an independent source of energy as a result of the inter-action between their electrical and magnetic components. They travel at the speed of light, and lose strength when passing through solids or liquids.

24. Fig. 7 shows trains of E.M. waves in space. It will be observed that the points of highest positive potential are the same distance apart in each successive wave train.

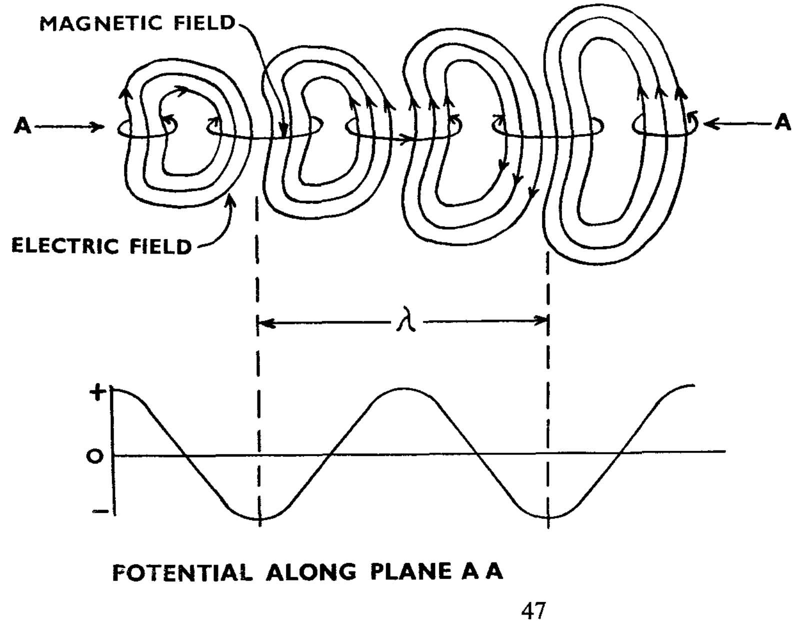


Fig. 7.
Trains of E.M. Waves in Space

25. Fig. 8 shows the relationship between potential and distance in space as applied to a train of E.M. waves.

$$\text{Frequency} = \frac{\text{Speed}}{\text{Wavelength}}$$

$$= \frac{3 \times 10^8}{60} = 5 \text{ mc/s}$$

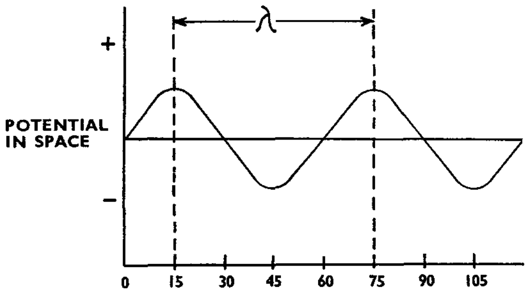


Fig. 8.

Relationship between Potential and Distance

26. Fig. 9 shows the relationship between potential at a given point in space, and time, as a train of E.M. waves passes a point.

1 cycle takes $0{\cdot}2 \times 10^{-6}$ seconds.

$$\text{Frequency} = \frac{1}{0{\cdot}2 \times 10^{-6}} \text{ c.p.s.}$$

$$= 5 \times 10^6 \text{ c.p.s.}$$

$$= 5 \text{ mc/s}$$

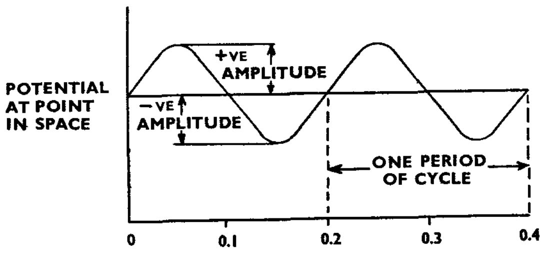


Fig. 9.

Relationship between Potential and Time

Current and Voltage Distribution in Simple Aerials

27. To obtain the greatest efficiency from a transmitting aerial it must be of a certain size, depending on the frequency in use. The radiated energy is proportional to the square of the aerial current, and the greatest radiation is obtained when the changes of current in the aerial are at their maximum. Fig. 10 shows a simple aerial fed at its centre ; if the length of this conductor were equal to the wavelength of the generated signal the aerial would become an oscillatory circuit, resonant with the transmitted signal. Since there is no path the value of the current at the ends of the aerial will be zero. In this state of resonance a point of zero current also exists at the centre of the aerial. If the inductance and capacitance of the aerial were constant, the current and voltage distribution would be sinusoidal.

28. The distribution of current in an aerial one wavelength long is shown by the heavy curve in Fig. 10. It should be noted that the R.M.S. value of current flowing is shown here ; instantaneous values of current for each portion of the aerial vary sinusoidally reaching zero twice in each cycle.

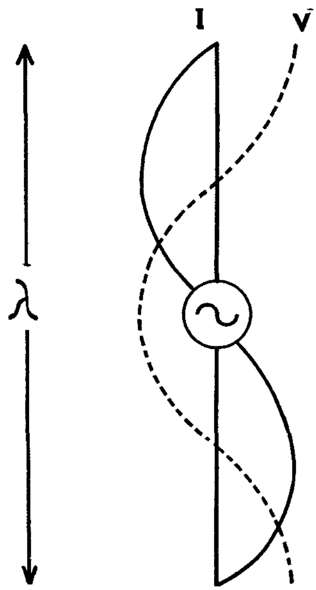


Fig. 10.

Distribution of Current and Voltage in Full-Wave Aerial

29. The voltage distribution along the aerial is represented by the dotted line in Fig. 10. The voltage is greatest at points corresponding to zero current, and vice versa. In an aerial of about half the wavelength, the distribution of voltage

and current is shown in Fig. 11 ; here the current at the centre of the aerial is maximum and the voltage zero. The centre of the aerial (point B in Fig. 11) may be regarded as at zero potential. If the aerial were connected to earth at this point the distribution of current and voltage along the aerial would be unaffected. The lower part of the aerial may therefore be cut away leaving the generator connected to earth.

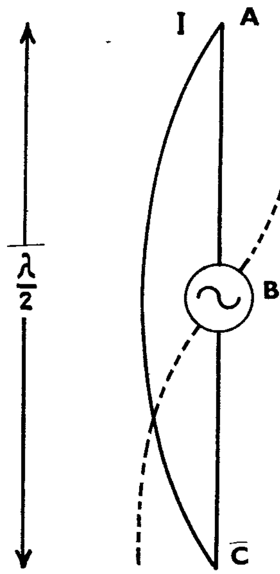


Fig. 11. Distribution of Current and Voltage in Half-Wave Aerial

30. In Fig. 12(a) the length of the aerial is now about quarter wavelength ; the currents in the aerial are attended by corresponding earth currents, producing the effect of an image aerial in the earth. Waves radiated towards earth are reflected from the earth's surface in the manner shown in Fig. 12(b). The amount of reflection depends on the conductivity of the earth and the reflected waves appear to originate from points on the image aerial. With this type of aerial the total current may easily be measured by an ammeter connected at the point of low potential.

31. There are two basic forms of transmitting aerials : the half-wavelength dipole aerial and the quarter-wavelength earthed aerial. The term "dipole" denotes any symmetrical aerial the two ends of which are at opposite potential to earth point. The selection of an aerial for a particular task is influenced by many factors ; two of the most important being the frequency band to be used and ease of installation. For example, a fixed aerial fitted to an aircraft is limited in length by the size of the aircraft.

Aerial Circuit Resistance

32. Only part of the energy injected into an aerial circuit is radiated. Energy radiated from an aerial is directly proportional to the square of the aerial current. From this constant the value of aerial-radiation resistance can be derived, hence :

Aerial Current^2 × Radiation Resistance = Power Radiated.

33. Aerial circuit losses are due to :—

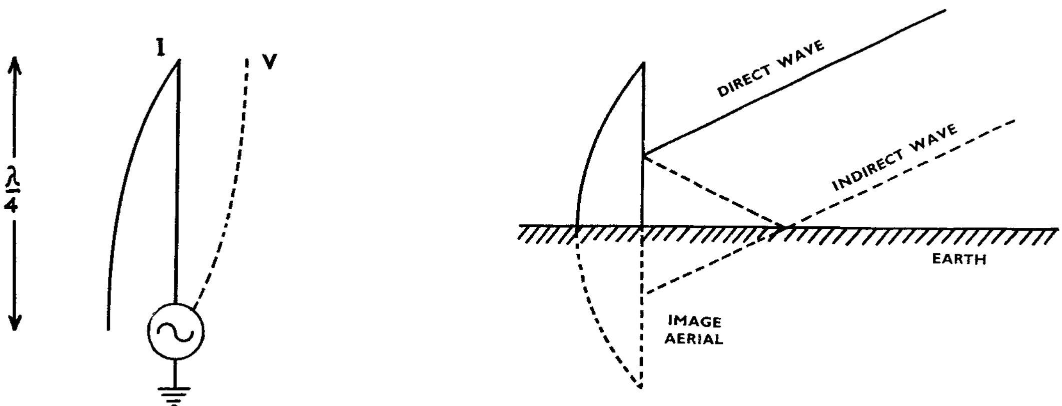
(*a*) Resistance of aerial conductors, including that of the aerial tuning device.

(*b*) Resistance of the earth-return path.

(*c*) Imperfect dielectrics.

(*d*) Leakage over the surface of insulators caused by atmospheric deposits, *e.g.* dirt, moisture, etc.

(*e*) Corona or brushing, *i.e.* breakdown of dielectric.



(a) Fig. 12. Quarter-Wave Aerials (b)

34. These losses cannot be measured individually, but their total effect is the same as that of a separate resistance in an aerial circuit composed of loss-free components. The equivalent resistance may be called the loss resistance and the following equation is derived :

Aerial Current^2 × Loss Resistance = Power Expended in Aerial Circuit Losses.

The sum of the radiation resistance and loss resistance gives the total resistance of the aerial circuit.

35. Fig. 13 shows the general variation of aerial resistance with wavelength. (The principal sources of loss resistance only are shown.)

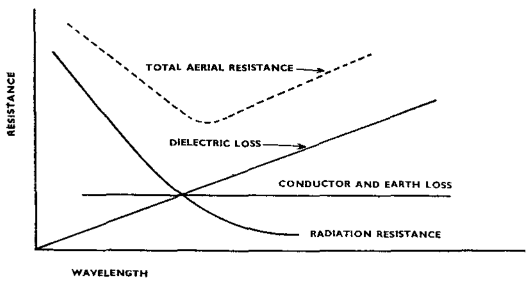


Fig. 13. Variation of Aerial Resistance with Wavelength

Effective Height

36. Fig. 14(a) shows an earthed vertical aerial AB. The current distribution is as indicated by the dotted line I.

37. An aerial may be regarded as comprising many small sections (see Fig. 14(a)). The current in any one of these small sections may, for all practical purposes, be regarded as constant throughout the section. At any point in space away from the aerial, the field strength emanating from each aerial section is proportional to the product of the length of the section and the currrent flowing through it. The field strength set up by the whole aerial is the sum of the fields of each part.

38. If another aerial, CD (see Fig. 14(b)), were constructed so that the current was constant throughout its length, and the value of the current was the same as at the base of aerial AB (Fig. 14(a)), and if the height of CD were such that the rectangle formed had the same area as the area formed by the current curve of aerial AB in Fig. 14(a), then the field strength at any point around the aerial CD would be equal to similar points around aerial AB. The length of CD is then called the "effective height" of AB. The effective height of an aerial may be described as "that length of an aerial which, if excited at all points along it by a current of the same value as that existing at the point of maximum current on the aerial itself, would produce the same field strength at all points as if it were the actual aerial".

39. If the current distribution in a vertical aerial a quarter wavelength long is sinusoidal, the effective height of the aerial is $\frac{2}{\pi}$ of its physical length. An aerial designed for working on long waves is usually short in proportion to the wavelength and has a large top ; this ensures that the current in the vertical uplead is constant. As the top does not normally radiate, the effective height of this aerial will be approximately equivalent to its physical height.

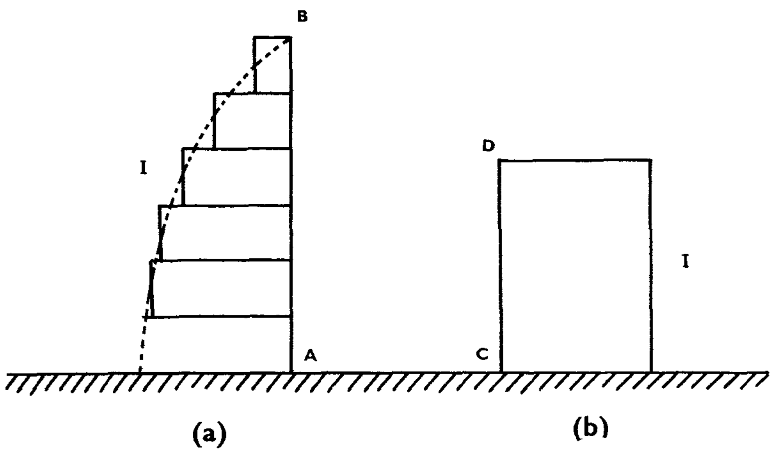


Fig. 14. Earthed Vertical Aerial

40. The term "effective height" arose from early experiments with vertical aerials. The same factors apply, however, with, for example, a horizontal short wave aerial of overall length equal to half a wavelength, as the term "effective height" means in effect "an equivalent length of aerial supplied with constant current".

41. In practice, the effective height of an aerial is obtained from field strength measurements made at some distance from the aerial ; the value thus obtained is therefore less than a theoretical calculation of the current distribution in the aerial.

42. The radiation resistance Rr and the effective height h are connected by the formulæ :

$$Rr = \frac{160\pi^2 h^2}{2} \text{ ohms, where the value of h}$$

and λ are in the same units.

For an aerial $\frac{\lambda}{4}$, $h = \frac{2}{\pi} \times \frac{\lambda}{4}$ and $Rr = 40$ ohms; for a long wave aerial, however, Rr may be as low as 0·1 ohms.

The power radiated, $Wr = I^2Rr$

$$= I^2\, 160\pi^2 \frac{h^2}{\lambda^2}$$

$$= I^2\, 1580 \frac{h^2}{\lambda^2}$$

From this it is evident that to radiate power efficiently $\frac{h}{\lambda}$ must be as large as possible.

Aerial Coupling to Transmitter and Selection of Feeding Points

43. Figs. 10, 11, and 12 show the current and voltage distribution in simple aerials ; it will be observed that, for earthed aerials of quarter wavelength or odd multiples of quarter wavelength, current maximum occurs at the earthed end of the aerial and at this point the voltage is at a minimum. The aerial impedance at any point along the aerial is given by the $\frac{V}{I}$ ratio. This is at its lowest value when the current is at a maximum and highest when the current is at minimum. At points of minimum impedance the aerial may be *current fed*, and at points of maximum impedance the aerial may be voltage fed. In current fed aerials a coupling coil is inserted in the aerial at the point of minimum impedance and current is induced in the coil, and in the whole aerial, by means of current flowing in a primary coil in the transmitter circuit.

44. In coupled aerials the coupling coil may be placed at the earthed end of the aerial. The coupling circuit may be located at a point where the aerial enters the station ; the transmitter may be placed in any convenient position. Fig. 15 shows a suitable method of coupling the aerial to the transmitter for current feeding.

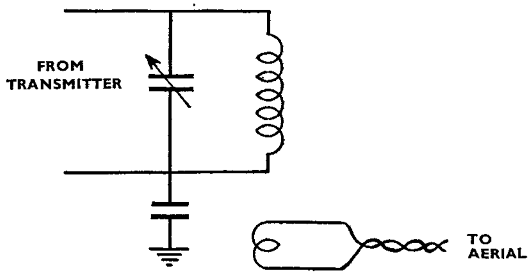


Fig. 15. Coupling Aerial to Transmitter for Current Feeding

Current Fed Aerials

45. In the half-wave dipole shown in Fig. 11, the current and voltage values at the centre of the aerial indicate minimum impedance. This type of aerial, therefore, whether erected vertically or horizontally, may be current fed at its centre. A feeder, able to deliver the energizing current with low loss to the aerial from the transmitter circuit, is used to connect the aerial with the coupling circuit. Special care must be taken to match the impedance between aerial and transmitter.

End Fed Aerials (Voltage Feed)

46. The current at the ends of an unearthed aerial is practically zero and the impedance at these points is high. To produce a satisfactory current in such an aerial a very large exciting voltage has to be applied between the ends of the aerial. Such a voltage is obtained from an inductor in a resonant circuit of high "Q". Fig. 16 illustrates a simple aerial coupling circuit for voltage feeding. Aerial impedance is matched by the high impedance across the anti-resonant circuit. Aerial current may be adjusted for maximum value by suitable choice of aerial tap and coupling between inductors.

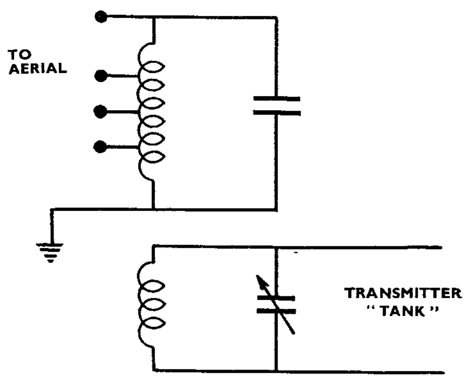


Fig. 16. Aerial Coupling for Voltage Feeding

Aerial Tuning Circuits

47. The effect of a wave on an aerial may be likened to that of an alternator inserted in the aerial circuit, producing a radio frequency voltage of very small value. In Fig. 17(a) the capacitor C_1 is made variable so that the circuit may be tuned to resonate at the desired frequency. The inductor L_1 may be made variable in order to increase the tuning range. The aerial has a distributed capacitance and if this is represented by the term Ca the effective capacitance used in tuning the aerial is equal to $\frac{C_1\,Ca}{C_1 + Ca}$.

48. An alternative method of tuning the aerial circuit is shown in Fig. 17(b). In the resonant condition the aerial offers maximum impedance; the circulating current in the anti-resonant circuit is at a maximum and the actual aerial current is at its minimum. The distributed capacitance of the aerial is now in parallel with the tuning capacity C_1, and the effective tuning capacity is equal to $C_1 + Ca$.

49. The aerial capacitance Ca is naturally not the same for all aerials. Ca varies with height, length, and chord of the aerial, as well as with atmospheric conditions. Because of this it is not possible to calibrate the dial of a variable aerial capacitor with any degree of accuracy. Another important factor affecting aerial capacitance is poor aerial insulation (referred to previously in this chapter). The effects of poor insulation and varying aerial capacitance are minimized by using the circuit shown in Fig. 17(a). The inductance L_2 is connected between aerial and earth and the inductor L_1 of the parallel circuit L_1 C_1 is loosely coupled to L_2. The inductor L_1 of the secondary circuit has many more turns than the primary inductor L_2 and, therefore, by means of mutual induction an E.M.F. may be induced in the secondary circuit which is greater than the voltage across L_2 itself.

50. The capacitor C_1 may now be used to tune the circuit L_1 C_1 to the desired frequency, the effects of aerial capacitance and poor insulation being greatly reduced. Considerable improvement in the selectivity of the tuned circuit L_1 C_1 is obtained, resulting from the reduction in damping effect due to aerial radiation and loss resistances. The alternating voltage set up across the inductor or capacitor by the circulating current is applied to the detector or to an amplifying circuit before the detector.

51. The resonant rise in voltage in a tuned circuit is equal to EQ, where E is the applied E.M.F. and the magnification factor $Q = \frac{\omega L}{R}$. The voltage V (see Fig. 17(a)) will depend on the value of the inductor. As L is increased so the capacitance C will be decreased. The inductance should therefore be as large as possible, as the effective resistance increases as L is increased. The capacitance should be as small as possible.

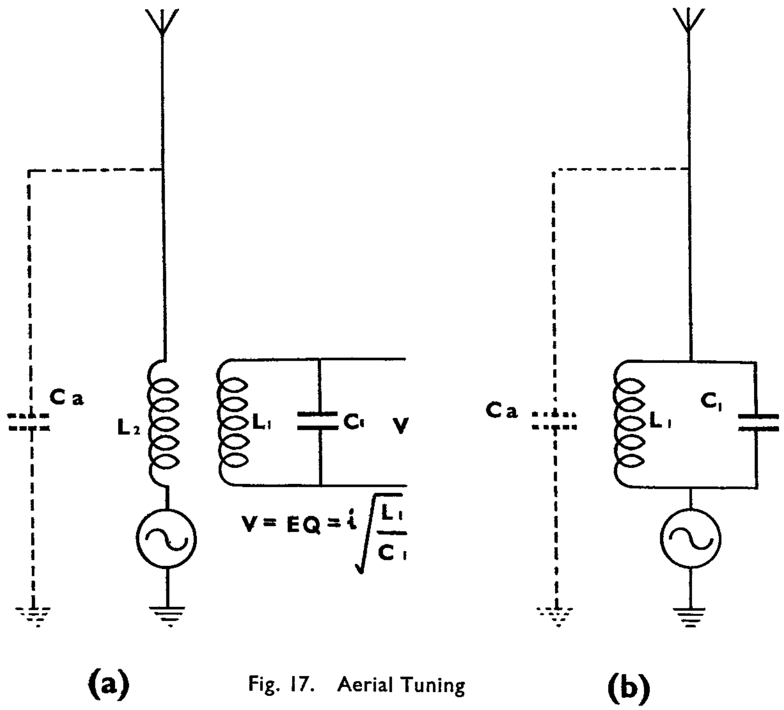


Fig. 17. Aerial Tuning

SECTION 2

BASIC RADAR PRINCIPLES

CHAPTER 13

INTRODUCTION TO RADAR

HISTORY OF RADAR

General

1. Radio Direction and Ranging, or RADAR as it is now known, is developed from the original Radio Location, and is simply using radio waves to indicate the range and direction of an object in the path of the radio wave. The object will reflect some of the power contained in the radio waves in the form of an echo, and this echo may be detected.

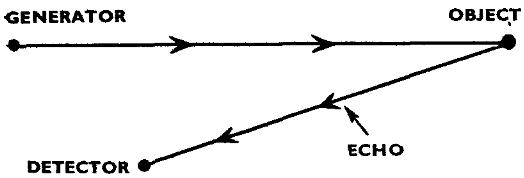


Fig. 1. Detected Echo

Location of Objects by Sound

2. The use of echoes to indicate the presence of an object is not new; any child shouting at a cliff and listening for the echo to return is employing the same principle, using sound waves. A bat is known to emit squeaks in the supersonic range of waves to detect the presence of obstructions in its line of flight, the returning echoes indicating the range to the bat. It has also been possible for many years to detect the presence of large objects under water, again by echoes. In all these cases the speed of the wave has limited the use of sound waves to comparatively slow-moving objects. The speed of sound being about 1,100 feet per second, an aircraft moving at 600 miles per hour (880 feet per second) will be moving almost as fast as the wave trying to give warning of its presence. Also, sound waves suffer from considerable absorption and deflection from obstructing objects, and to produce an appreciable echo from any distance would require great power from the sound generator.

Use of Electro-Magnetic Waves

3. Electro-magnetic waves travel at a constant speed of 186,240 miles per second. Research has discovered the presence of various ionized layers in the upper atmosphere possessing the property of reflecting short waves. The heights of these layers were established and used to calculate optimum short-wave communication ranges. It was additionally found that short waves were also reflected from small objects such as aircraft, but it was not until the early 1930's that use was made of this to locate and identify fixed or moving objects.

4. Once it was established that an aircraft gave a detectable echo from the electro-magnetic wave striking it, the immense superiority of a method based on this principle over the optical or sound systems of ranging and detection became apparent. The wave travelling at approximately 186,000 miles per second gives almost immediately an echo of a target many miles away. The direction of the target is indicated by the direction of the returning echo. The range is indicated by half the time taken for the wave to travel from the generator or transmitter to the target, and be reflected back again to the receiver that picks up the echo. The receiver has to be very sensitive to detect the weak echoes.

5. The sea gives weak echoes compared with the land, and reflection is at its maximum from built-up areas. Where three reflecting surfaces meet, at corners or angles in walls of buildings, practically all the radiated energy is reflected back.

Application to Moving Objects

6. It was discovered later that suitable radar equipment could be installed in aircraft to locate moving or stationary targets, and as aids to navigation. To appreciate the advantage of using electro-magnetic waves, consider the speed of wave travel as approximately 186,000 miles per second (or 300×10^6 metres per second).

$$\text{Wave travels 1 mile in } \frac{1}{186{,}000} \text{ second} = \cdot 000005376 \text{ second} = 5 \cdot 376 \text{ microseconds.}$$

The wave has to travel to the object and return, so in radar terminology the mile is the equivalent of a journey of two miles:

The wave travels 1 *Radar Mile* in $5 \cdot 376 \times 2$ microseconds $= 10 \cdot 7$ microseconds.

7. Briefly an electro-magnetic wave takes approximately 10 microseconds to travel to an object one mile away and return to a receiver situated at the same place as the transmitter. If 200 miles were arbitrarily accepted as the maximum range required, and $^1/_{10}$ mile the minimum range, the times required by the wave to travel these return journeys are:—

(*a*) 1 mile takes 10 microseconds.

(*b*) 200 miles takes 2 m/secs. (milliseconds).

(*c*) $^1/_{10}$ mile takes 1 microsecond.

All times are based on statute miles and approximated to appear as whole numbers for simplicity, the small inaccuracies being unimportant at this stage.

8. It was now obvious that warning could be obtained of even fast-moving targets and, as electro-magnetic waves suffer less attenuation than sound waves, the ranges at which objects could be detected would be greater.

Measurement of Time

9. A difficulty arose, however, in measuring such small intervals of time. Mechanical clocks obviously cannot handle times corresponding to one thousandth or one millionth part of a second, and so an electronic device called a *Cathode Ray Tube* (C.R.T.) is used. This gives a pictorial presentation of distance along a line proportional to the time interval to be measured. The line is drawn on a fluorescent screen at the end of the tube by the rapid movements of a spot of light, produced by a high velocity beam of electrons striking the fluorescent screen.

Power Requirements of Radar

10. Considerable power is required to produce an electro-magnetic wave of such strength that after suffering attenuation for 400 miles the very small amount reflected back will still produce a detectable echo in the receiver. Actual peak power used in certain radar transmitters is 500,000 watts (500 KW), and may be as high as 2 million watts (2 Megawatts) in ground equipment.

PULSE TECHNIQUE

Reasons for Using Pulses

11. In order that a sensitive receiver may be situated close to the transmitter and still be able to differentiate between the large transmitter signal and the very weak echo from the object, pulse technique is employed. The radio frequency (R.F.) power is radiated in very short bursts of large amplitude repeated many times per second with comparatively long periods of no radiation between each pulse.

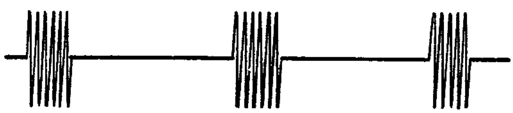


Fig. 2. R.F. Pulses

This allows the receiver to pick up the transmitter pulse first, and then after a certain interval of time to detect the echo, before the next transmitter pulse occurs. The transmitter and echo pulses are used to deflect the line on the C.R.T., and the distance between the two deflections is proportional to the time interval between. This is measured, and after converting to miles will give the range of the object.

Fig. 3. Transmitter and Echo Pulses

Receiver Signal Input

12. If a maximum range of 200 miles is required, the time between the transmitter and echo pulses will be approximately 2 milliseconds, so immediately after this period of time the next transmitter pulse could occur. This would give a *Pulse Recurrence Frequency* (P.R.F.) of 500 per second. In practice, a "waiting period" is necessary to prevent spurious "pick-ups" from objects outside the equipment's operational range. In short-range operation this waiting period may be as long as five times the duration of the necessary time interval, because objects beyond the operational range of the equipment could produce strong echoes.

13. The P.R.F. is made as high as possible to eliminate flicker in the display on the cathode ray tube, and to increase the brilliance of signals. Too high a P.R.F. would seriously cut down the maximum range, because each transmitter pulse would occur before the previous one had time to travel to the maximum range and return an echo.

14. The P.R.F. of any equipment therefore depends on many factors, and is determined by the operational use of the equipment. In practice it usually lies between 400 and 5,000 pulses per second, but for certain operational requirements a P.R.F. of 50 pulses per second is used.

Pulse Shape

15. For reasons which will be more apparent later, the ideal pulse shape is a square wave. To produce such a wave the R.F. oscillations must reach maximum immediately and cease instantaneously. The steep leading edge of the wave will produce an echo which may be used to indicate the range, and the sharp cut-off prevents obscuring any adjacent weaker echoes. The flat top and steep sides are essential for maximum pulse power. This ideal is seldom possible, but equipment is carefully designed to produce and maintain waves of as square a pattern as possible.

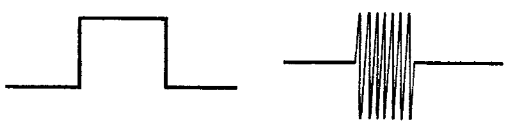


Fig. 4 Square Wave

Pulse Width

16. A narrow pulse is essential for high definition of the C.R.T. presentation, but design limitations prevent the production and maintenance of even an almost square pulse unless a certain number of cycles of R.F. oscillations are included. In practice at least 200 cycles are required. With a carrier frequency of 20 megacycles this would necessitate a pulse at least 10 microseconds wide.

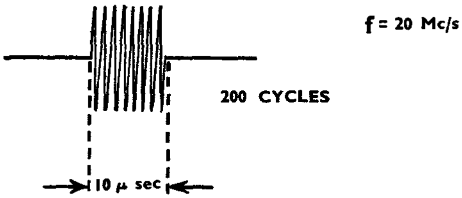


Fig. 5. 10μ Seconds Pulse

With a carried frequency of 3,000 mc/s (10 cms.) the pulse width can be less than 1 microsecond and still contain more than 200 cycles in each pulse.

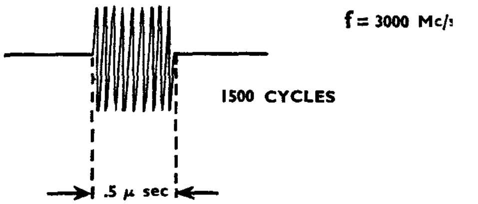


Fig. 6. 5μ Seconds Pulse.

17. Considering that 10 microseconds represents one radar mile, a pulse width of 10 microseconds will fail to differentiate between objects less than one mile apart, because the echo produced by the pulse striking the farthest object will return before the echo from the nearest object has ceased, and the result will appear as one large signal on the C.R.T. Also the echoes of objects at ranges of one mile or less from the transmitter will be obscured on the C.R.T. by the transmitter pulse. On the other hand, $^1/_5$ microsecond pulse width will indicate differences of 35 yards in range, but the R.F. energy in the echo will be less than with a 10 microseconds pulse, assuming equal peak power. Thus the pulse width used will depend on the operational functions of the equipment and its carrier frequency. In practice pulse widths between $\frac{1}{2}$ microsecond and 10 microseconds are used.

Power Ratio—Input to Output

18. During every second, if a particular transmitter is sending out 670 pulses of 1 microsecond duration, it is actually functioning for 670 microseconds in every second, or approximately $2\frac{1}{2}$ seconds per hour. Its *Peak Power* whilst transmitting is 500 kW but the *Mean Power* is :

Mean Power

$$= \frac{\text{P.R.F.} \times \text{Pulse Width} \times \text{Peak Power}}{10^6} \text{ Watts}$$

$$= \frac{670 \times 1 \times 50{,}000}{10^6}$$

$$= 33 \cdot 5 \text{ Watts.}$$

So by employing the pulse technique considerable peak power can be given to the bursts of R.F. energy, with a very low mean power, without having large, high-power components in the equipment.

Radiation of Pulses

19. To determine the direction of the object, the radio waves are radiated mainly in one direction or *beamed* by the transmitter aerial system, and the returning echo is detected by a beamed receiver aerial system exactly aligned to the transmitter aerial. By rotating or elevating the whole aerial assembly any area can be *scanned*

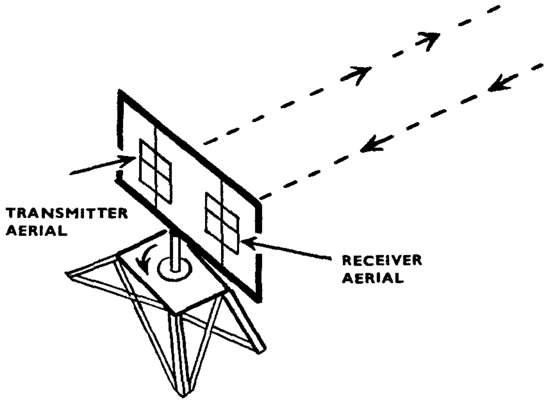


Fig. 7. Rotating Aerial System

for echoes, and the direction of the assembly read off a scale when the echo is maximum. Because of the difficulties of accurately aligning separate transmitter and receiver aerials in a rotating system, one aerial system, called a *scanner*, is made to act as a transmitting aerial when the transmitter pulses, and as a receiving aerial at all other times. An electronic switch called a "T.R." switch changes over the aerial at the P.R.F., and another called the "anti-T.R." switch prevents damage to the sensitive receiver while the transmitter is pulsing.

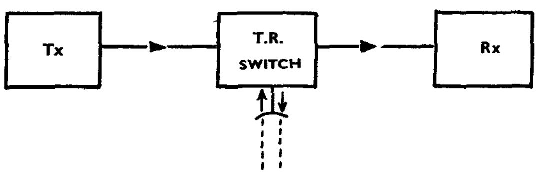


Fig. 8. T.R. Aerial Switch

20. An added advantage of this system of directional or beamed radiation is that the R.F. energy from the transmitter is concentrated into the area to be scanned, and only a small proportion is radiated in unwanted directions. This improves the strength of the signal, and consequently the echo, without employing higher transmitter power.

PRIMARY AND SECONDARY RADAR SYSTEMS

Primary Radar

21. If the radiation from a radar transmitter is intended to strike a distant object and be reflected without any assistance from that object, the system is called "Primary Radar". The strength of the returning echo will depend on the strength of the transmitter pulses and the distance between the transmitter and the object. As a rule the echo is of very small amplitude.

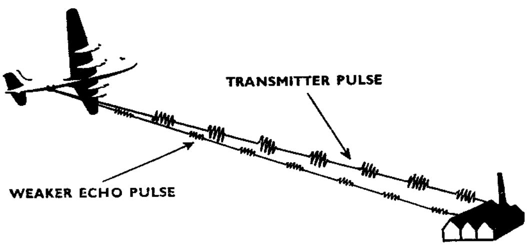


Fig. 9. Example of Primary Radar

Secondary Radar

22. Certain installations are designed to operate in conjunction with some form of re-radiating equipment, to which the transmitter pulse is radiated. On receipt of a particular transmitter pulse, this "Beacon", as it is called, will send a pulse back to the original transmitter. Such a system is known as "Secondary Radar".

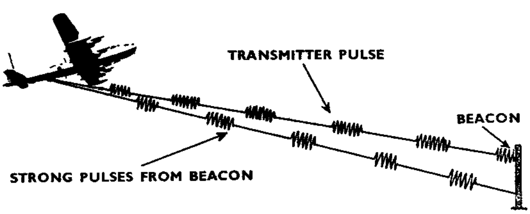


Fig. 10. Example of Secondary Radar

THE CATHODE RAY TUBE

General

23. The C.R.T. is a vacuum tube used in radar equipment as an indicator to give the operator a visual presentation of the time delays between the transmitter pulse and the echoes in terms of distance across the *screen* of the tube. It can be regarded as an indicating device with a pointer having no inertia. The beam of electrons is made to produce a pinpoint of light which can be moved across the screen of the tube in any direction. The brilliance of the light can also be varied.

24. If the spot of light is made to trace the same path rapidly many times per second, the operator will see a steady line called a *trace*. By applying the output from the receiver to the C.R.T. the line can be deflected, or varied in intensity, whenever a pulse is detected by the receiver. By synchronizing the repetition speed of the trace with the P.R.F. of the transmitter the echoes can be made to occur at the same place on each trace, thereby appearing stationary. The deflection caused by the transmitter pulse will also appear stationary, because it occurs at the same time on each trace, and the distance between the transmitter blip and the echo is proportional to the range of the object.

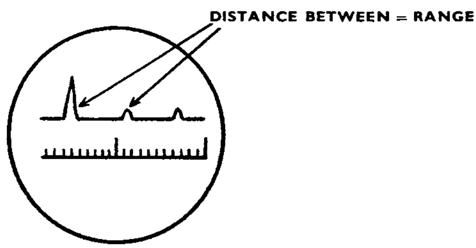


Fig. 11. Method of Measuring Range

The Electron Gun

25. Basically the C.R.T. is an electron gun inside a vacuum or gas-filled tube, and similar to the ordinary thermionic valve.

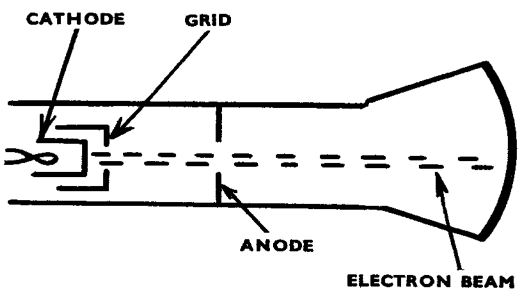


Fig. 12. Basic C.R.T.

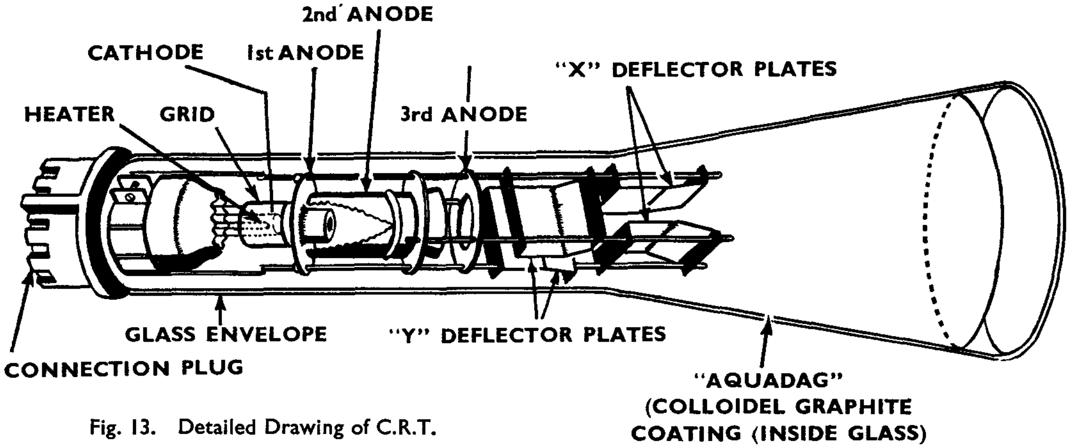


Fig. 13. Detailed Drawing of C.R.T.

The C.R.T. consists of the following main parts:—

(*a*) *Cathode.* The cathode cylinder is oxide coated at its narrow end, is heated by an internal filament, and emits a random cloud of electrons.

(*b*) *Anode.* The electrons are attracted and accelerated by a plate with a hole in the centre, held at a high potential of several thousand volts with respect to the cathode; this plate is the anode. The majority of electrons emitted by the cathode form a rough beam after shooting through the hole in the centre of the anode, and travel at high speed towards the fluorescent screen at the other end of the tube.

(*c*) *Grid.* The number of electrons in the beam, and therefore the intensity of the beam, is controlled by the grid or cylinder; this has a hole through which the beamed electrons pass. Being negative in potential to the cathode, and located between the cathode and anode, the grid reduces the divergence of the beam to allow it to pass through the small hole in the anode. The grid is adjustable in potential, and forms the "Brilliance Control" of the C.R.T.

Focussing

26. To ensure that the diffused beam of electrons hits the screen as a very small point, the beam must be focussed in just the same way that a light beam from a lamp must be focussed to produce a well defined spot of light on a screen and not a large blur.

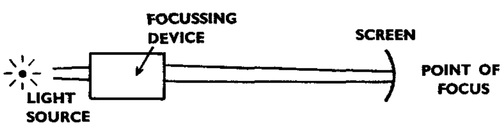


Fig. 14. Necessity for Focussing

Deflection

27. The focussed beam must also be deflected across the face of the C.R.T. horizontally and vertically to produce the required trace. These functions are accomplished in either of two ways, separately or in combination: *i.e.* electrostatically and electro-magnetically. Commonly found combinations are:—

(*a*) Electrostatic focussing and deflection.
(*b*) Electro-magnetic focussing and deflection.
(*c*) Electrostatic focussing and electro-magnetic deflection.

Electrostatic Focussing

28. In precisely the same way that a light beam can be focussed by a system of lenses to converge at a point, so by passing the electron beam through a suitably formed electrostatic field the beam can be converged to strike the screen at a small point.

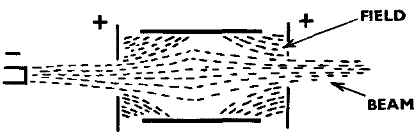


Fig. 15. Electrostatic Focussing

29. This electrostatic field is produced by using three anodes. The first and third, or accelerating anodes (numbered consecutively from the cathode end) take the form of discs fixed across the tube with small holes in their centres, and the second or focussing anode is a cylinder fixed along the axis of the beam between the two disc anodes. Generally, but not invariably, the first and third anodes are connected together to a high (4 kV) potential, with respect to cathode. The second anode is at the lower ($\frac{2}{3}$ or $\frac{3}{4}$) potential than the others, and is made variable to make the focal point of the beam coincide with the surface of the fluorescent screen. This forms a "Focus Control" for the C.R.T.

Electrostatic Deflection

30. Electrostatic deflection is accomplished by two pairs of metal plates :—

(a) "*Y*" *Plates.* To deflect the beam up and down, a pair of deflector plates are mounted, one above and one below the beam and beyond the third anode, and are fed with deflection voltages. They are known as the

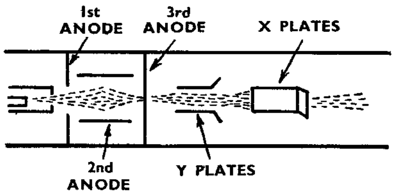


Fig. 16. Electrostatic Deflection

"Y" plates and signals from the receiver are fed to them to cause vertical deflection of the trace. Supposing a deflection voltage is applied such as to make the upper plate more positive than the lower plate. The resultant electric field between them will cause the beam to be deflected upwards. Conversely,

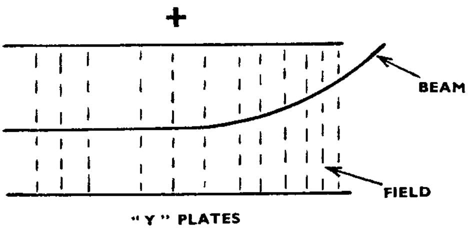


Fig. 17. Action of "Y" Plates

if the lower plate is made more positive than the upper plate the beam will be deflected downwards. By splaying out the ends of the plates it is possible to obtain greater deflection.

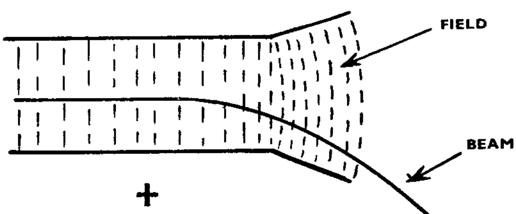


Fig. 18. Reverse Action of "Y" Plates

(b) "*X*" *Plates.* Another pair of deflection plates mounted beyond the "Y" plates, and vertically in the tube, are called the "X" plates. They are used to produce horizontal deflection of the beam. The "X" plates are generally used to produce the basic trace across the tube, and are therefore fed with a trace deflection voltage. This is called the "Time-Base" voltage.

Plate Voltages

31. If the mean value of the voltages applied to the "X" and "Y" plates were appreciably different from that of the third anode, distortion of the trace would occur as the beam was deflected. This fault can be remedied by applying a symmetrical voltage to the "X" and "Y" plates, with a mean value the same as that of the third anode. These mean voltages are made variable to align the spot or trace vertically and horizontally, and form the "X" and "Y" "Shift" controls or "Zeroing" controls. To obviate having high potentials on the "X" and "Y" plates, the final anode is usually fixed at 0 volts or earth, while all previous anodes, cathode, and grid, are made proportionally more negative. This also prevents spurious deflection of the beam by fields set up between the final anode and earthy objects near the screen. The method of connecting the components of an electrostatic C.R.T. to the supply voltages is shown in Fig. 19.

32. In Fig. 19 the cathode is placed at a potential of − 3·9 kV by virtue of being connected to the negative end of R_6. Control of the intensity of the electron stream is achieved by varying the potential on the grid between − 3·9 kV and − 4 kV. This is done by the potentiometer P_4. Anode 1 is connected to the negative end of the R_4, which is at a potential of − 2 kV. Anode 2 is connected to the moving arm of the potentiometer P_3 ; this gives the variable voltage required on Anode 2 for focussing the electron beam. The potential is variable about a point − 3·5 kV. Anode 3 is connected to the junction of R_2 and R_3, which is at earth potential.

33. Across the potentiometers P_1 and P_2 and resistances R_2 and R_3 approximately 300 volts are developed ; these are applied to the deflection plates "X" and "Y". The potentiometers are differentially connected so that an increase in positive potential on X_1 will produce a negative increase on X_2. This becomes necessary to prevent deflection distortion, which is caused when the potentials on X_1 and X_2 are not equal and opposite ; the field produced by this condition causes the electron beam to be de-focussed at either end of its deflection travel. The voltages are made equal and opposite by keeping the centre of the potentiometers at earth potential ; this is achieved by earthing the centres of R_2 and R_3 which are in parallel with P_2. Voltages for a typical 4 kV C.R.T. (VCR 517) are :

Cathode, − 3·95 kV.

Grid, about − 4·00 kV (variable by 50 volts for brilliance control).

Anode 1, − 2·00 kV.

Anode 2, − 3·00 kV (variable for focus control).

Anode 3, Earth.

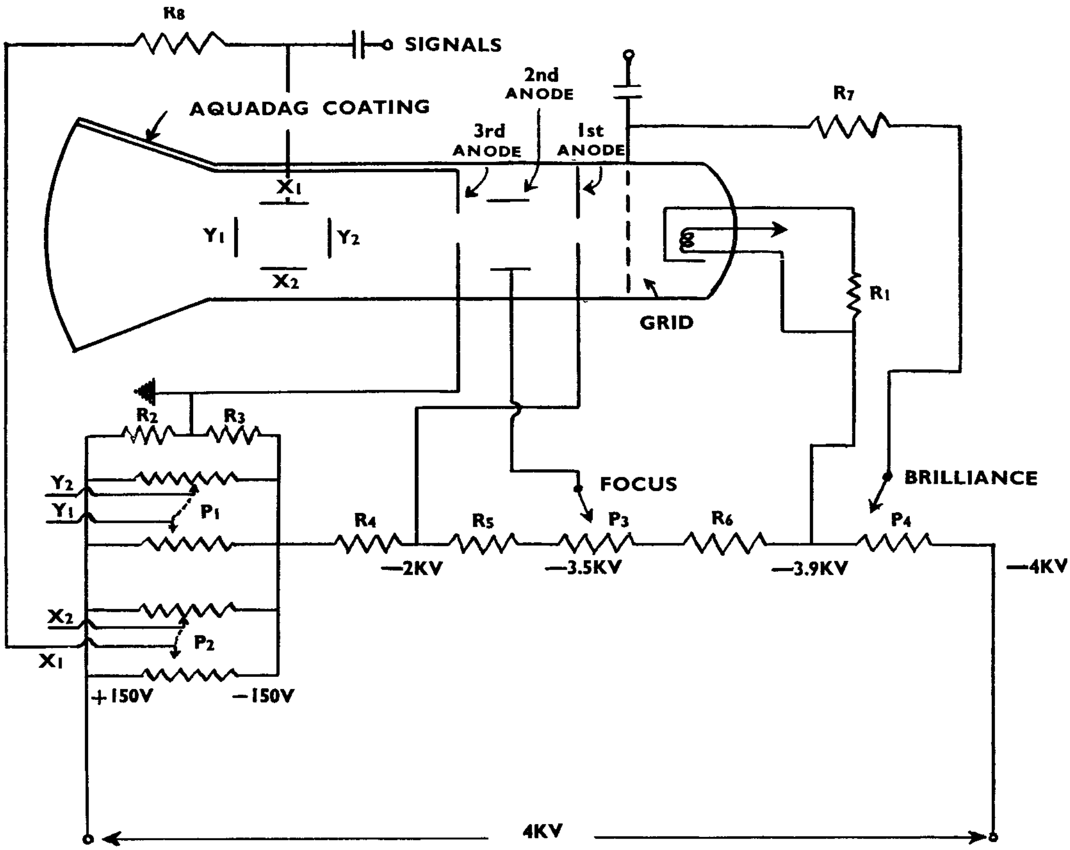


Fig. 19. Circuit Connections to Electrostatic C.R.T.

Electro-Magnetic Focussing

34. The electron gun forms the basis for this type of electro-magnetic C.R.T. The "Aquadag" is often the only form of final anode used, and is therefore extended further down the tube. A second or screen grid is fitted on some electro-magnetic C.R.Ts. to isolate the control grid from the high potential anode section and so increase the sensitivity of the control grid. Because of the absence of large internal deflection and focussing plates the tube can be smaller and of simpler construction.

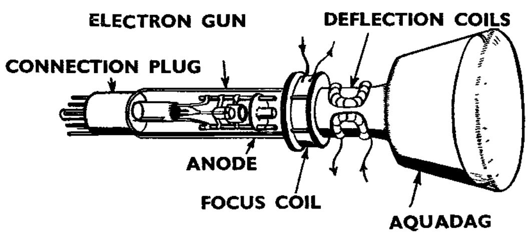


Fig. 20. C.R.T. Employing Magnetic Deflection Coils

The electrons moving very fast are converged into a beam by a focussing coil wound on a soft iron core and mounted around the tube beyond the grid, and strike the screen at the focussing point with maximum speed.

35. When a direct current is passed through the focus coil a magnetic field is set up, mainly parallel to the axis of the C.R.T. Electrons from the cathode will pass through this field at different angles, those travelling parallel to the field being unaffected, while those travelling at an angle to the field will be deflected back towards the axis of the tube. They will all converge on the axis at a point on the screen. In the electrostatic tube many of the electrons are attracted to the first anode and do not reach the screen ; thus for the same amount of power more electrons will reach the screen in an electro-magnetic tube and consequently a brighter spot will be obtained.

Electro-Magnetic Deflection

36. Adjustment of the position of the spot on the screen, as well as the focus, is effected by varying the current through the coil, and by varying the position of the axis of the coil relative

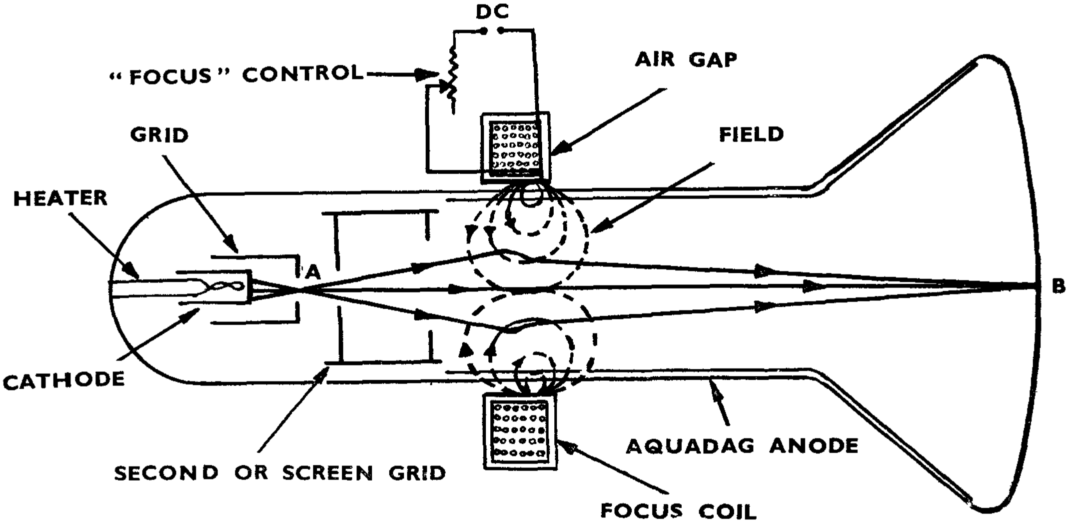


Fig. 21. Diagram of E.M. Focussing Showing Spiralling Beam

to the axis of the C.R.T. One or two pairs of coils, mounted on a circular or square soft iron yoke and placed round the neck of the C.R.T., are supplied with deflection currents. The magnetic fields produced are mainly across the tube and deflect the beam vertically or horizontally depending on which coils are energized. If both coils are energized by a different amount, the spot will move in a direction proportional to this difference under the influence of both magnetic fields. A current to produce a horizontal trace is fed to one pair of coils and a current proportional to the receiver output to the other pair.

Rotating Deflection Coils

37. In some C.R.Ts. designed for a particular purpose, one pair of coils is mounted on a circular yoke that can be mechanically rotated round the tube. By a combination of mechanical movement and variable deflection current, the spot can be moved to any position on the screen. Trace or time-base current is fed to this coil, while the receiver output fed to the grid causes the spot to become brighter when an echo is detected. To obtain the same result, instead of applying a positive signal to the grid a negative signal on the cathode is often arranged.

Note. The focussing and deflection are produced by currents in this C.R.T. whereas a voltage was employed in the electrostatic C.R.T. to produce the same results.

Connections to Supply

38. The methods of connecting the various supply voltages to an electro-magnetic C.R.T. are shown in Fig. 23.

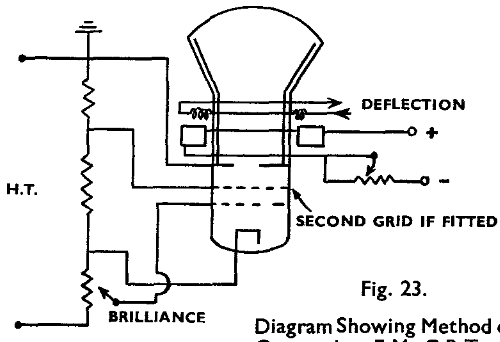


Fig. 23.

Diagram Showing Method of Connecting E.M. C.R.T. to Supply

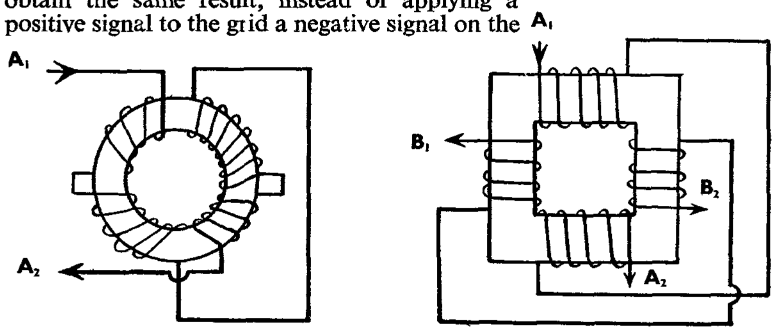


Fig. 22. Types of Electro-Magnetic Deflection Coils

Electrostatic Focussing and Electro-Magnetic Deflection

39. To employ the advantages of both types and reduce the disadvantages, some special C.R.Ts. have the normal electrostatic focussing anodes and the deflection plates are replaced by coils.

Relative Advantages and Disadvantages

40. To summarize the above, the relative advantages and disadvantages of the two types of C.R.T. are listed :—

(*a*) *Electrostatic C.R.T. Advantages.*
  (i) Simple power and deflection circuits.
  (ii) No bulky coils and mechanisms.

(*b*) *Electrostatic C.R.T. Disadvantages.*
  (i) Brilliance of spot is limited.
  (ii) Brilliance is altered when focussing.
  (iii) Size of screen is limited owing to high deflection voltage required.
  (iv) Not robust.

(*c*) *Electro-Magnetic C.R.T. Advantages.*
  (i) Simple and sturdy construction.
  (ii) Bright spot possible.
  (iii) Shorter length than E.S. type.
  (iv) Larger screens possible.

(*d*) *Electro-Magnetic C.R.T. Disadvantages.*
  (i) Special circuits are required to provide deflection current.
  (ii) Power is wasted in resistance of focussing coils.
  (iii) Heavy and bulky, with coils.

Waveforms to Produce a Trace

41. It has been stated that the spot must move rapidly across the screen from left to right, and at a constant speed, to produce the illusion of a steady line. By causing the line to be deflected up or down when the transmitter pulses, and when the echo is detected, the distance between the two deflections can be measured. Provided the speed of horizontal travel of the spot is constant, and synchronized to the transmitter pulses, the distance can be calibrated in miles or yards. It is possible to use a perspex scale, or suitably generated deflections (Pips) spaced equally along the trace.

42. Clearly then, a voltage must be applied to the "X" plates of the electrostatic C.R.T.—or a current to the horizontal deflection coils of the electro-magnetic C.R.T.—that starts to increase when the transmitter "fires" and increases linearly until the spot has travelled to the other side of the screen. The voltage must then fall almost instantaneously to the starting level to allow the spot to "fly back" and be ready to increase again when the transmitter next fires. Such a shape of voltage variation is called a Time-Base Waveform.

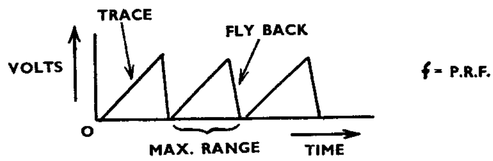


Fig. 24. Time-Base Waveform

43. **Sawtooth Waveform.** The sawtooth waveform, so called because of its shape, is the ideal for a linear time-base. In practice the rise may not be perfectly straight or linear, and the fall or fly back is seldom instantaneous.

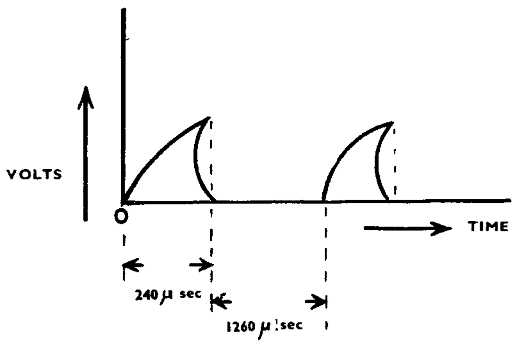


Fig. 25. Sawtooth Waveform

It must be remembered that for certain radar equipments the time is very short indeed. H2S uses a trace 240 microseconds long but the whole cycle occupies 1,500 microseconds. There are therefore 1,260 microseconds occupied by the fly back and waiting period. With an instantaneous fly back the spot would not be seen, but when the fly back is comparatively slow the spot is blacked out during the unwanted period by applying such a large negative voltage to the grid that no electrons reach the screen. The length of the rising portion of the waveform, or sweep, will depend entirely on the maximum range of the equipment and is often adjustable in steps by the range switch.

44. **Haystack Waveforms.** Where deflection is produced by coils, the self inductance of the coil would distort the trace if a normal sawtooth waveform were used. The type of waveform for producing a linear trace with coil deflection is called a haystack waveform and requires rather more complicated circuits for its production.

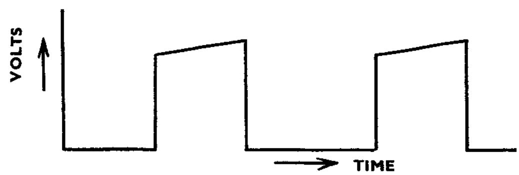


Fig. 26. Haystack Waveform

TYPES OF DISPLAY

The Display as a Picture on the C.R.T.

45. The picture on the screen of the C.R.T. is called a display and the operational requirements of various equipments call for a different presentation of the echoes. A few of the more general types will now be discussed.

Type "A" Display

46. Type "A" is the simplest type and has already been mentioned. It gives an indication of range horizontally in a particular direction. To determine the direction of an object the transmitter radiation is beamed and rotated to scan the area under observation. The blip indicating the object will appear at its maximum height on the tube when the aerial assembly is "pointing" at the object.

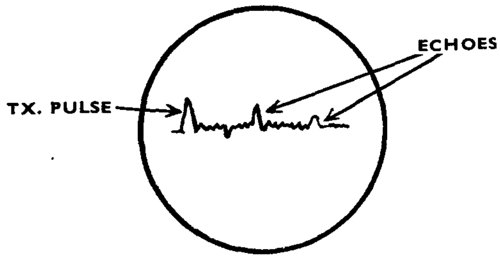


Fig. 27. Type "A" Display

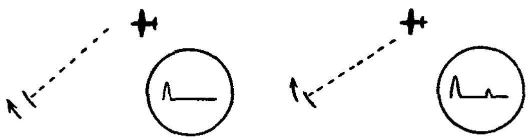


Fig. 28. Type "A" Displays

A particular application of Type "A" display is used in H2S, where the whole tube is rotated through 90 degrees to give range upwards. The radiation from the aircraft aerials in a downward direction will be reflected from the ground, and appears as first ground returns.

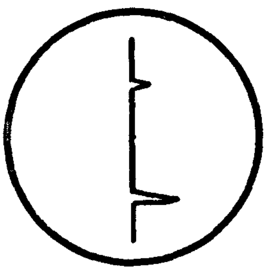


Fig. 29. Vertical Trace

The visual scale used in conjunction with this presentation is calibrated in thousands of feet, and indicates the height of the aircraft above the ground immediately beneath.

Type "L" Display

47. This is really a combination of two Type "A" displays back to back, and the tube is again turned through 90 degrees to give range upwards.

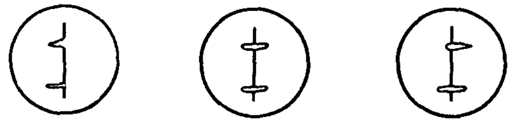


Fig. 30. Type "L" Displays

The Type "A" display will indicate only range, but the Type "L" will indicate range upwards, and the relative variation of the size of the "blip" on either side of the vertical trace will indicate the deviation to left or right from an object towards which the aircraft is heading. In practice, Secondary Radar is used if the object is a beacon and the aircraft equipment (REBECCA) triggers the beacon into operation. The pulse from the beacon is detected by the aircraft equipment as a much stronger signal than an ordinary echo. To produce this kind of display two receiving aerials are used. One aerial is mounted on each side of the aircraft (usually underneath the main plane). Signals from these aerials are fed through the receiver to the vertical deflection ("Y") plates of the C.R.T. By alternately switching the aerials to the receiver and at the same time switching the output off from the receiver to one or other of the "Y" plates, signals from the port aerial are fed to the left deflection "Y" plate and signals

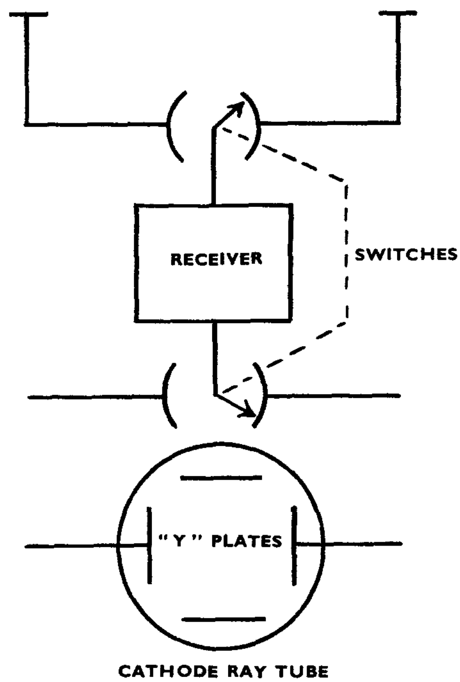


Fig. 31. Ganged Aerial Switching

from the starboard aerial to the right deflection plate. The receiving aerials have maximum sensitivity in the forward area and in directions to port and starboard of the line of flight. When the aircraft is headed towards the beacon each aerial will detect the same strength of signal, and blips on the C.R.T. will be equal. When the aircraft heading is to port the starboard aerial will receive the strongest signal, and the blip on that side of the tube will be larger, while the other becomes smaller. It is used for homing onto a beacon.

Type "M" Display

48. To enlarge the scale and range of the C.R.T. the Type "A" display can be extended beyond the screen, chopped off, and made to appear below the first part of the trace.

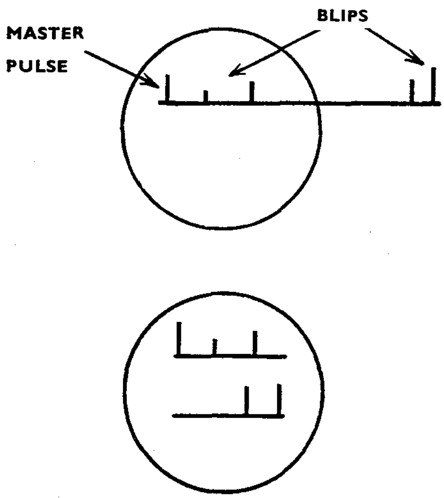


Fig. 32. Split Presentation

This principle is used in GEE where very accurate range measurements are required. To make these measurements easier, a specially formed downward deflection, or *strobe marker*, used to select a particular echo, is adjustable along each trace. The strobes are adjusted separately to bring the blips accurately within each strobe, and a special scale is incorporated to read off the exact position of each strobe in relation to the master transmitter pulse. The time interval between, and therefore the distance, will give the range of the beacons producing the blips far more accurately than normal methods.

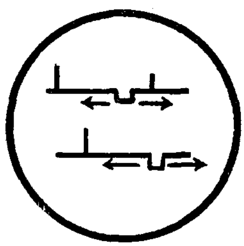


Fig. 33. Strobe Marker

Type "P" or "PPI" Display

49. When it is desired to present a complete picture of the ground area below and beyond the aircraft, a plan position indicator is used. In this case a trace is produced that starts at the centre of the C.R.T. and travels outwards towards the edge. The whole trace is steadily rotated at a definite rate so that after one complete revolution the whole face of the screen has been covered by the spot. A special C.R.T. is used, with a screen having a long afterglow. This means that the screen still glows slightly even after the spot has passed on, and the screen therefore appears to have a slight glow all the time.

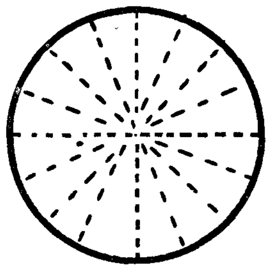


Fig. 34. Rotating Time-Base

Fig. 35. P.P.I. Display

(*a*) *Aerial.* The aerial is designed to produce narrow radiation pattern in azimuth, with the elevation radiation pattern depressed below the horizontal. The angle of depression may be made adjustable. The aerial or scanner rotates through 360 degrees in synchronization with the trace, and so scans, or illuminates, a large area of ground below with the aircraft at the centre. Any object on the ground, depending on its reflecting properties, gives an echo that appears on the screen as a brighter spot or area, and in position corresponding to its ground position relative to the aircraft, with range measured radially from the centre outwards. This is arranged by feeding the signals from the receiver to the grid of the C.R.T. to vary the intensity of the beam from the strength of the echoes. The brilliance of the screen illumination is adjusted so that only the echoes paint a picture on a darker background.

CHAPTER 14

TYPICAL RADAR LAYOUT

Introduction

1. It should now be possible to consider in more detail the various basic components of a complete radar installation. These are :—

(*a*) Transmitter.

(*b*) Receiver.

(*c*) Indicator.

(*d*) Timing device.

(*e*) Aerial with T.R. and anti-T.R. switch.

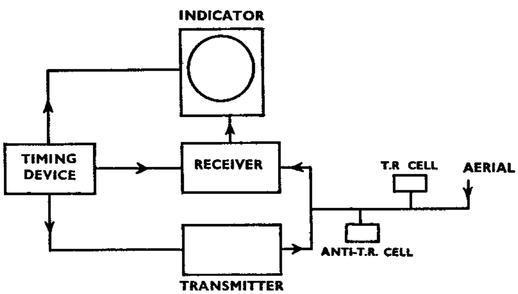


Fig. 1. Basic Radar Installation

TRANSMITTER

2. The transmitter consists of an oscillator designed with a high degree of stability, and some form of modulator to cause the oscillator to work in short bursts so producing the characteristic pulses of R.F. energy.

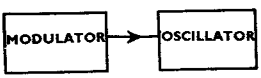


Fig. 2. Basic Radar Transmitter

Early radar experiments were made within the only available frequency band that was of any use for radar, *i.e.* 20 mc/s to 80 mc/s (15 metres to 3·75 metres). Frequencies lower than this were found to be unsuitable because of the large aerial arrays necessary, and the poor reflecting properties of aircraft wings and fuselages at lower frequencies. The many problems associated with the production of oscillations at much higher frequencies had not then been overcome, and so we find even now equipment developed in the early days working in this frequency band. C.H. and GEE are examples (GEE is not true radar).

Low-Frequency Oscillator

3. The type of oscillator employed in this band is generally the tuned-anode tuned-grid with a push-pull amplifier following. Valves are made with filaments capable of delivering a considerable current for the very short periods of time they are operating. The electrodes are usually large, well spaced to handle the high potential difference without "flash over", and air cooled. To improve the stability of the oscillations, push-pull circuits are used throughout and Class "C" conditions of bias maintain the maximum efficiency from the transmitter.

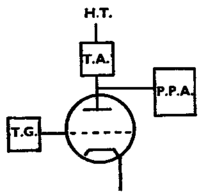


Fig. 3. Low Frequency Oscillator

4. A continual search for smaller aerial arrays capable of being rotated, and the inclusion of more R.F. cycles of oscillation into narrower pulses, led to the use of the 200 mc/s (1·5 metres) band. A half-wave dipole at this frequency would be about 75 centimetres, or 30 inches, long. A narrow pulse of 1 microsecond duration is practical in this band.

High-Frequency Oscillator

5. At frequencies above 100 mc/s, the valve inter-electrode and stray capacitance and inductances are large enough to prevent conventional circuits from tuning to resonance. In addition, the losses in coils and capacitors become so large that the magnification or "Q" of the circuit is low. These losses are :—

(*a*) $I^2 R$ heat losses.

(*b*) Dielectric losses.

(*c*) Radiation losses.

Specially designed low-loss valves and components are therefore necessary. In addition, R.F. amplification is difficult to achieve. The T.A.T.G. oscillator in push-pull is still used, but in place of normal tuned circuits consisting of inductor and capacitor a lecher line system is used.

Tuned Line Oscillator

6. A pair of parallel lines, short-circuited at one end, and fed at the open end with a voltage of the frequency at which the line is resonant, will respond in a manner similar to that of a parallel resonant circuit. The lines are adjusted so that with all stray capacitance and inductance they behave as a resonant $\frac{1}{4}$-wave line.

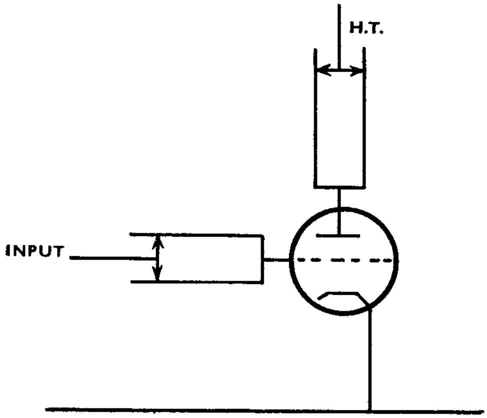


Fig. 4. Tuned Line Oscillator

If both the anode and grid circuits of a push-pull oscillator are replaced by tuned parallel lines, oscillation can be easily maintained at high frequencies.

Adjustment of Frequency

7. The adjustments of frequency and for matching are made by moving sliding shorting bars and the variable taps along the lines. In practice the lines need not be straight, and for economy of space and ease of adjustment are bent into an arc of a large radius (see Fig. 5). This type of oscillator can be used quite conveniently up to about 600 mc/s (0·5 metres), but beyond this frequency, in the centimetre bands, a different technique is necessary.

Modulator

8. The modulator is used to switch, or trigger, the oscillator on and off, thus producing pulses of R.F. at the correct P.R.F. and of correct width. In some equipments the modulator is itself triggered at the P.R.F. by the timing circuits, while in others the modulator is used for triggering the oscillator and also for timing the other circuits in the receiver and indicator. In general the modulator produces a square voltage waveform of the correct width and at the correct time. This is fed to the oscillator allowing it to draw current only during the pulse period.

RECEIVER

Superheterodyne Receiver

9. The superhet type of receiver is generally used in radar equipment. It must be carefully designed for pulse working, and must possess certain characteristics essential to preserve the pulse shape.

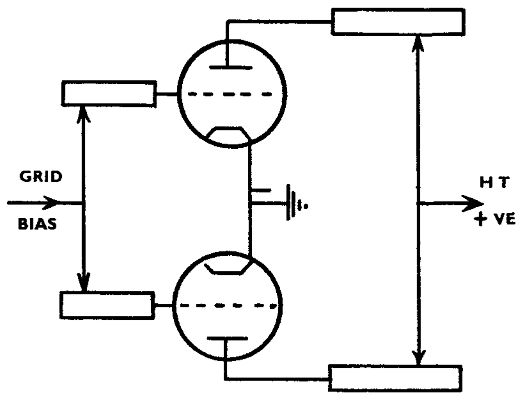


Fig. 5. Push-Pull Tuned Line Oscillator

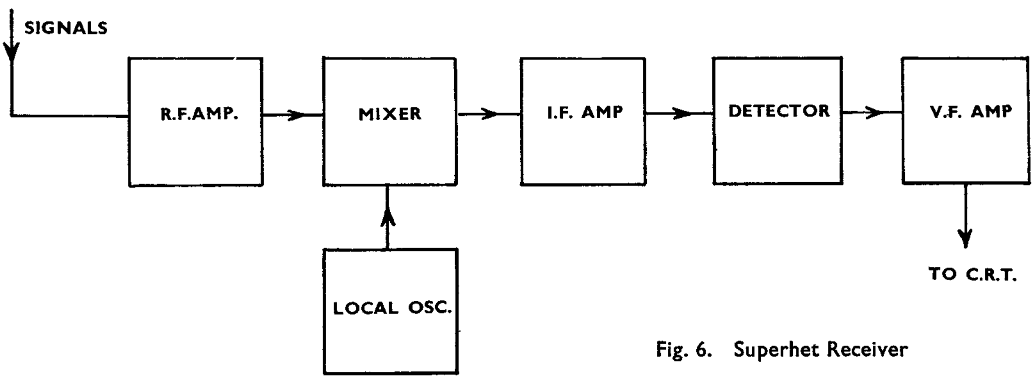


Fig. 6. Superhet Receiver

For a receiver designed to pick up echoes on 200 mc/s the output of the R.F. amplifier is mixed with a steady 155 mc/s oscillation from the local oscillator in the mixer stage. The resultant 45 mc/s output is amplified in the I.F. stage and, after detection, appears as a square wave form at the P.R.F. of the transmitter. This voltage is amplified in the video amplifier, so called because it is designed to handle a larger band of frequencies than an audio amplifier. The amplified waveform is now passed out of the receiver by coaxial cable to the indicator via the output matching stage. This stage acts as a "distortionless transformer" between the high impedance of the video amplifier and the low impedance coaxial cable.

Bandwidth

10. If an exact reproduction of the pulse shape is to be obtained on the indicator screen, the receiver must be sensitive to the whole range of frequencies carried by the pulse. Thus it follows that the signal frequency and I.F. stages of the receiver must have very broad band-pass characteristics. In order to pass a recognizable pulse of 1 microsecond width, the signal and I.F. circuits must have a band-pass characteristic of at least 4 mc/s. For example, a receiver designed to work with a transmitter producing 1 microsecond pulses at 200 mc/s must pass all frequencies between 198 mc/s and 202 mc/s.

Sensitivity

11. The echoes received are very weak, and a high sensitivity is necessary in the receiver. This requires extra stages of amplification. Amplification at frequencies above 700 mc/s is difficult to achieve, and so the greater part of the amplification necessary takes place in the I.F. stages where the frequency is lower (45 mc/s). Where possible the addition of an R.F. amplifier will improve the signal-to-noise ratio.

I.F. Stages

12. As a standard practice, the I.F. used in radar sets is 45 mc/s irrespective of the radar frequency in use. To even out the response curve of circuits tuned to 45 mc/s, to cover a band of 4 mc/s, special circuit arrangements are necessary, as follows :—

(*a*) Damping resistors are connected across the I.F.

(*b*) Successive stages are detuned to each side of 45 mc/s.

(*c*) Tight coupling is used between tuned circuits producing a "double hump" response curve.

In practice a combination of all three methods is frequently found.

Noise

13. The high degree of amplification in the I.F. stages will be given equally to the signal and any "noise" voltages produced in the first stages. These are similar to voltages producing "background mush" on a broadcast receiver, but they appear on the C.R.T. screen as random deflections or bright spots, and are called "grass".

14. To reduce this interference to a minimum, while maintaining the signal amplitude, the R.F. stages (if used), and to a lesser extent the mixer of the receiver, are specially designed to produce the minimum noise voltages. Separate oscillator stages are invariably used owing to the high noise voltages produced in a frequency changer type of valve. In the centimetre band special oscillator valves are required.

Distortionless Detector

15. To preserve the pulse shape the detector is usually a diode, and is designed to pass frequencies from 0 to 2 mc/s with equal amplitude and minimum phase distortion. Naturally no amplification is possible with a diode, and in fact the detection stage in a radar receiver always has a gain of less than 1. The output pulse is then amplified by the video amplifier having a response curve which is fairly flat over a wide band of frequencies from 0 to 2 mc/s.

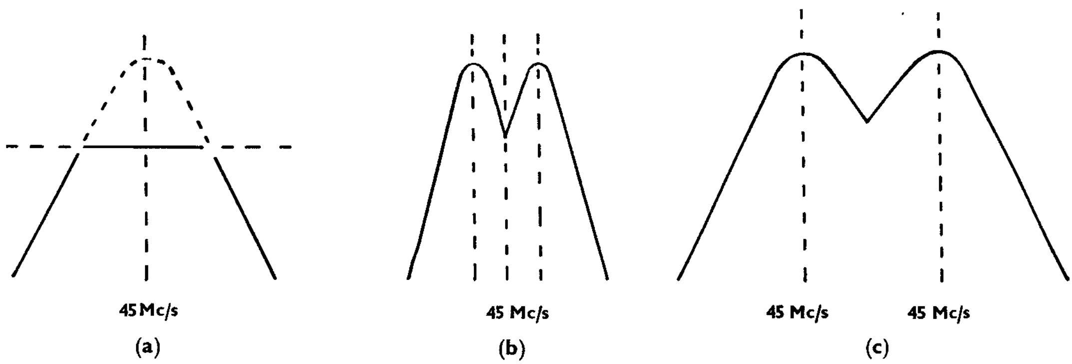


Fig. 7. I.F. Response Curves

Output Matching

16. In most installations the receiver is separate from the indicator and the signals, etc., are fed to the indicator via a coaxial cable. All coaxial cables will have some natural capacity, and unless special precautions were taken the square pulse shape would be distorted in the cable. Simply stated, the output from the receiver is taken at a low impedance level, so that the shunting effect of any low reactance capacity will be at a minimum. The circuit used to provide such a low impedance output could be a transformer but that itself would introduce distortion, and so a cathode follower circuit is used.

Head Amplifier

17. Where the transformer and receiver units are separate, it is often the practice to convert the received signals to the I.F. and amplify them in the transmitter unit. This ensures a high signal/noise ratio to feed to the main I.F. amplifier stages through a coaxial cable. If the signals from the common aerial were fed from the T.R. switch—usually mounted in the transmitter unit—straight into a cable, a certain amount of extra noise voltages would be generated, and the already weak signal would be still weaker. This would result in a low signal/noise ratio. In practice, the local R.F. oscillator, the mixer, and one or two stages of I.F. amplification, are contained in a head amplifier in the transmitter unit. An output matching stage feeds the amplified 45 mc/s signal to the main receiver I.F. strip.

Interference and Selectivity

18. The range of most radar equipment is intentionally limited, so that echoes produced by other installations on the same frequency but outside that range will not affect the working of the equipment. Echoes on the same frequency and within the operational range of the equipment would not be locked to the same P.R.F. as the indicator time-base, and would not therefore remain on the screen. Selectivity is therefore the least important factor in a radar receiver, and, as already stated, it must be sufficiently low to pass a band of 4 mc/s width. The losses in the R.F. circuits at high frequencies are sufficient to damp the tuning and flatten the response curves.

INDICATOR

19. The indicator consists essentially of a cathode ray tube, with the associated time-base, locking, and amplifier circuits. The power supplies are sometimes incorporated in the same unit. The signal voltages fed to the indicator from the receiver will consist of :—

(*a*) Noise.

(*b*) Transmitter pulses.

(*c*) Echoes.

The noise voltages, being interference, are reduced as far as possible by careful receiver design. The transmitter echo pulses are larger in amplitude and will occur with regularity at the P.R.F. of the equipment. The whole train of voltages is fed to the grid or cathode of a C.R.T. for brilliance modulation, and it appears as bright marks along the trace. Alternatively, the voltages can be fed to the "Y" plates of the C.R.T., and appear as deflections at right angles to the trace.

Time-Base

20. The trace on the C.R.T. is produced by the time-base generator. To prevent C.R.T. distortion, and to give an adequate voltage for the trace, a push-pull time-base voltage is often used. This is obtained from some form of time-base generator followed by a para-phase amplifier. The exact shape and time occupied by the trailing edge of the time-base waveform is unimportant, for this represents the fly back and waiting period before the next pulse occurs. During this time the C.R.T. is blacked out by a large negative voltage on the grid which cuts off the electron beam. This blackout pulse can be replaced by a positive voltage to brighten the C.R.T. during the period of the trace only. These pulses are usually provided from the same square wave generator that supplies the time-base generator, as both are correlated in time. The square wave generator is usually triggered from the master oscillator that supplies the synchronizing pulses for the whole equipment and thereby locks all circuits to a common P.R.F. Typical waveforms for the whole chain are shown in Fig. 9.

Calibration System

21. Some form of transparent range scale is mounted over the face of the screen in certain installations ; or alternatively a series of calibration pips are generated electronically and fed to the C.R.T. together with the signals, or switched in separately, and appear as brighter spots or deflections. These pips are used to simplify reading off ranges, and to be accurate they must be locked to the start of the time-base.

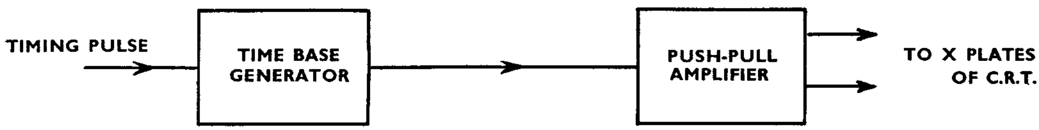


Fig. 8. Push-Pull Time-Base Generator

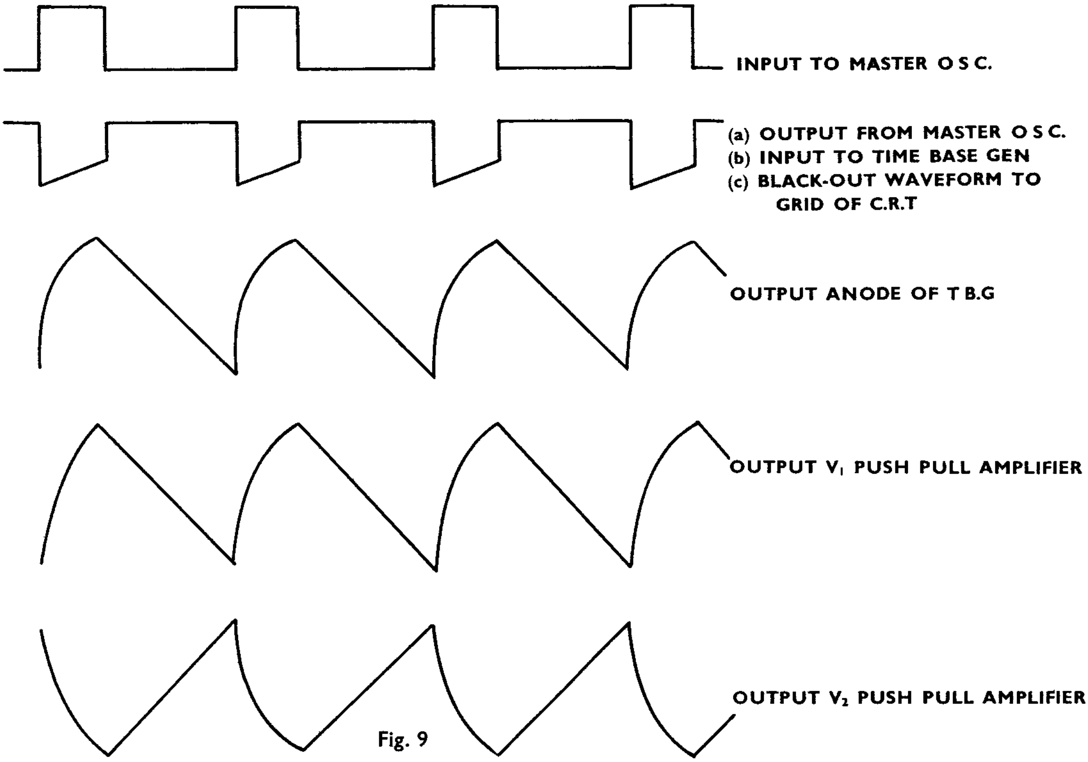


Fig. 9

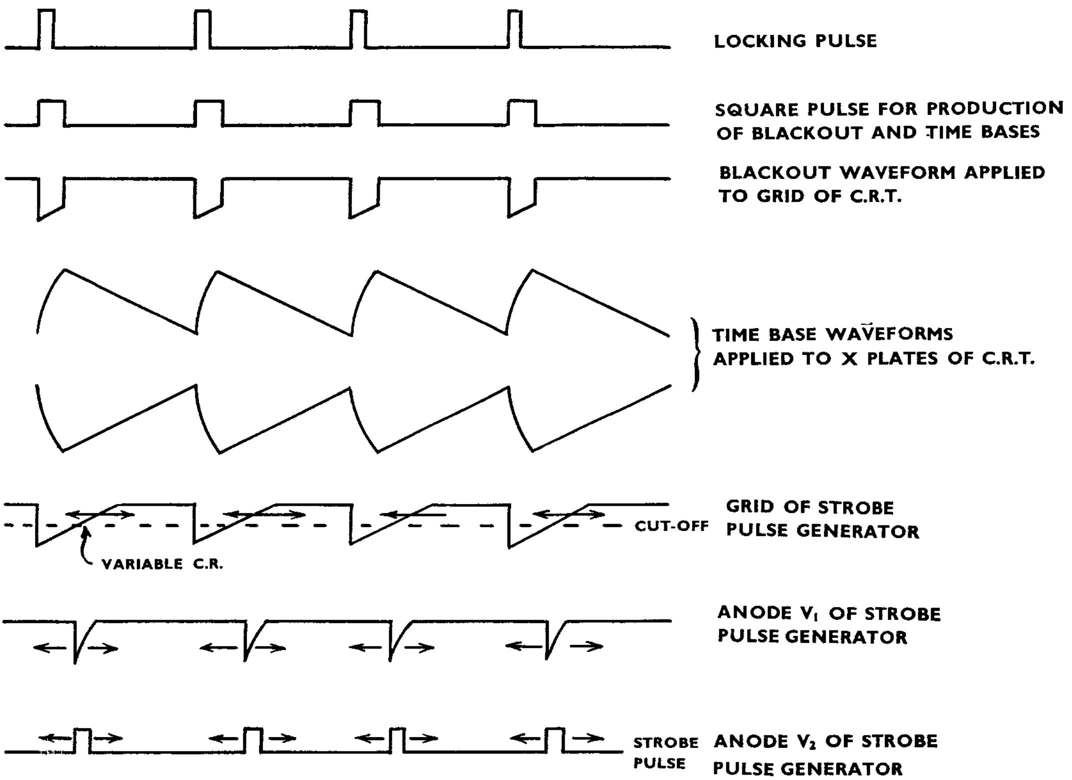


Fig. 10. Calibration Pips

The same square wave that controls the start of the time-base also controls an oscillator. This oscillator starts up at exactly the same instant each time, and stops when the time-base has finished. The frequency of the oscillator will depend on the distance between range marks. Pips are produced in a shaping circuit from the peaks of the oscillator output.

22. Calibration pips every five miles will be spaced apart by :

$$\frac{5 \times 2 \times 1{,}000}{186{,}000} \text{ milliseconds}$$

$$= \frac{1}{18 \cdot 6} \text{ m/s}$$

$$\text{P.R.F.} = 18 \cdot 6 \times 1{,}000 = 18 \cdot 6 \text{ kc/s.}$$

Synchronizing Circuits

23. To secure the necessary locking between the time-base and the calibration pips, both are timed from the master oscillator in the timing circuits. When strobe markers are used they are given an adjustable delay to make them move along the trace, but they too are locked in relation to the time-base P.R.F. and are therefore controlled in time by the master oscillator. The whole chain of special circuits used for timing the transmitter receiver, indicator time-base, and calibration circuits, is often contained within the indicator unit ; but may, in complicated equipment, form a separate unit.

AERIAL

Function of the Aerial

24. This highly important component is dealt with more fully elsewhere, but a brief idea of its functions in relation to the other components is necessary at this stage.

25. The R.F. oscillator in the transmitter unit produces bursts of R.F. energy with considerable peak power during the bursts. To obtain the largest echo from an object at the maximum range of the equipment the whole of this energy should be directed towards the target. The returning echo will be very much weaker, and to pick up this echo the aerial must be extremely sensitive and free from losses.

Common Transmitter and Receiver Aerial

26. It is now common practice to utilize one aerial which is switched to the transmitter while it is producing the burst of R.F. and then switched to the receiver to detect any returning echoes. The polar diagram of an aerial array is the same when used for receiving or for radiating ; thus the receiving aerial is exactly aligned to receive echoes in the same direction as the radiated pulse. The requirements for a radar aerial can be summarized as follows :—

(*a*) The polar diagram should have a high radiation (and sensitivity) in a required direction, with minimum radiation in the unwanted directions.

(*b*) Losses introduced should be at a minimum.

(*c*) It should be capable of handling the high transmitter output at one instant, and detecting the weak echo at the next instant.

Feeder Line

27. It is seldom possible to have the aerial positioned by the transmitter and connected directly to it, so some form of feeder line is used to feed R.F. between the aerial and the transmitter or receiver. This feeder line must also be capable of handling the maximum transmitter power and the weak echo without introducing loss to either.

CHAPTER 15

BASIC RADAR CIRCUITS

TIME CONSTANT

Charging a Capacitor

1. Practically all the special circuits used in radar make use of the voltage waveform obtained when a capacitor is charged through a resistor. Immediately an input voltage is applied to a resistance and condenser in series, there will be no charge on the condenser and so the full voltage applied will appear across the resistance. The capacitor will start to charge at a fast rate, but as the charge builds up a voltage across C in opposition to E the charging current decreases ; therefore the charging rate will fall. In theory the capacitor never fully charges ; but after a certain interval of time, when the voltage across it has risen to 99·3 per cent. maximum, for all practical purposes it is considered charged. As the voltage builds up across C, charging current decreases and therefore the voltage across R will fall. The sum of VC and VR must at all times equal the input E, so that the curve for VR is the same shape as that for VC but falling as VC rises. These curves are illustrated in Fig. 1.

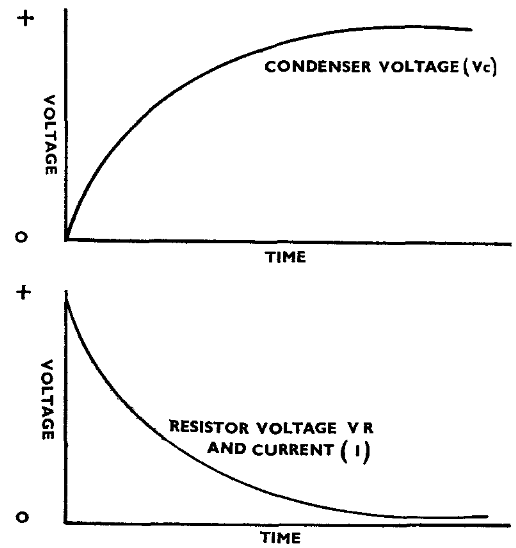


Fig. 1. Curves Illustrating the Charging of a Capacitor

Discharging a Capacitor

2. Until the input is disconnected, the circuit conditions will remain constant with no charging current, no voltage across R, and the full input dropped across C. Now suppose the input is removed and the bottom of R shorted to the left-hand plate of C. The capacitor will start to discharge through R setting up a discharging current, opposite in direction to that of the original charging current. This will cause a voltage drop across R, of opposite polarity to that previously indicated during the charging process, and equal in amplitude to VC. The initial high rate of discharge of C will not be maintained because the charging current falls as VC falls. The capacitor becomes discharged for all practical purposes after a certain interval of time, and then the circuit remains static with no current or voltage anywhere. An exponential curve, as shown above, illustrates the amplitude of voltage across C or R at any time ; but calculations using these curves are involved.

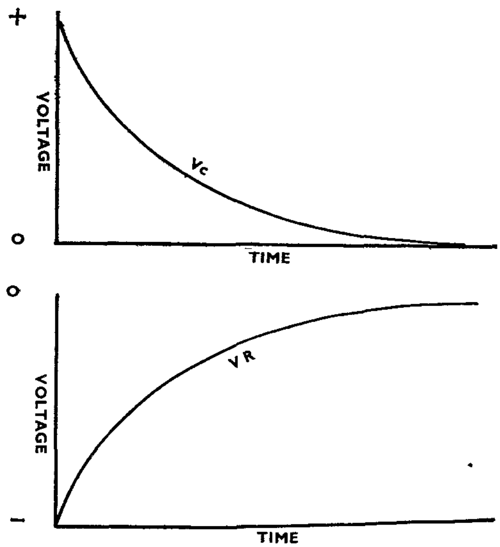


Fig. 2. Curves Illustrating the Discharging of a Capacitor

Expression for Time Constant

3. From the mathematical expression for a voltage rising exponentially it can be shown that the capacitor will have reached approximately $\frac{2}{3}$ full charge in a time equal to the product of capacitance C in farads and resistance R in ohms. The answer in seconds is called the time constant of the particular circuit.

4. The time constant of any capacitor and resistor in series can be defined as the time taken for the voltage across the capacitor to reach 63·2 per cent. (or about $\frac{2}{3}$) of full charge.

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Expressed as : T (in secs.) = C (in Farads) × R (in Ohms).

For convenience of calculation : T in secs. = C in Microfarads × R in Megohms.

This formula T = CR is a fundamental factor in radar circuitry and has a significant effect on the circuit to which it is applied. For example :

What value of resistor is required to produce a Time Constant of 2 millisecs. with a capacitor of ·002 p.F. ?

$$T = C \times R \qquad C = \cdot 002 \text{ p.F.}$$

$$T = \cdot 002 \text{ Secs.}$$

$$R = ?\ M$$

$$R = \frac{T}{C} = \frac{1}{1} = 1\ M$$

Application of a Square Waveform

5. Now consider, instead of a D.C. supply, an input to the C.R. circuit consisting of a series of pulses of square waveform. During the time the pulse is applied, the capacitor has time to charge to $\frac{2}{3}$ full charge ; at which time the input falls to zero. The capacitor will now discharge at the same rate, and having a much longer time interval available before the next pulse is applied will therefore discharge completely (for all practical purposes). Each successive pulse is a repetition of this action ; the resultant waveform is shown in Fig. 3. The voltage tapped from the capacitor is known as the *Integrated* output, while an output from the resistor is called the *Differentiated* output. Note that VR is at all times equal to E − VC.

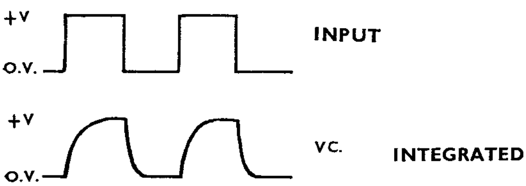


Fig. 3. Input to C.R. Circuit

Output Waveform

6. The amount by which the input is distorted will depend on the relationship between the time constant, the time duration of each pulse, and the time interval between pulses. If the period between pulses is 500 microseconds, the capacitor would not have time to discharge fully between pulses and the output would be a different shape.

Medium and Long C.R. Values

7. If the C.R. time is approximately equal to the time period of one pulse (or ½ cycle if symmetrical) it is called a medium C.R. An example of this waveform is shown in Fig. 4, but has little practical value. If the C.R. time is appreciably longer, *e.g.* three or more times the time period of one pulse, it is called a long C.R.

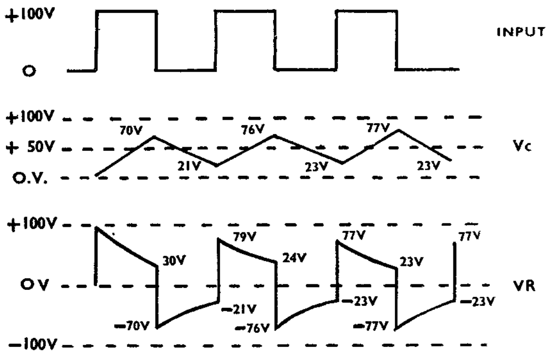


Fig. 4. Medium C.R.

8. In a time equal to $\frac{1}{10}$ of the C.R. time, the capacitor acquires very little charge, therefore the voltage across the resistor is almost constant. The time available before the next pulse occurs is sufficient for the capacitor to discharge completely. If the pulses were spaced by 500 microseconds (or a symmetrical square wave) the capacitor would not discharge completely, and each succeeding pulse would leave the capacitor with a little more charge until the waveform settled down to a mean level of charge equal to the mean of the input voltage. In these conditions the voltage across the resistor follows the input shape, but with a mean potential of zero.

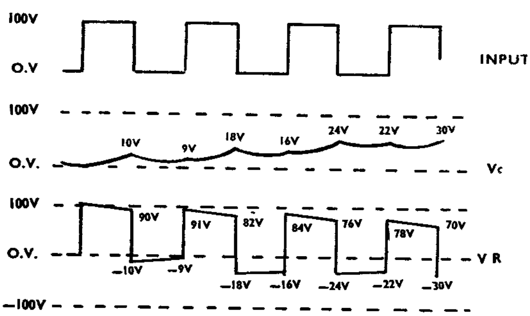


Fig. 5. Long C.R.

9. If the time constant is made very long compared with the input time the output across R is the same as input E. An obvious use for this type of circuit is in coupling between successive stages when distortion of the waveform is not wanted.

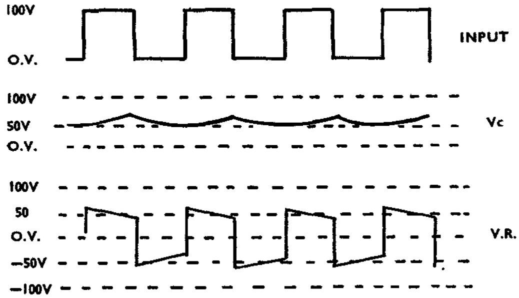


Fig. 6. Long C.R.—Steady Conditions

Short C.R.

10. A combination of C.R. found in many radar circuits is called a short C.R., in which the time constant is $\frac{1}{5}$ or less of the time duration of the input pulse. The combination of capacity and resistance having a time constant of 50 micro-seconds will produce the waveforms shown as VC and VR (Fig. 7). The capacitor can charge

Fig. 7. Differentiated Short C.R.

to $\frac{2}{3}$ full charge in the first $\frac{1}{10}$ of the input pulse, and therefore the voltage across the resistor falls quickly to zero giving rise to a well-known "peaky wave-form". The negative peak in the VR waveform caused by the input falls instantaneously to zero whilst the capacitor still retains its charge. No matter how quickly the capacitor discharges, initially the whole of its voltage will be reflected as a negative voltage across R quickly rising to zero. Remember that VC+VR must always equal E. This negative going peak or "pip" is often a useful output for timing circuits, as it conveniently occurs at the same instant as the "trailing" edge of the input pulse.

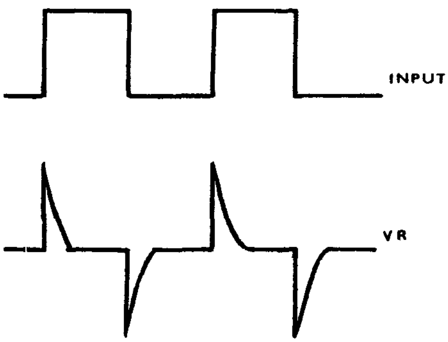


Fig. 8

Limiting

11. In Fig. 9 the positive going pulse has been removed to leave only the negative going pulse. Some variation of this removal action is common in radar and is effected by a *limiter circuit.*

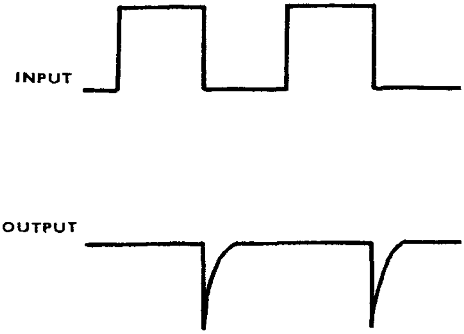


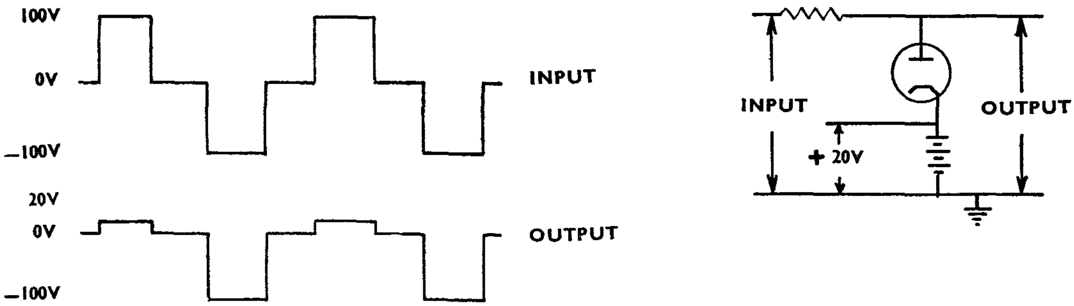
Fig. 9

Action of the Diode

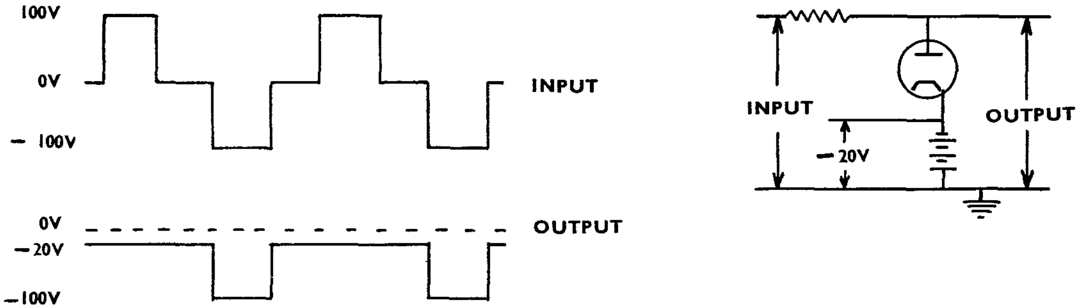
12. The property of a diode valve in having a high impedance in its non-conducting direction compared with a low impedance in its conducting direction is used here. When the positive going pulse is applied to the circuit the cathode of V is made positive with respect to its anode, the valve is inoperative, and therefore the greater proportion of the voltage is dropped across the load R. This explains the very small positive pip on the waveform, which is due to valve inter-electrode and stray wiring capacities. During the period of the negative going pulse, the diode conducts, and, offering a low impedance in this direction, only a very small proportion of the negative pulse is dropped across the valve, the majority appearing at the output across R. By reversing the diode connections the negative pulse can be limited, leaving only the positive going pulse. (*See* Fig. 11.)

Limiting to a Potential

13. It may be necessary to limit all pulses to a particular level to prevent overloading, or to provide a definite value of trigger voltage. This can also be achieved by a limiter circuit, biased to the voltage limit required. The cathode of the diode is made positive with respect to anode by a preset voltage tapped off from the H.T. supply via R2 R3. The valve is therefore inoperative, and the output waveform appears across its high impedance. When the input pulse exceeds in amplitude the bias on the valve, the latter conducts and no further increase of output waveform is possible.

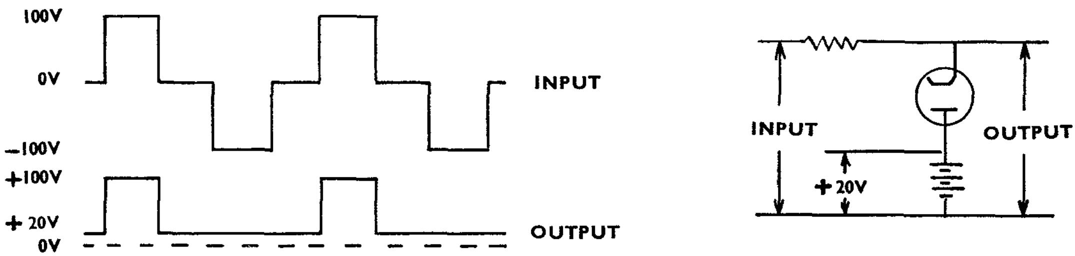


(a) LIMITING AT A POSITIVE POTENTIAL

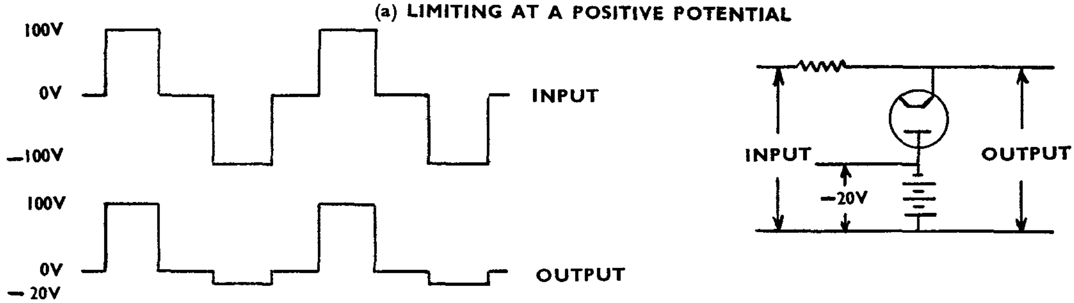


(b) LIMITING AT A NEGATIVE POTENTIAL

POSITIVE LIMITING BY A PARALLEL DIODE CIRCUIT



(a) LIMITING AT A POSITIVE POTENTIAL



(b) LIMITING AT A NEGATIVE POTENTIAL

NEGATIVE LIMITING BY A PARALLEL DIODE CIRCUIT

Fig. 10. Positive and Negative Limiting by a Parallel Diode Circuit

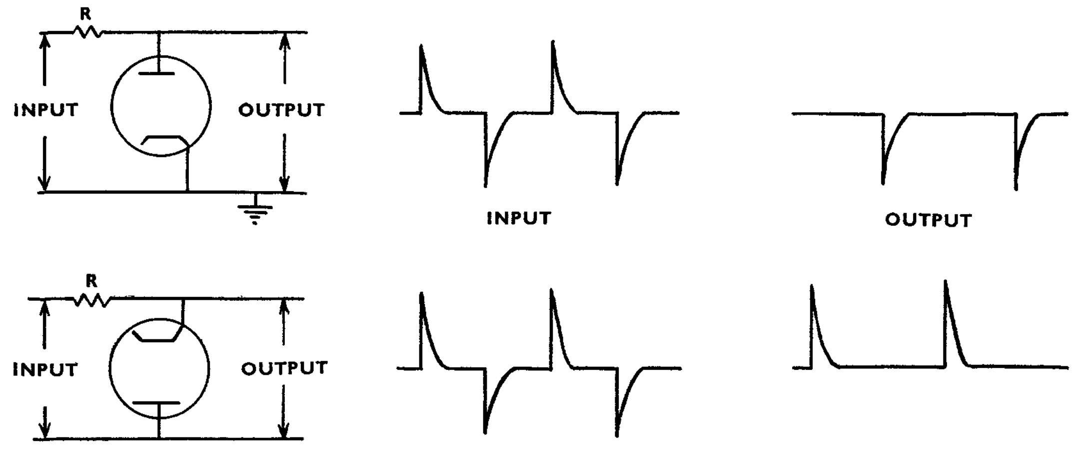


Fig. 11. Effect of Diode

Limiting a Sine Wave Output

14. A sinusoidal input applied to a similar circuit can have the peaks squared off, but where such a circuit is employed to produce a square wave a triode or pentode usually replaces the diode, and both top and bottom are squared in the same circuit (Figs. 12 and 13).

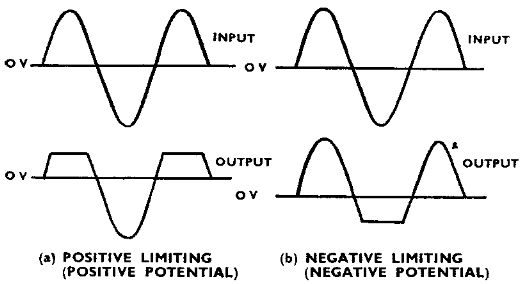


Fig. 12

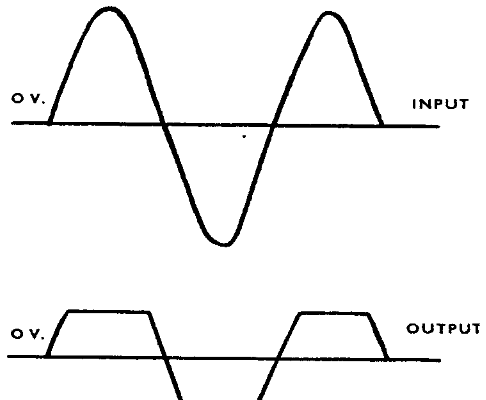


Fig 13.

The positive peaks are limited by grid current, aided by the grid stopper resistor R ; while the negative peaks fall below the grid base of the valve and thereby are also limited.

Further Applications of Limiting

15. Other uses of limiting circuits are :—
(*a*) Selecting particular pulses (Fig. 14).

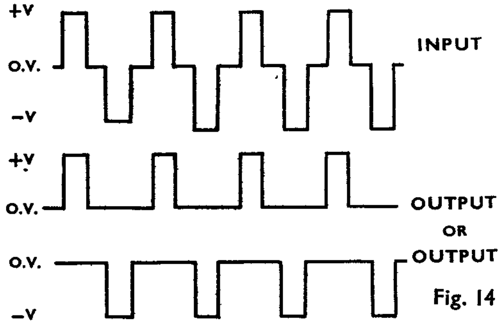
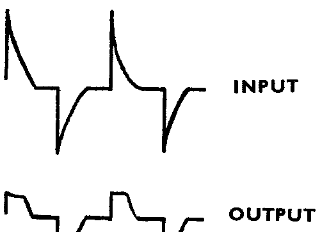


Fig. 14

(*b*) Removing unwanted distortion in waveform (Fig. 15).



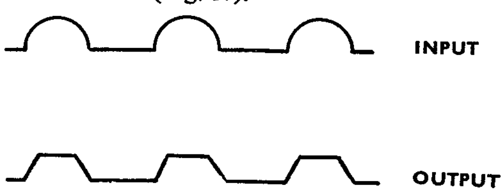


Fig. 15

(*c*) Producing a square shaped waveform from a peaky wave (Fig. 16).

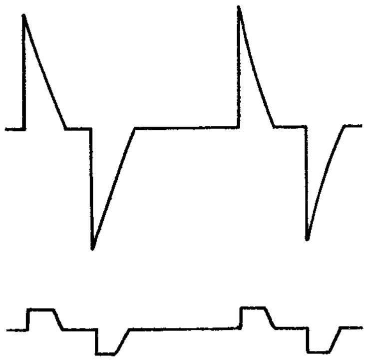


Fig. 16

A point to note here is that if the time constant of the C.R. network producing the peaky wave is varied, then the width of the output square wave can be varied likewise (Fig. 17).

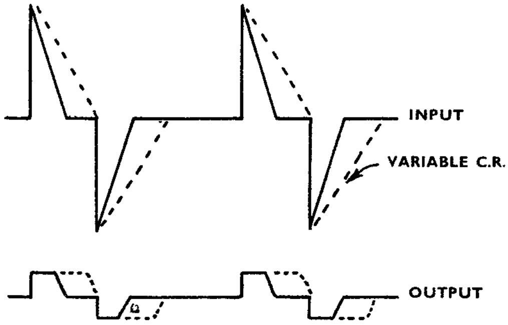


Fig. 17

Clamping

16. When using a long C.R. as coupling between stages, the output across R is almost identical to the input waveform, but the mean level is changed to zero (see Fig. 5). This variation of the mean level of a waveform is often undesirable, and to prevent it the positive or negative output peak is *clamped* to a particular level: (*a*) to earth, (*b*) to a positive voltage, (*c*) to a negative voltage, (*d*) to a base line potential, or (*e*) to a peak potential. The particular reference level chosen will depend on the requirements of the whole circuit. For example, a bright-up waveform for a C.R.T. having three different ranges, produced from three different ratios of square wave, is shown in Fig. 18. It will be obvious that each wave in the output waveform, although similar in amplitude, rises above the mean level by a different amount. The result will be a brilliance differing on each range.

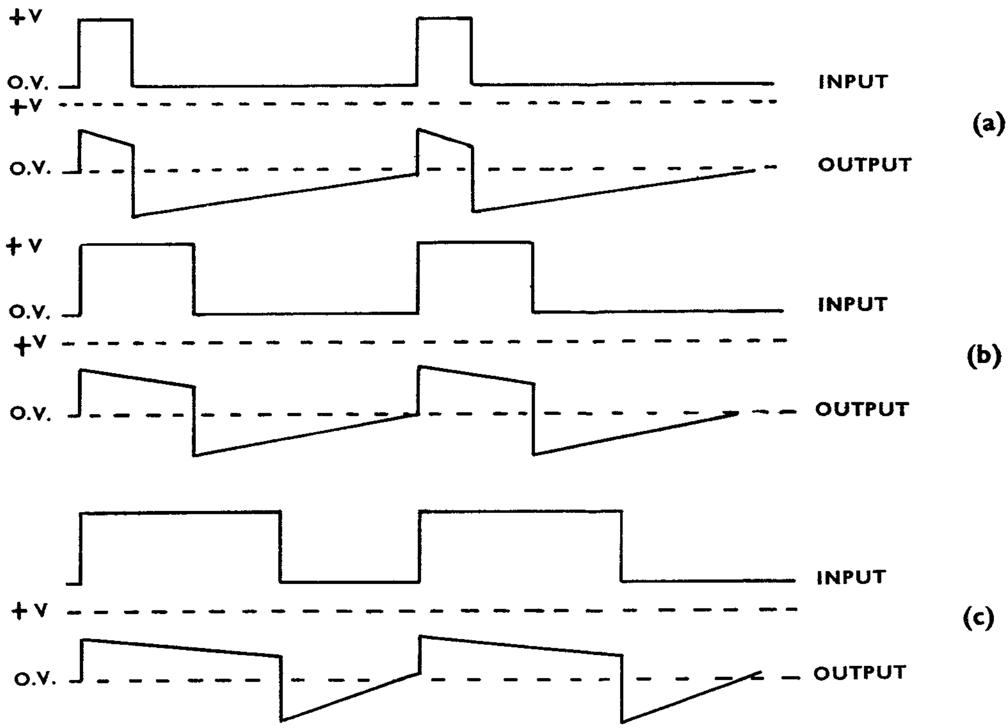


Fig. 18. Ratio of Square Waves

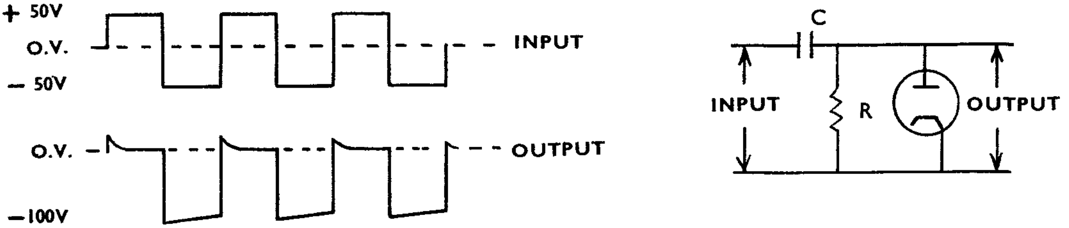


Fig. 19. Square Waveform Applied to Negative D.C. Restorer Circuit

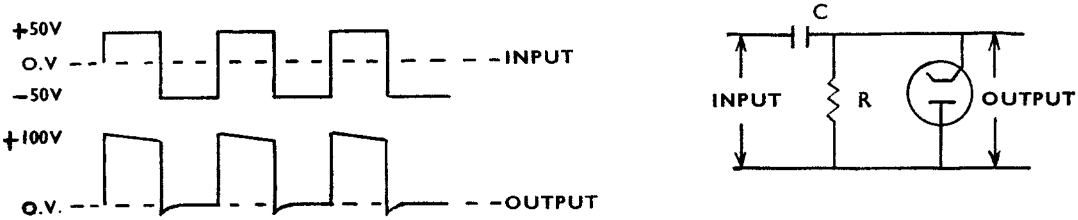


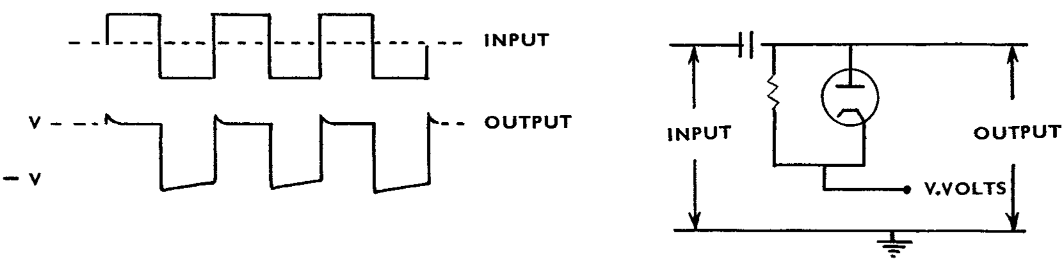
Fig. 20. Square Waveform Applied to Positive D.C. Restorer Circuit

Purpose of the Diode

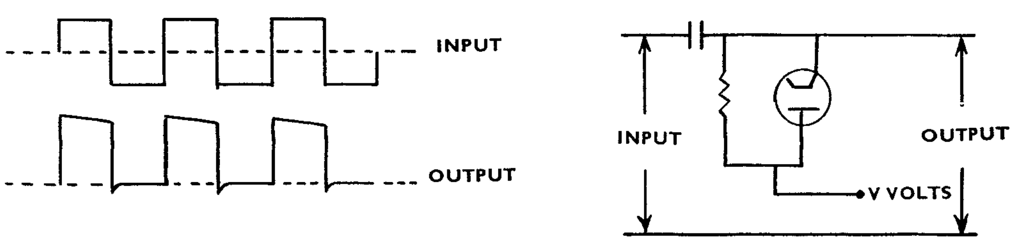
17. If a diode is connected across the output resistor R, it will conduct when the top end of R is made positive. The diode has a low impedance when conducting, thus C can rapidly charge to + 50V, but when the input falls by 100V down to − 50V the diode is inoperative. Thus C must discharge through R, and as this is arranged to be along C.R. little change takes place across C, the full 100V appearing across R. When the input rises to + 50V, C is still almost fully charged, and cannot change its charge immediately, so VR rises to just above 0 volts. The diode conducts, C quickly recharges to its full 50V again, VR remaining steady at 0 volts. (*See* Fig. 20.)

Negative Clamping and D.C. Restoration

18. This action is repeated leaving VC varying by a few volts about 50V, and VR following the shape of the input, but all the time below zero. This is called negative D.C. restoration to earth. In other words, the whole waveform is pushed down below earth, and varies between earth and approximately 100V no matter what the shape of the waveform is. The peaks are clamped to earth potential. (*See* Fig. 19.)



NEGATIVE D.C. RESTORATION TO POTENTIAL V



POSITIVE D.C. RESTORATION TO POTENTIAL V

Fig. 21

Positive Clamping

19. By connecting the lower end of R, and the cathode of the diode to some particular positive or negative potential with respect to earth, the peaks of the output waveform can be clamped to that potential.

Clamping to a Fixed Potential

20. With the diode connected the other way round, the base line can be clamped to earth, or to some particular potential. In this case the diode conducts whenever VR goes negative and allows the capacitor C to charge to the negative going peaks of the input waveform. This is called positive clamping, or D.C. restoration to a positive potential. (*See* Fig. 21.)

MULTIVIBRATORS

Simple Two Triode Multivibrators

21. It should now be apparent that a square wave is an essential waveform in all radar equipment, and in fact it generally forms the master waveform to initiate the whole chain of timing and locking circuits. In para. 14 a method of squaring a sine wave was mentioned, but the most common system for the production of square waves is the use of some form of *Multivibrator.* A simple self-running multivibrator using two triode valves to produce two antiphase square waves is shown in Fig. 22. The values are typical for a 50-cycle square wave. (*See* Fig. 22.)

Action of the Multivibrator Circuit

22. The principle of operation is simple, each valve being cut off in turn by the other, until the capacitor connected to the grid has had time to discharge and remove the cut-off voltage from the grid.

23. Assuming V_1 conducts first when the supplies are connected, V_1 anode current will reduce the anode voltage, and via C_2 drive the grid of V_2 negative below its cut-off level. C_2 discharges through R_2 reducing the bias on V_2 until it conducts, V_2 anode voltage falls, putting a heavy negative bias on V_1 grid via C_1, and V_1 ceases to conduct. The action is repeated with C_1 discharging through R_1 finally allowing V_1 to conduct again, and cut off V_2 when the whole cycle is repeated. The rounded shoulder in the anode waveform of V_2 and the pip on the waveform of V_1 anode and grid are caused by the sudden charge of C_1, through the low grid cathode impedance of V_1, during the short period its grid is driven positive.

Factors Covering Waveform

24. The duration of each pulse is determined by the time taken for the particular capacitor to discharge through its associated resistor, or in other words the time constant of that circuit. If both outputs are of the same value both pulses will be equal and form a symmetrical square wave.

Example : $C = \cdot 01\ \mu F\ R = 1\ M$

$$CR = \cdot 01 \times 1 \times 10^6\ \mu s$$

$$\text{Each pulse} = 10{,}000\ \mu s$$

$$\text{Frequency} = \frac{10^6}{2 \times 10{,}000} = \frac{100}{2}$$

$$= 50 \text{ cycles per second.}$$

Variation of R_1 or R_2 individually or together will alter the width of each pulse or the frequency of the square wave.

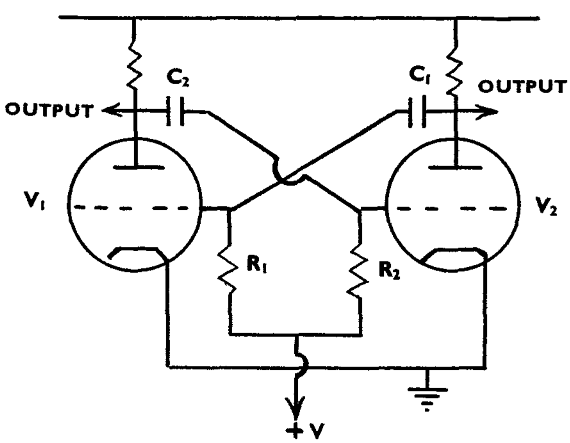
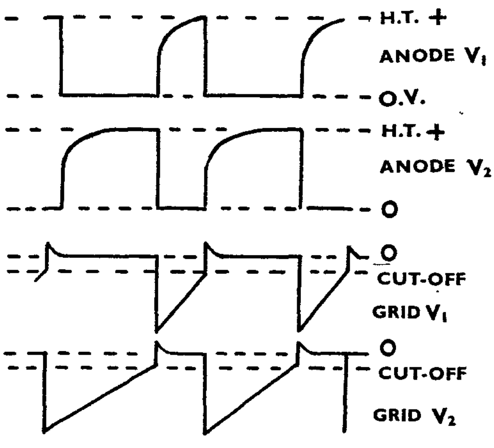
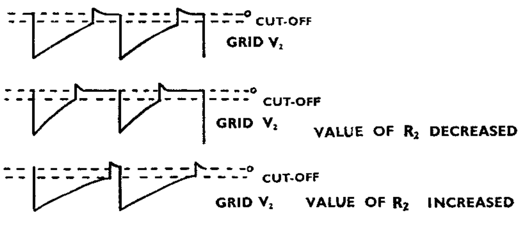


Fig. 22. Double Triode Multivibrator



WAVEFORMS



*NODE WAVEFORM WILL FOLLOW SIMILAR VARIATIONS

Fig. 23

Output Waveforms

25. A square wave output can be taken from either anode load, and from earth. The fact that the two square waves are in opposite phase is useful in circuits where a fixed delay is wanted.

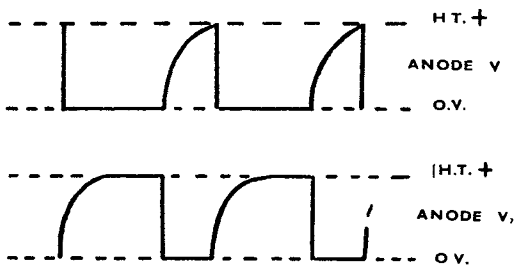


Fig. 24

Flip Flop

26. A special form of multivibrator used to provide a delay on the timing edge of a waveform is called a flip flop.

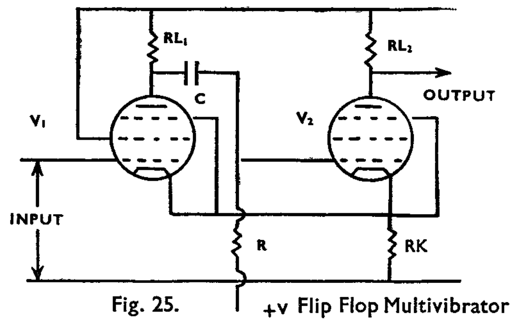


Fig. 25. +v Flip Flop Multivibrator

Circuit Action of Flip Flop

27. The circuit is normally "dead" with V_1 cut off by V_2 cathode current producing a bias voltage across RK but is triggered into operation by the positive pips applied to the grid of V_1. When V_1 conducts, it lowers the grid of V_2 below cut-off voltage via capacitor C; and V_2 remains cut off until the capacitor C has discharged through R by a sufficient amount to allow V_2 to conduct again. When V_2 conducts the cathode bias increases and cuts off V_2, C quickly charges up to H.T. and the circuit is again "dead" until the next input pulse arrives.

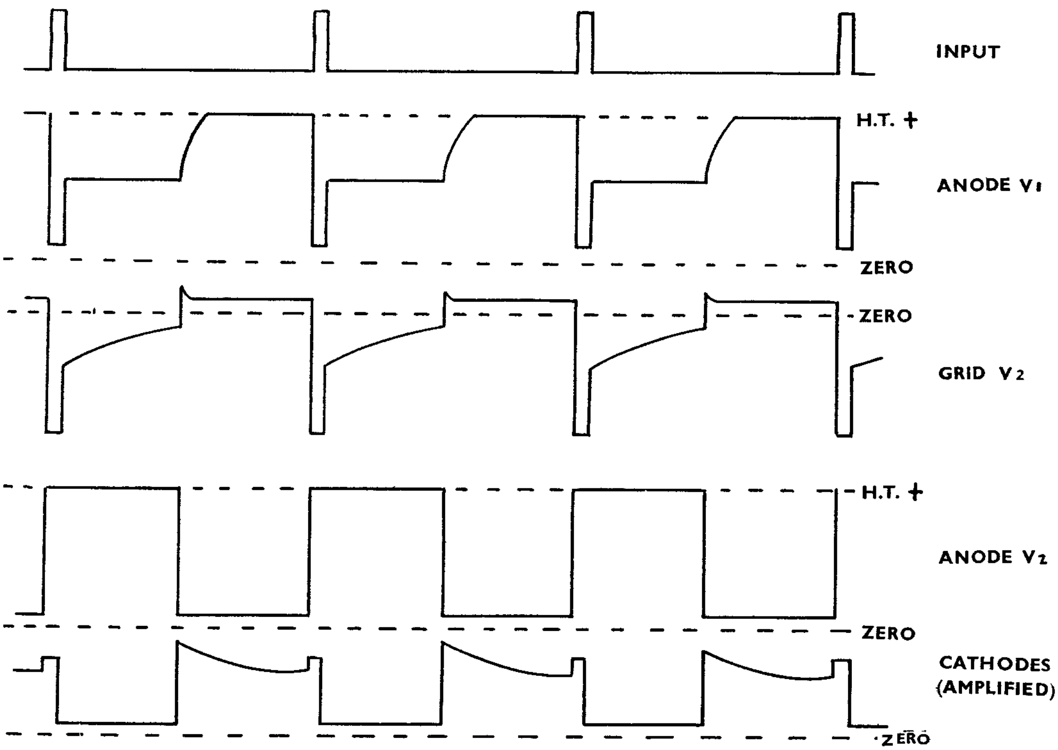


Fig. 26

Output Waveforms

28. An output, in the form of the square wave, can be taken from the anode of V_2. A smaller output voltage waveform can also be taken from the cathode which is in antiphase to the output from V_2 anode. The width of the pulse, or the time at which the "trailing edge" occurs after the triggering pip, depends on the "delay time". (*See* Fig. 26.)

Adjustment of Delay Time

29. The delay time (period when V_2 is cut off) can be varied by altering R. Alternatively, if R is returned to a positive potential it can be varied to produce a variable delay.

TIME-BASE GENERATOR

Requirements

30. It has been shown that to produce a trace on a C.R.T. a time-base waveform of sawtooth shape is necessary. It is important that the rising edge shall be as straight as possible, and synchronized with the timing waveform. This ensures an even speed of travel of the spot across the screen during the period when echoes are expected.

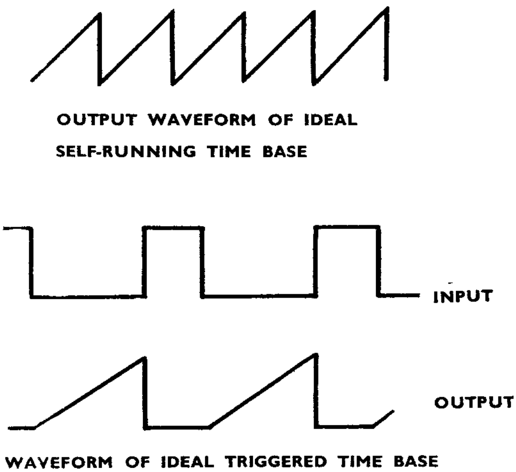


Fig. 27

Principle of Action

31. The rising voltage across a charging capacitor is the basis of all time-base circuits, and many systems are employed to eliminate the curvature of the exponential charging curve. By ensuring a constant charging current, no matter what the state of charge of the capacitor, the characteristic curve can be considerably straightened. (*See* Fig. 28.)

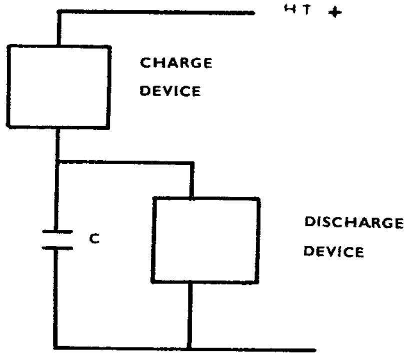


Fig. 28. Fundamental Time-Base Circuit

The Miller Time-Base Generator

32. The Miller time-base circuit employs the principle of a high gain amplifier with a charging capacitor C connected across from output to input. Having a high gain, the voltage change Vi is small for a large change across Vo. If E is a high potential compared with the small changes of Vi, the voltage across R is fairly constant. This means in effect that from a charging aspect C is connected across a constant current course. The simplified Miller time-base circuit and waveforms produced are shown in Figs. 29 (a) and (b).

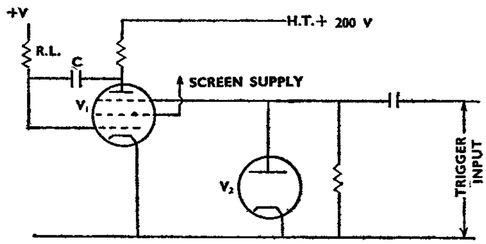


Fig. 29 (a). Basic Circuit of Suppressor Triggered Miller Time-Base

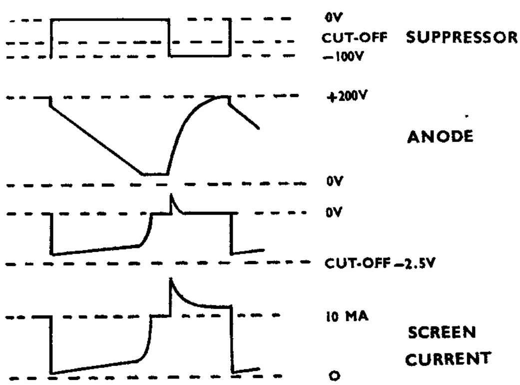


Fig. 29 (b). Waveforms Produced by Miller Time-Base Circuits

Action of Circuit

33. The diode V_2 clamps the positive peaks of the suppressor voltage to earth. Thus the suppressor grid is normally held at a negative potential below the cut-off of V_1 anode. The anode is at H.T. potential, grid at earth due to grid current, so C is charged to the full value of the H.T. supply. When the square wave input to the suppressor grid raises it above cut-off, V_1 conducts, and the rising anode current causes the anode voltage to fall. This fall is instantaneously transferred via C to the grid, and the tendency of the anode current to rise is checked by a corresponding fall of grid volts. The net result is a very slight fall of both anode and grid volts, enough to bring the grid volts down to almost cut-off and prevent further grid current. Capacitor C can now discharge through R at a constant rate, permitting only a slight rise of grid volts. Owing to the high amplification of V_1 the resultant fall of anode potential is steep and linear. The discharge of C is curtailed when the input square wave drives the suppressor below cut-off. The capacitor then recharges via R.L. to H.T. and the circuit awaits the next triggering pulse.

Output Waveform

34. The waveform taken from the anode is used as the time-base, the speed of flyback being unimportant as the C.R.T. is only brightened up during the actual trace period. The G1 waveform amplified and limited before applying to the cathode of the C.R.T. could form a bright-up waveform.

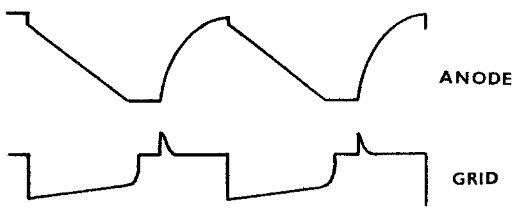


Fig. 30

Control of Waveshape

35. The triggering waveform determines the frequency of operation of the Miller time-base circuit, but the value of C must also be changed for a different trace duration. The amplitude of sweep can be controlled and adjusted by altering the positive potential to which G1 is returned via R.

Paraphase Amplifier

36. To prevent defocussing the beam in a C.R.T. when a deflection voltage is fed to the deflector plates, it is usual to employ balanced deflection voltages on both plates, so that as one plate is made negative the other is made positive by an equal amount. The beam is still deflected correctly, but the mean potential of the pair of plates remains constant; and so the electrostatic field from the focussing plates is unaffected. A further advantage of balanced or push-pull deflection is a doubling of the beam deflection for a given voltage change per plate.

37. Various forms of push-pull or paraphase systems are used; a typical floating paraphase amplifier is shown in Fig. 31. The output from the amplifier V_1 is fed to one "X" plate, and a small proportion is also fed to the grid of V_2, the output of which is in antiphase to V_1 output and can be adjusted to be equal to amplitude.

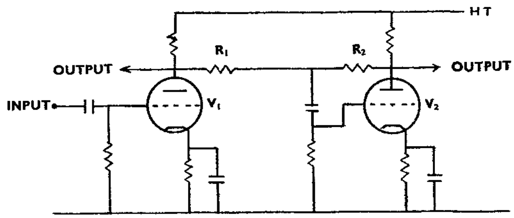


Fig. 31. Floating Paraphase Amplifier

Action of P.P.A.

38. (*a*) The full output from V_1 anode is fed to the X1 plate of the C.R.T. and via R_1 to the grid of V_2 as a reduced waveform.

(*b*) The amplified and inverted version of V_2 anode is fed back negatively via R_2 to the grid of V_2 and will therefore be a reduced voltage, similar but in opposition to that from R_1.

(*c*) The difference between the voltages across R_1 and R_2 is applied to the grid of V_2, and the final amplitude from V_2 anode will be almost equal and in antiphase to the output from anode of V_1.

(*d*) Note that the two outputs can never be exactly equal, because if they were no voltage difference would be available for the grid of V_2, and there would be no output from V_2.

(*e*) The circuit is self-adjusting for all changes in V_1 output, but owing to the negative feedback of V_2 output the amplification of V_2 must be high to produce an output almost equal to that of V_1.

(*f*) The adjustment of V_2 cathode resistor and therefore bias will alter the average current through the valve, and hence the average potential of V_2 anode as compared with V_1. This acts as a horizontal shift control, owing to its effect on the X2 waveform.

The Halver

39. A particular form of triggered multivibrator, called a halver, which can be used to produce square waves at half the frequency of the triggering pulse, is shown in Fig. 32. In this case the input is an unequal square wave, and must be differentiated by a short C.R. to provide the correct triggering pulses.

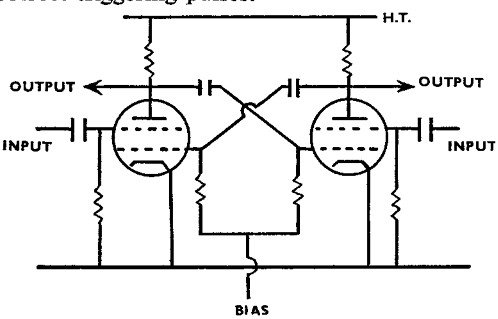


Fig. 32. Halver Circuit

Action of the Circuit

40. Each valve is cut off in turn by the negative pips of the triggering pulse and returns to conducting only when the associated capacitor has had time to discharge through its resistor. The square wave input is differentiated by R_1 C_1 and R_2 C_2 and applied to both suppressor grids as negative or positive going pips. Assuming that V_1 was already cut off during the previous cycle, the negative pip will now cut off V_2. The resultant rise of V_2 screen to H.T. voltage, applied to V_1 grid, will lift the latter into conduction. Its screen voltage falls, driving V_2 grid well below cut-off even after the triggering pip has ceased. The next negative input pip will drive the grid of V_1 below cut-off, which in turn releases the grid of V_2, allowing that valve to conduct. This action is repeated, producing antiphase square waves at the anodes, at half the frequency of the original square wave input. (*See* Fig. 33.)

41. A typical use for a halver circuit would be to suppress alternate time-base traces, thereby increasing the waiting period and preventing distant echoes from appearing on wrong traces and presenting a false apparent range.

Strobe Marker

42. A strobe marker is used in many displays, either as a simple spot or deflection on a trace that can be adjusted to "mark" a particular echo, or to produce an enlarged version of that part of a display including a particular echo. Very accurate measurements can then be made on the "strobe time-base". The essential waveform is a strobe pulse, or square wave of some definite width, that occurs at a predetermined time after the start of the transmitter pulse and the time-base trace.

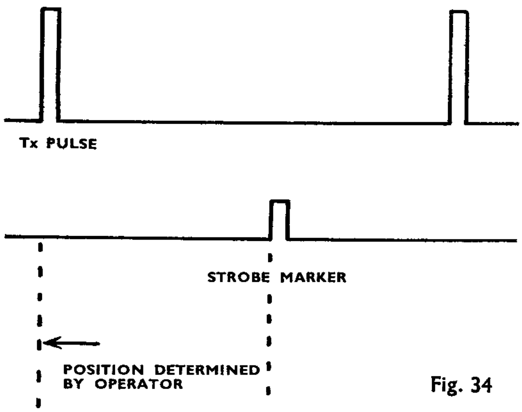


Fig. 34

43. The strobe marker is produced from the master square wave in three stages :—

(*a*) The delay circuit.

(*b*) Differentiator circuit.

(*c*) Pulse shaper.

(*See* Fig. 35.)

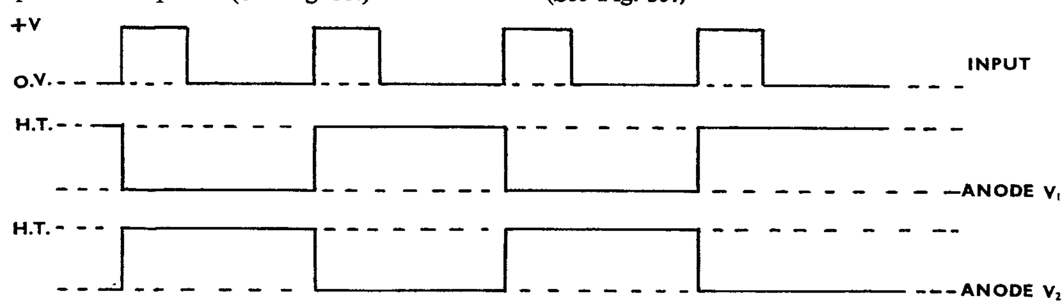


Fig. 33

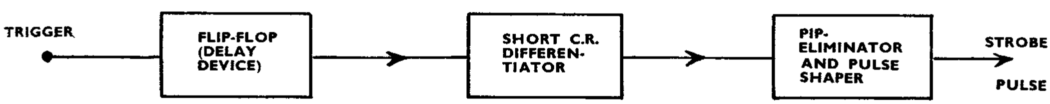


Fig. 35. Strobe Marker Stages

A small strip or deflection of the trace can be produced by applying the strobe pulse to the "Y" plate of the C.R.T. Alternatively, by applying it to the grid a bright spot can be made to appear.

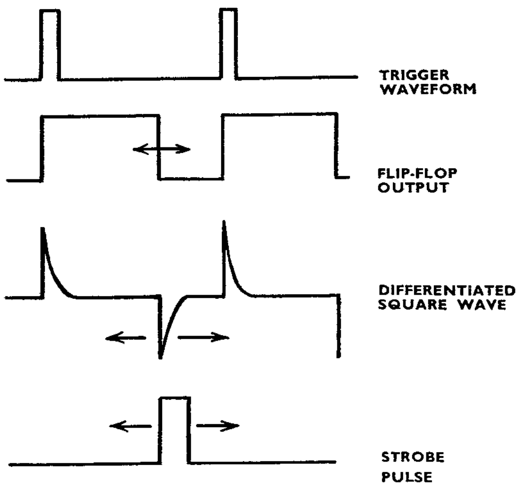


Fig. 36. Strobe Marker Stage Output.

Cathode Follower

44. The cathode follower is generally used as an output matching device, because the output taken from the cathode is at a low impedance, while the grid input impedance is very high. It is also used as a "buffer" or "isolator", partly owing to the fact that some small changes of capacitance in the output circuits cannot be reflected at its grid. The name is derived from the fact that the voltage variation across the cathode output follows in phase with the grid input waveform and no inversion takes place.

45. There is no load in the anode, and the cathode resistor decoupling is usually omitted. Thus the whole voltage variation caused by the change of grid volts will appear across RK. If Vg rises, Ia rises and so does VK. Unfortunately this is in opposition to Vg, and therefore the voltage gain from the stage must be less than unity. By choosing a large value of RK and a valve with a high mutual conductance (g_m) and a high amplification (μ) the loss of output is reduced to a minimum.

46. (*a*) *Output Impedance*. Assuming the cathode resistor RK has a fairly high value, say 10 K, it can be shown mathematically that the output impedance presented to the load is never greater than the internal resistance $\frac{1}{g_m}$ in ohms. This is often in the order of a few hundred ohms, much less than the conventional anode output impedance. In this case, of course, the circuit shown in Fig. 37 would be used, as a resistor of 10 K would produce more than the permissible cathode bias voltage for the valve if Rg were returned to earth.

(*b*) *Input Impedance*. By similar calculations it can be shown that the input impedance, or the load on the previous circuit, is very high, in the order of megohms.

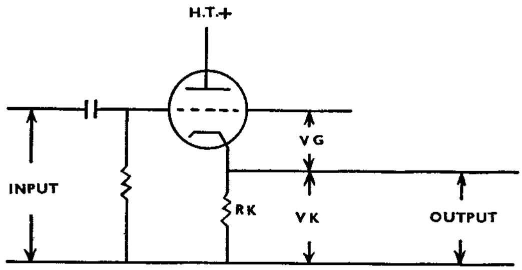


Fig. 37. Basic Cathode Follower Circuit

47. Thus the cathode follower circuit is capable of transforming with minimum distortion, and only a slight loss, voltage waveforms from a high impedance source down to the low impedance of a coaxial cable. Other important uses of a cathode follower will be seen when the individual equipments are considered.

Delay Line

48. It is sometimes necessary to produce a square voltage waveform with a large peak and a short duration, *e.g.* 4 kV for 1 microsecond. The normal valve squarer cannot produce such a pulse, therefore a delay line is used. A delay line is often called an "artificial transmission line", and it behaves as such. It has already been seen that a voltage applied to a length of open circuit transmission line will travel down the line, be reflected in phase and return to the source; adding to the original input voltage V_2. Slight losses will of course occur.

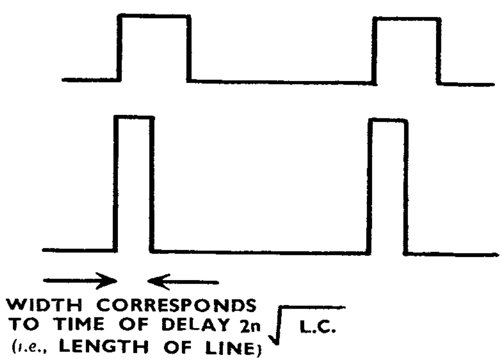


Fig. 38. Delay Line

The time taken by the voltage to travel to the end of the line, be reflected, and return to the generator, is very small, and to make this time equal 1 microsecond a long line would be necessary.

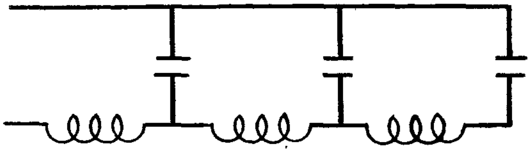


Fig. 39. Delay Line Showing Three Sections

Line with Lumped Inductance and Capacitance

49. By replacing a line with evenly distributed inductance and capacitance by one having lumped sections of L and C joined together, the time taken by the voltage to travel its length is greater. If a voltage of 8 kV is applied to this line via R, it will charge up C_1 via L_1 which will charge C_2 via L_2, etc. Thus the voltage along the line will rise exponentially to the H.T. level of 8 kV. Now switch S_1 is closed, the full line voltage (8 kV) is dropped across the resistance of the line and resistor R_1 in series. Assuming they are equal, the line voltage will fall to 4 kV, and 4 kV will appear across RL. This fall of 4 kV will travel along the line, discharging each section down to 4 kV. It will then be reflected at the open end and discharging each section to zero, so that when it reaches RL the voltage VRL will fall to zero. The duration of the pulse across RL will depend on the time taken by 4 kV to travel the line twice and can be increased by adding more sections of L and C.

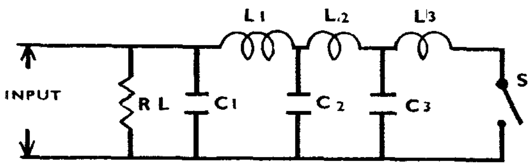


Fig. 40 (a) ← n SECTIONS →

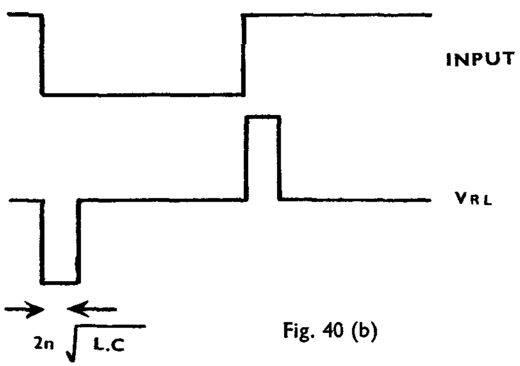


Fig. 40 (b)

Ringing Choke Charging

50. To overcome the serious disadvantages of having an H.T. supply twice the pulse peak, the resistor R is replaced by a choke.

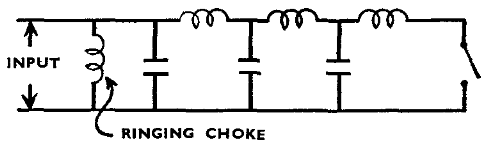


Fig. 41 (a)

It can be shown that the charging curve for the line is now oscillatory, and at one instant the voltage rises to twice the input. At this instant the switch is timed to close, producing the same effect as before.

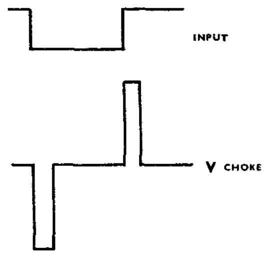


Fig. 41 (b)

CHAPTER 16

CENTIMETRE TECHNIQUE

Centimetre Bands

1. The frequency bands and wavelengths at present in use are :—

(*a*) S band ... 3,000 mc/s ... 10 cms.

(*b*) X band ... 10,000 mc/s ... 3 cms.

(*c*) K band ... 24,000 mc/s ... 1·25 cms.

The primary advantage of these bands is that aerials using very narrow beams, and small enough for installation in aircraft, are practicable; associated components are also smaller. Narrow beams and shorter pulses result in improved definition and targets are thus more easily identified. One of the limiting factors in the use of some airborne radar equipment is the effect of ground returns; the use of narrow beams minimizes this and range is improved.

TRANSMISSION LINES

Reasons for Using Transmission Lines

2. The purpose of a transmission line is to transfer R.F. energy from the transmitter to the aerial with minimum loss or distortion. Various types are in use, including the following :—

(*a*) Twin or balanced lines separated by less than a wavelength.

(*b*) Concentric or coaxial lines.

(*c*) Hollow pipes or waveguides.

Parallel Twin Wire Transmission Line

3. For frequencies up to 600 mc/s, the parallel twin wire transmission line can be used; the space between and around the conductors may be filled either with air or with a solid dielectric. For frequencies above 600 mc/s the radiation losses become prohibitive. To reduce heat loss as caused by the resistance of the conductors, one is made larger and surrounds the smaller. With the outer conductor earthed, radiation losses are reduced to a minimum (see Fig. 1).

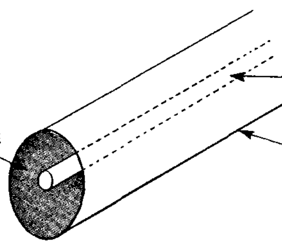


Fig. 1. Parallel Twin-Wire Transmission Line

Coaxial Cable

4. Coaxial cable is flexible and therefore convenient for use in aircraft. It can handle reasonably large voltages without arcing across. Its use is, however, generally limited to frequencies below 1,000 mc/s, because above this frequency the losses from a polythene dielectric become too large. By using air as the dielectric between the conductors, and by supporting the inner conductor by quarter wavelength stubs as shown in Fig. 2, coaxial cable can be used for frequencies above 1,000 mc/s.

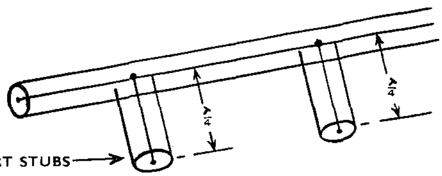


Fig. 2. Coaxial Support Stubs

5. A serious disadvantage of this type of coaxial cable is that it must be constructed for one particular frequency. At all other frequencies the supporting stubs are no longer a correct quarter wave, and are therefore not insulators. As the frequency rises, the current tends to keep more and more to the surface of the conductor, and it will carry a different value of current on either side. By silver plating the surfaces resistance can be reduced, but a point is reached where the resistance of the inner conductor becomes so large that the heat losses are prohibitive.

WAVEGUIDES

Evolution of the Waveguide

6. By using two parallel metal strips as shown in Fig. 3 it is possible to increase surface area, but radiation would still occur as magnetic fields forming complete closed loops will be set up around each metal strip.

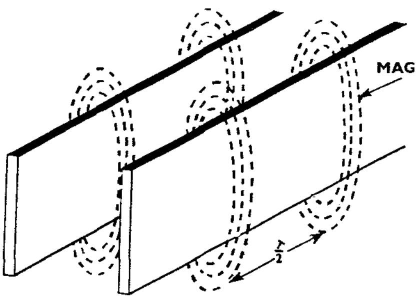


Fig. 3. Magnetic Fields Around Spaced Conductors

This can be avoided if top and bottom plates are added to form a completely closed channel, with a broad side not less than half wavelength across, as shown in Fig. 4.

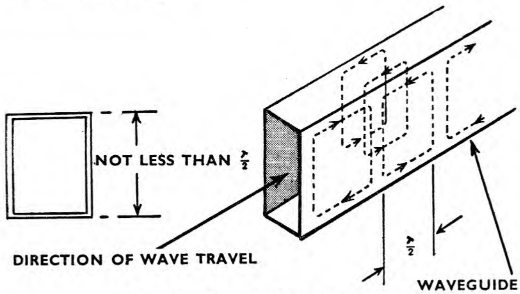


Fig. 4. Simple Waveguide

7. The magnetic field has now been enclosed in the waveguide, and so forms complete loops by linking up with the magnetic field approximately half a wavelength away. The wave now travels down the hollow pipe in the same way that sound waves travel down a speaking tube.

Propagation of the Wave

8. By confining the electro-magnetic wave within the waveguide its mode of travel is now different. The wave is injected into the waveguide usually by means of a rod or probe in the broad side, and travels down the waveguide reflected from side to side.

Matching the Waveguide

9. To prevent reflection from the ends of the waveguides, which would set up standing waves and waste energy, some device is necessary to match the waveguide to its load at both ends. At the injection end, the presence of the probe upsets the waveguide impedance ; to offset this and to obtain a perfect match a moveable piston is fitted to the end. By suitable adjustment of this piston along the "dead" end of the waveguide, a position can be found where reflection is prevented and all the injected energy is fed down the waveguide.

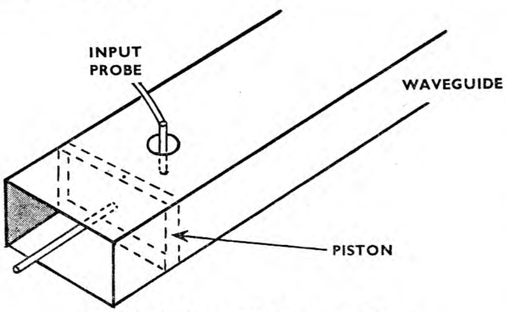


Fig. 5. Waveguide Matching Piston

10. At the other end, all the energy can be made to radiate from the end of the waveguide by the use of a suitably shaped horn (Fig. 6), which is designed to match the impedance of the waveguide to prevent reflection from the open end.

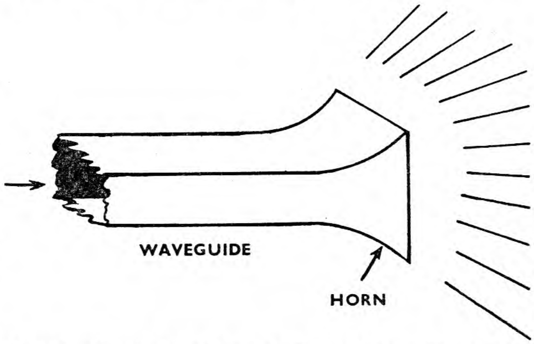


Fig. 6. Simple Method of Radiation from Waveguide

Advantages of Waveguides

11. Size limits the use of waveguides on the higher frequency bands. A waveguide for the broadcast medium band, for example, would have to be about 50 feet in breadth. In the centimetre band the advantages of waveguides over coaxial cable are :—

(*a*) Power losses due to heat are reduced.

(*b*) Radiation losses are eliminated.

(*c*) Dry air dielectric losses are low.

(*d*) Higher voltages may be handled.

Circular Waveguide

12. In a circular waveguide, as shown in Fig. 7, the pattern of the electric and magnetic fields changes, but the wave still travels down the guide or pipe. In this case, however, the wave is injected by a probe pointing into the end of the pipe.

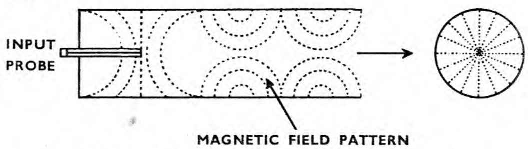


Fig. 7. Probe Fed Circular Waveguide

The losses in a circular waveguide are slightly greater than those in a rectangular one, and the waveguide is generally heavier. However, a circular waveguide is the only practical one in certain cases.

Bends, Twists, and Joints in a Waveguide

13. A run of waveguide from transmitter to aerial will seldom be in a straight line and it is necessary to include bends without affecting the

electric and magnetic fields ; provided certain rules are observed this may be achieved. When a curved bend is practicable the radius should be greater than two wavelengths, and a bend with a 45 degree corner can be adapted to prevent reflection at the corner. It is also necessary to alter the plane of the wide side of the waveguide. This is achieved by a twist, the total length of which should be equal to at least two wavelengths.

14. Joining pieces of waveguide by welding is impracticable, as the pieces could not afterwards be dismantled. Flanges bolted together may constitute a high resistance joint at very high frequencies, and the flanges are therefore separated slightly and made a quarter of a wavelength long. The gap between them causes no radiation at all, as it behaves as an open-circuited quarter wave line. In effect, the inside of the two pieces of waveguide will be an R.F. short circuit, and a complete path is provided for the wave as shown in Fig. 8.

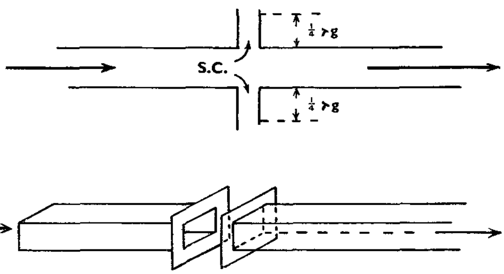


Fig. 8. Method of Joining Pieces of Waveguide

A more elaborate method is the choke joint using two quarter wave slots. The outer one, a shortened quarter-wave line, produces a high impedance at the far end of the inner one. This acts as an open circuited quarter-wave line, and the inside of the waveguide is virtually a perfect short circuit. By using a length of flexible ribbed rubber having a fine copper gauze on the inside, it is possible to obtain a flexible joint in a waveguide. It is also possible to make a "T" joint in a waveguide.

15. **Rotating Joint.** Aerials mounted on an aircraft are often of the rotating type and are fed from a waveguide, which must rotate without disturbing the electric and magnetic fields. A rectangular waveguide cannot achieve this because of its shape ; the circular type with a symmetrical field is therefore used. The changeover from rectangular to circular waveguide is arranged as a junction at the end of both waveguides, the symmetrical fields gradually building up in a circular guide without loss (see Fig. 9). The circular waveguide is cut into two parts radially so that the top part may rotate about the lower part. A rotating choke joint forms a convenient loss-free coupling. No losses occur at the rotating choke joint because the fields are symmetrical and can rotate ; and the quarter-wave slotted flanges prevent the exit of energy from the joint.

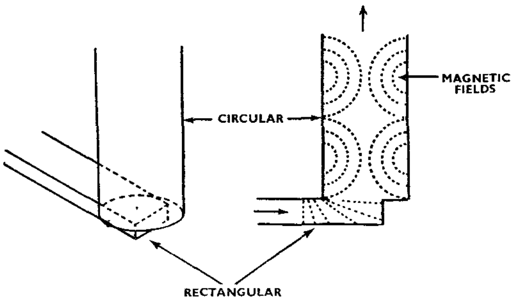


Fig. 9. Changeover from Rectangular to Circular Waveguide

RADAR AERIALS

The Half-Wave Aerial

16. The simplest form of aerial found in radar equipment is the half-wave dipole aerial. This consists of a metal rod cut to a resonant length of half a wavelength. When fed with R.F. energy, standing waves are set up and radiation takes place. If the field strength at points around the aerial were measured, it would be found that maximum radiation takes place at right angles to the aerial with practically zero radiation from the ends, as shown in Fig. 10.

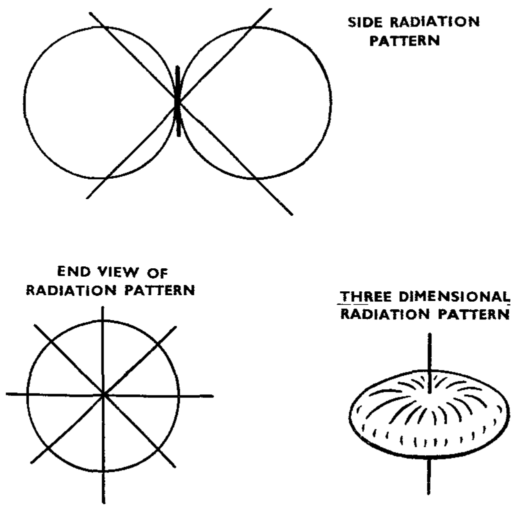


Fig. 10. Half-Wave Dipole Radiation Patterns

(60638)

Methods of Feeding

17. With standing waves set up about the aerial there will be points of maximum current and voltage. In the half-wave aerial, there will be a maximum current at the centre with zero voltage. Thus the feed is centre current fed.

18. An alternative method of feeding the half-wave aerial is at the end, where voltage is maximum and current is zero. This is often termed voltage feeding, as opposed to current feeding. To preserve the balance, another half-wave element can be added and fed from the other side of the transmission line, so as to be in phase with the first aerial.

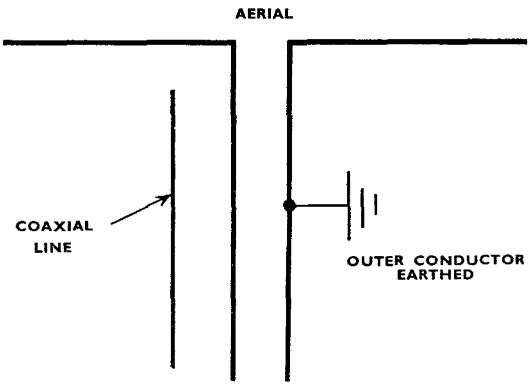


Fig. 11. In-Phase Twin Half-Wave Aerials

Balanced and Unbalanced Loads

19. The example given in para. 17 represents an unbalanced load on the transmission line, and the example given in para. 18 represents a balanced load. The coaxial type of line used in the aircraft is generally earthed through the outer conductor and therefore requires an unbalanced load. This is quite simple when the single half-wave or quarter-wave aerial is required, but when the dipole type of aerial is to be fed, some form of "balance to unbalance" transformer is necessary. Various methods of achieving this match are possible, one example being the quarter-wave sleeve.

Quarter-Wave Sleeve

20. If a half-wave dipole were connected as shown in Fig. 11 the feed to each half would be unequal and the R.F. path to earth would cause losses. This can be overcome by presenting a high impedance to the outer conductor at the aerial connection point, and is achieved by the use of a quarter-wave sleeve connected to the outer conductor, as shown in Fig. 12. In this instance the current path to earth is interrupted by the path round the inside of the sleeve. This is arranged to be a half-wavelength and, having an open-circuited end, the impedance at the other end near the aerial is infinity. All the R.F. energy from the line therefore takes the lower impedance path into the aerial.

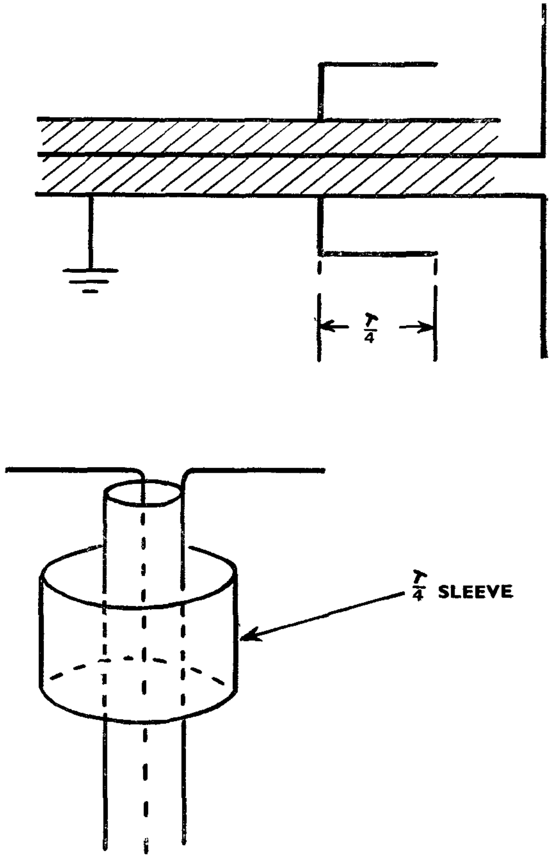


Fig. 12. Quarter-Wave Sleeve

Directional Properties

21. In radar it is often necessary to beam the radiation from an aerial in one direction. The width of the beam required will depend on the operational function of the particular equipment. The radiation pattern of a simple half-wave aerial shows that in a plane at right angles to the aerial the radiation is equal in all directions. A degree of beaming can be achieved by connecting a large number of half-wave aerials to a common feeder in such a way that they will all radiate in phase. This is called an array of stacked aerials, and to improve the beaming further the stacks can be fixed on either side of the main aerial (see Fig. 13). There is maximum radiation in two directions, *i.e.* to the front and to the rear of the array.

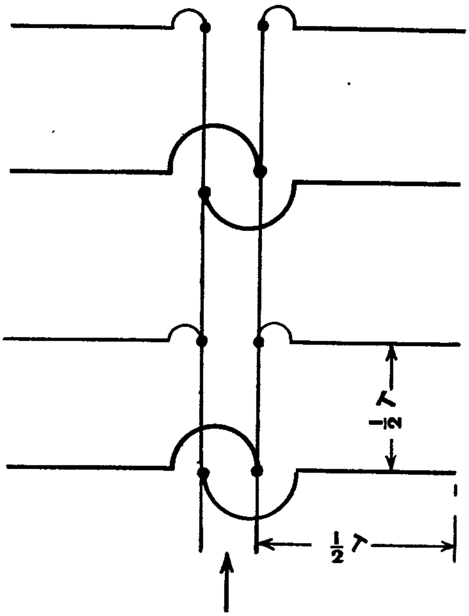


Fig. 13. Array of Stacked Aerials

22. By fixing suitable parasitic aerials behind the driven aerials, the radiation in the forward direction can be increased while that in the backward direction is reduced (see Fig. 14).

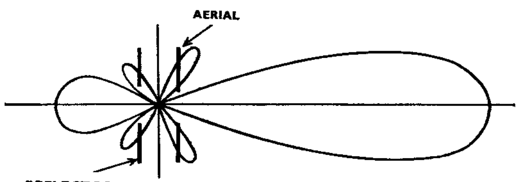


Fig. 14. Radiation Pattern Using Parasitic Aerials

23. By adding further parasitic aerials in front of the driven aerial, the forward beam increases with a corresponding reduction of the back beam. Each element of such an aerial array is carefully cut to length, not quite half wavelength, and the spacing between them is similarly exact. An example of this type of array is shown in Fig. 15 and is commonly used for aircraft aerials ; it is known as a Yagi aerial.

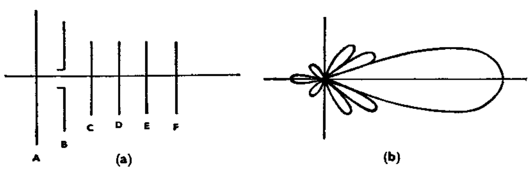


Fig. 15. Yagi Aerial

24. The driven element is the dipole aerial B, while A is the reflector and C, D, E, and F are the directors. It will be seen that the reflector is longer than the half-wave aerial, and the directors are shorter. The radiation pattern, or polar diagram, has one main lobe with smaller side lobes. To prevent wasting energy in these side lobes, and to prevent echoes from unwanted directions producing a detectable signal, the aerial arrays are carefully designed to give a long main lobe and very short side lobes.

Aerial Impedance

25. To obtain maximum transfer of energy from the line to the aerial, with no energy reflected back along the feeder, a perfect match between the line and aerial is necessary. The impedance of any aerial system depends on many factors, but the simple half-wave dipole as used on the higher frequencies presents a load on the transmission line of about 73 ohms. This forms a conveniently simple match to a normal 75 ohm coaxial cable type of feeder line. By adding further sections or elements to the aerial array the impedance is lowered considerably. To ensure a correct load on the transmission line a matching transformer is used.

Folded Aerials

26. Alternatively, the impedance of the whole aerial can be increased by using two half-wave conductors, one fed at the centre and the other joined to the driven aerial by conductors at the end. The whole unit is fed from the transmission line, and the resultant polar diagram is similar to that of a single half-wave dipole aerial. By altering the diameter of the aerial rods the impedance can be increased, so ensuring a perfect match for the line feeding it.

27. The aerials discussed so far will not produce a really narrow beam of radiation below, say, 15 degrees, without making an aerial array normally too unwieldy to fix to an aircraft. An alternative method of producing a narrow beam is to distribute the energy evenly over a large reflecting surface and then to radiate it from that surface. A simple example is the car headlamp, where the light radiated from the lamp is distributed over the reflector behind the lamp and then radiated from the reflector.

Size and Shape of the Reflector

28. The size of the main reflecting surface should be large in proportion to the wavelength of the energy it has to reflect. A reflector with an aperture size of at least ten wavelengths is necessary to produce a narrow beam. A reflecting plate to fill this requirement on the long, medium, or short wavelength would be too large for aircraft use. When, however, the radiated energy has a wavelength of 10 cms. or less, a small

reflector may be used that is capable of producing a narrow beam and can be mounted in an aircraft. In practice, a large flat plate does not make a good beam reflector, and a reflector of paraboloid shape is often used (see Fig. 16).

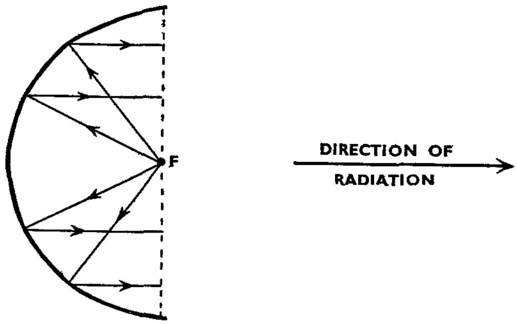


Fig. 16. Paraboloid Reflector

29. A source of energy at the focal point of the reflector will produce lines of radiation that reach the aperture of the reflector all in phase and following exactly the same direction, thus producing a narrow beam in one direction. The small side lobes of radiation shown in Fig. 17 are of no consequence, for so little energy will be radiated in their direction that echoes will be too weak to be detected.

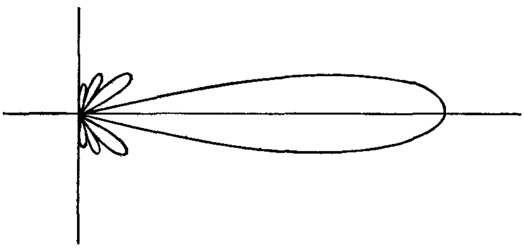


Fig. 17. Effect of Paraboloid

RADIATION

Types of Radiators

30. The basic paraboloid reflector could be a flat plate bent to the shape of a paraboloid as shown in Fig. 18 provided that the aperture "h" is greater than ten wavelengths the beam will be quite narrow.

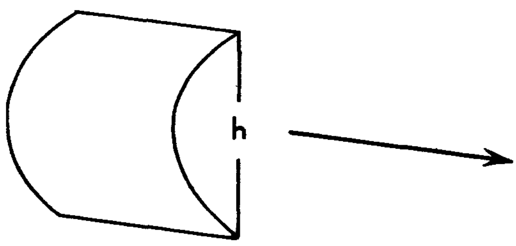


Fig. 18. Alternative Paraboloid Shape

31. A much more efficient reflector is of circular paraboloid shape. This is very similar to, but larger than, an ordinary car headlamp. For many operational requirements, a beam need not be narrow in all planes and to save space the top and bottom parts of the reflector can be cut away thus producing a fan shaped beam; with the sides filled in for structural strength it forms the "cheese type" of reflector, used in many equipments. It is not always possible to feed the whole area of a full circular paraboloid from a single radiating source, and thus the removal of the top and bottom to form a "cheese type" of reflector does not detract from its efficiency.

Feeding the Reflector

32. The simple half-wave aerial having a circular polar diagram can be used to feed a parabolic reflector or mirror. The top and bottom of the circular reflector receive little energy in comparison with the sides, and the radiation pattern will not therefore be symmetrical in all planes. This may be an advantage in that side lobes are reduced without a corresponding reduction in the main beam. Another important factor is the positioning of the aerial within the reflector. It should be at the focal point of the reflector, which is generally arranged to coincide with the plane of the aperture. This reduces the amount of energy "spilt" over the edge of the reflector, and also ensures maximum energizing of the reflector.

33. When a waveguide is used to feed the energy from the transmitter to the aerial, the open end of the waveguide can be extended outwards to form a horn and then fixed at the focal point of the reflector. A good impedance match can be obtained when a horn is used, and reflection back along the waveguide is reduced (see Figs. 19 and 20).

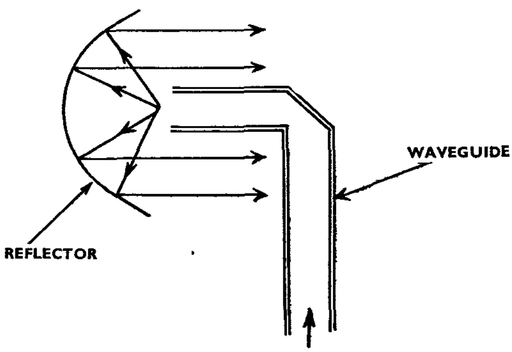


Fig. 19. Methods of Feeding the Reflector

Slot Radiators

34. A slot cut to an electrical half-wavelength in a large sheet of conducting material will radiate in the same way as a half-wave dipole aerial. The feed to the slot is, at its centre, like that of a

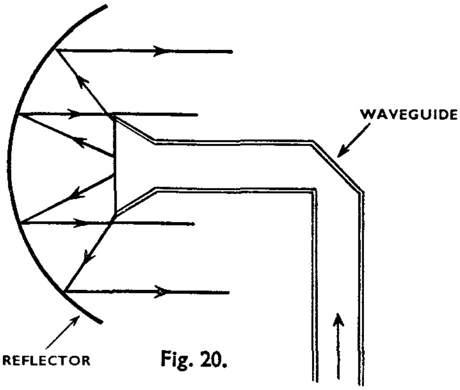


Fig. 20.

Methods of Feeding the Reflector (Horn Fed)

dipole, but the electric and magnetic fields are the reverse of those of a dipole aerial. This means that the E.M. wave from a vertical slot will be horizontally polarized, as compared with the vertically polarized wave from a vertical dipole (see Fig. 21).

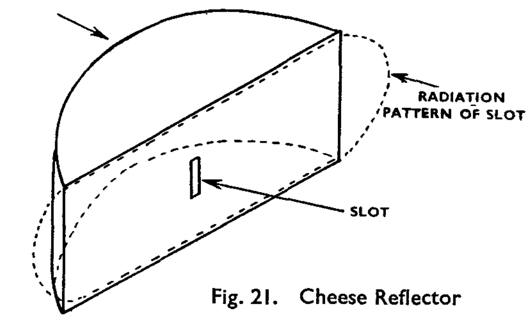


Fig. 21. Cheese Reflector

35. It is impracticable to cut a slot in a large flat plate, but a slot cut in a cylindrical plate will radiate. A further advantage of this system is that the opposite side of the cylinder will act as a reflector.

Slots in Waveguides

36. Energy can be radiated from a waveguide by cutting slots in the narrow face, as shown in Fig. 22.

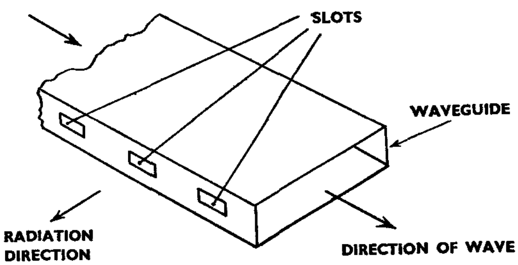


Fig. 22. Radiating Slots in Waveguide

The amount of radiation from each slot will depend on the angle of the slot. Not all the energy arriving from the transmitter will radiate from the slots, and the residue is absorbed by a resistive load at the end to prevent reflection back down the waveguide.

Reflector with Slotted Waveguide Feed

37. This type of waveguide slot radiator is particularly useful for feeding a long cheese reflector. The slots are cut in the face of the waveguide nearest the reflector. An even feeding of the reflector is obtained by varying the angle of the slots (see Fig. 23).

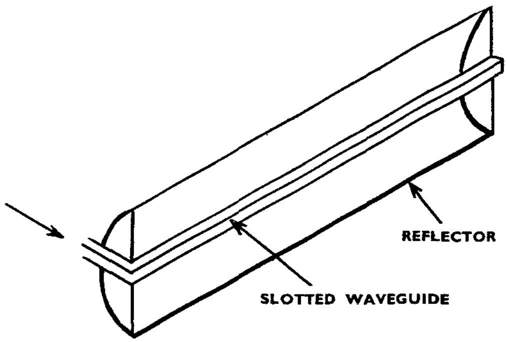


Fig. 23. Slotted Waveguide

Radiation Pattern

38. Parabolic radiators (see paras. 28 and 29) will produce one main lobe with small unavoidable side lobes, as shown in Fig. 24.

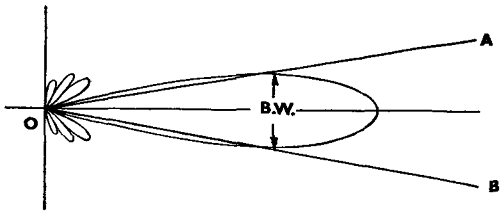


Fig. 24. Effect of Parabolic Reflector

39. The echoes resulting from radiation in the side lobe direction are too weak to be detected. Echoes from targets lying outside the lines OA and OB would similarly be too weak to be determined, and therefore the beamwidth (BW) can be regarded as the angle subtended by lines passing through a point of half peak amplitude.

Rotating Scan

40. Having met the requirements of high definition by the use of a narrow beam radiation, the field of scan has been restricted. If coverage of a large area is necessary, the only method of scanning the area is to rotate or deflect the beam by movement of the whole aerial system. On the

longer wavelengths, the size of the aerial necessary would preclude its use as a moveable array on an aircraft. Such a limitation does not apply in the centimetre bands, where a complete scanner can be mounted externally on the aircraft and still be rotatable through 360 degrees. It is usually enclosed in a streamlined perspex cover (see Fig. 25.)

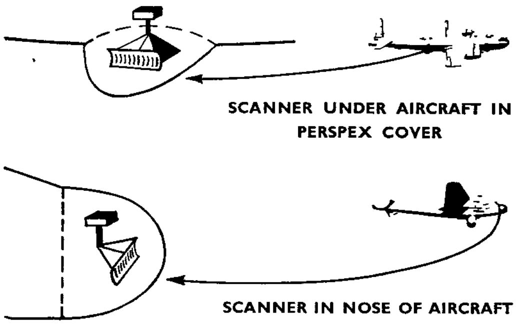


Fig. 25. Rotating Scanner

41. The aerial system may consist of a waveguide terminating in a horn, and feeding a parabolic, or part of a parabolic, reflector. In some cases, where a specially shaped radiation pattern is required, a particular shape of reflector is designed to give that pattern.

42. The speed at which a scanner rotates is governed by many factors (see Chapter 13, para. 49). The mechanism necessary to rotate the aerial system, and in some cases to elevate it as well, is complicated; correct synchronization between angular movement of the aerial and the position of the trace on the C.R.T. is essential.

CIRCUIT COMPONENTS

Tuned Circuits

43. In the lower frequency bands, tuned resonant circuits consist of an inductance and a capacitor. They can be made to have a high amplification factor with little difficulty. As the frequency increases to that above about 200 mc/s, the circuit becomes almost wholly capacitive. With increasing frequency the current tends to keep to the outside, or to the skin of conductors, and, unless the skin resistance is made very low, heat losses will occur. Other losses caused by radiation from the components, dielectrics, and wiring all tend to decrease the efficiency of the tuned circuit to a point where it ceases to have any selectivity at all. Connecting wires at centimetre wavelengths may be more than a wavelength long and unwanted radiation would take place from them. It is necessary, therefore, to replace these "lumped" inductances and capacitances by "distributed" inductance and capacitance. Transmission line ideas and methods are used. (See Fig. 26.)

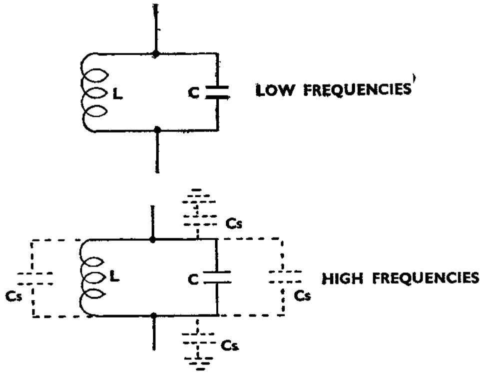


Fig. 26. Distributed Inductance and Capacitance

Open and Closed Parallel Line Circuits

44. The property of a quarter-wavelength of short-circuited line is to present an infinite impedance at its open end at the resonant frequency. This makes it suitable to replace the well known parallel-tuned circuit with lumped inductance and capacitance. By silver-plating the outside of conductors, a low resistance skin is formed and heat losses are reduced. This is essential when the quarter-wave element forms the oscillatory circuit of a high-power transmitter.

45. Above 600 mc/s or so, the radiation from an open wire circuit becomes excessive, and a coaxial form of circuit element is used. Radiation is cancelled out, and the larger surface area available reduces the skin resistance. When such a circuit is used to replace L and C in an oscillator, a special valve is required that actually fits within the coaxial lines, thus reducing the connecting wiring to a minimum.

Cavity Resonators

46. Unfortunately, as the frequency increases so L and C must decrease, *e.g.* to oscillate at 10 cms. (3,000 mc/s) the circuit may have 0·1 micro Henry inductance with a capacitance of 2·3 pica farads. By using only one turn of wire the circuit will resonate at a very high frequency. If a large number of these loops are arranged with their open ends joined as shown in Fig. 27, the result will be a cavity possessing the same properties of resonance and having the same natural frequency as the original loop. Such a cavity is called a *Rhumbatron.*

The Rhumbatron

47. The rhumbatron consists of a circular or square cavity within which the electric and magnetic fields of the oscillatory wave are confined. The voltage being at a maximum at the

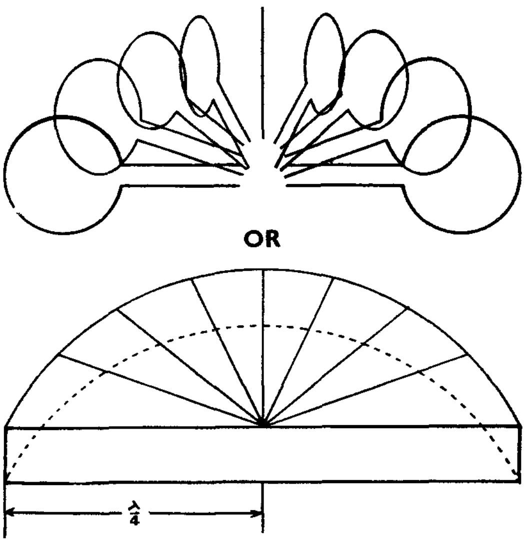


Fig. 27. Illustrating Principle of Rhumbatron

centre, the electric field will be concentrated at that point. The magnetic field will form closed loops around the inside, being maximum at the outside and decreasing towards the centre (see Fig. 28.)

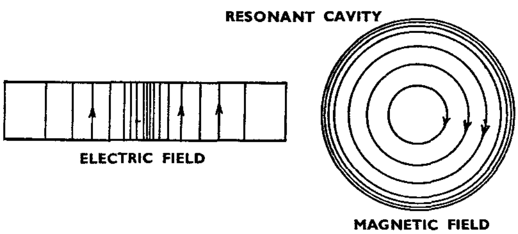


Fig. 28. Fields in Rhumbatron Cavities

48. Because of the internal silver-plating the skin resistance is very low, and, as a result, heat losses are reduced to a minimum. In addition, as the cavity is totally enclosed, the electro-magnetic field cannot radiate and losses through radiation are thus minimized. The circuit magnification of the rhumbatron is therefore very high.

49. The frequency at which the rhumbatron will resonate depends on the values of L and C, or, in other words, the physical size of the cavity. This can be adjusted by means of plungers screwed into the circumference, or by applying pressure to the flexible side of the rhumbatron as shown in Fig. 29. The shape of a practicable rhumbatron, as shown in Fig. 30, is designed to provide a narrow lip aperture at the point of maximum voltage, *i.e.* at the centre.

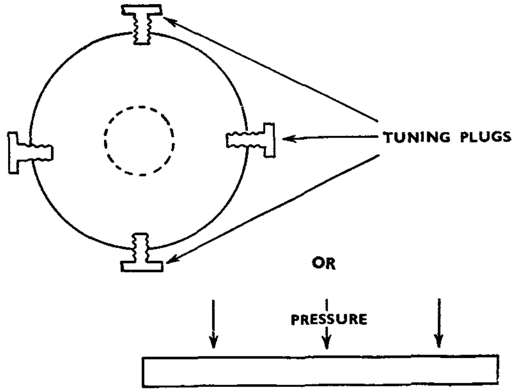


Fig. 29. Method of Tuning Rhumbatron

50. Among the possible methods of feeding energy into a rhumbatron, or of picking energy up, is the loop inserted into the side. By rotating the loop, the degree of coupling can be altered by varying the number of lines of the magnetic field cutting the loop. Alternatively, the electron stream can be shot across the lips at the centre of the rhumbatron. The speed of the electrons will be varied by the oscillating electric field concentrated across the lips. This is called velocity modulation of the electron stream, and forms the basis of the Klystron oscillator.

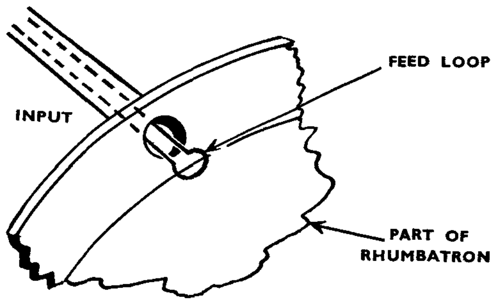


Fig. 30. Feeding Rhumbatron

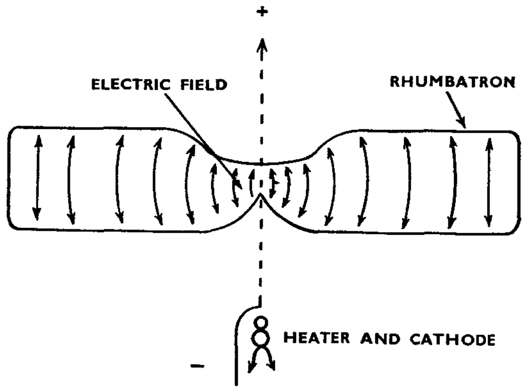


Fig. 31. Velocity Modulation

Limitation of Standard Valves

51. The inherent inter-electrode capacitance and electrode inductance in a normal valve puts a limit on the frequency at which the valve can be used. It is quite possible for the valve itself to provide more inductance and capacitance than is required in the whole circuit to tune it to a very high frequency.

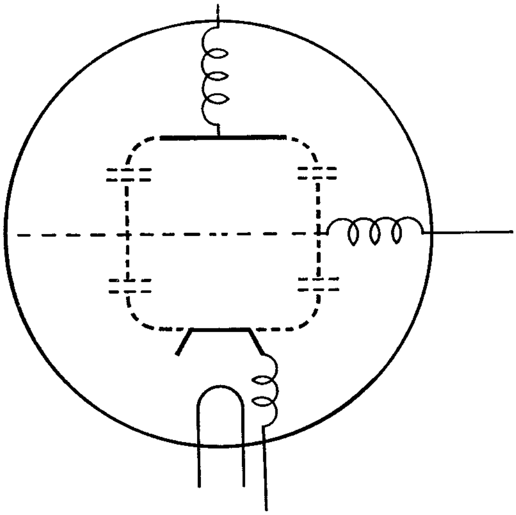


Fig. 32. Inherent Inductance and Capacitance in a Normal Triode Valve

52. Another very serious limitation of the normal valve is the time taken by an electron to travel from the cathode to the anode, in comparison with the time of one input cycle. At 600 mc/s, for example, with say 300 volts H.T. on a normal valve, the electrons would not reach the anode before the phase or grid volts had changed considerably. This would result in a fall of anode current, and considerable phase change within the valve. Under these conditions, it could not be used as an oscillator.

Use of Acorn Valves

53. To reduce as far as possible the stray capacitance and inductance, and to reduce the distance an electron has to travel from the cathode to the anode, a miniature valve called an acorn valve, is used for receivers as shown in Fig. 33.

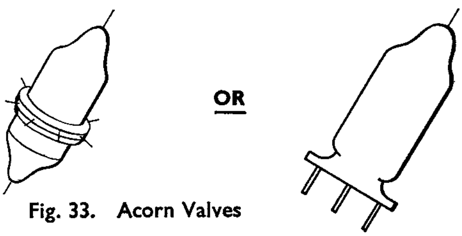


Fig. 33. Acorn Valves

Its small size precludes its use for transmitters or circuits where high-power dissipation is required.

54. These miniature valves can be used in parallel line oscillators up to about 600 mc/s. Above this frequency the radiation loss from the lines becomes excessive. To overcome this difficulty, special miniature valves are constructed to fit into the end of various sizes of coaxial line. They can be made to oscillate up to about 5,000 mc/s depending on the coaxial line constances, the valve inductance, and the capacitance.

Construction of Coaxial Line Oscillator

55. In Fig. 34 it will be seen that the anode is a disc extending beyond the valve to face up with the outer coaxial line. This, with the grid coaxial line, forms the anode/grid circuit. In conjunction with the cathode line, the grid line also forms the grid/cathode circuit. Both circuits are tuned by plungers which vary the effective length of the lines and therefore the oscillator frequency. (See Fig. 34.)

The Mixer Stage

56. In a superhet receiver, the frequency changer stage is often the source of most of the noise voltage produced. In radar receivers handling very weak signals, the noise voltage level must be kept to a minimum or the range will be reduced. At ultra-high frequencies where R.F. amplification is virtually impossible, the frequency changer or mixer stage becomes the first stage, and is the most critical consideration in the reduction of noise voltages. The normal type of valve is useless as a U.H.F. mixer because of the high noise voltages produced; therefore a crystal mixer or low-power detector is invariably used in centimetre equipment.

CRYSTALS

The Mixer Crystal

57. The crystal used in a mixer stage consists, basically, of a fine pointed tungsten whisker, touching a smooth silicon surface, as shown in Fig. 35. The whole assembly is sealed with wax

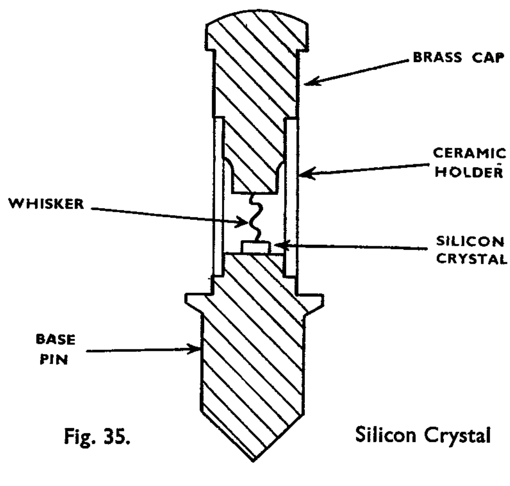


Fig. 35. Silicon Crystal

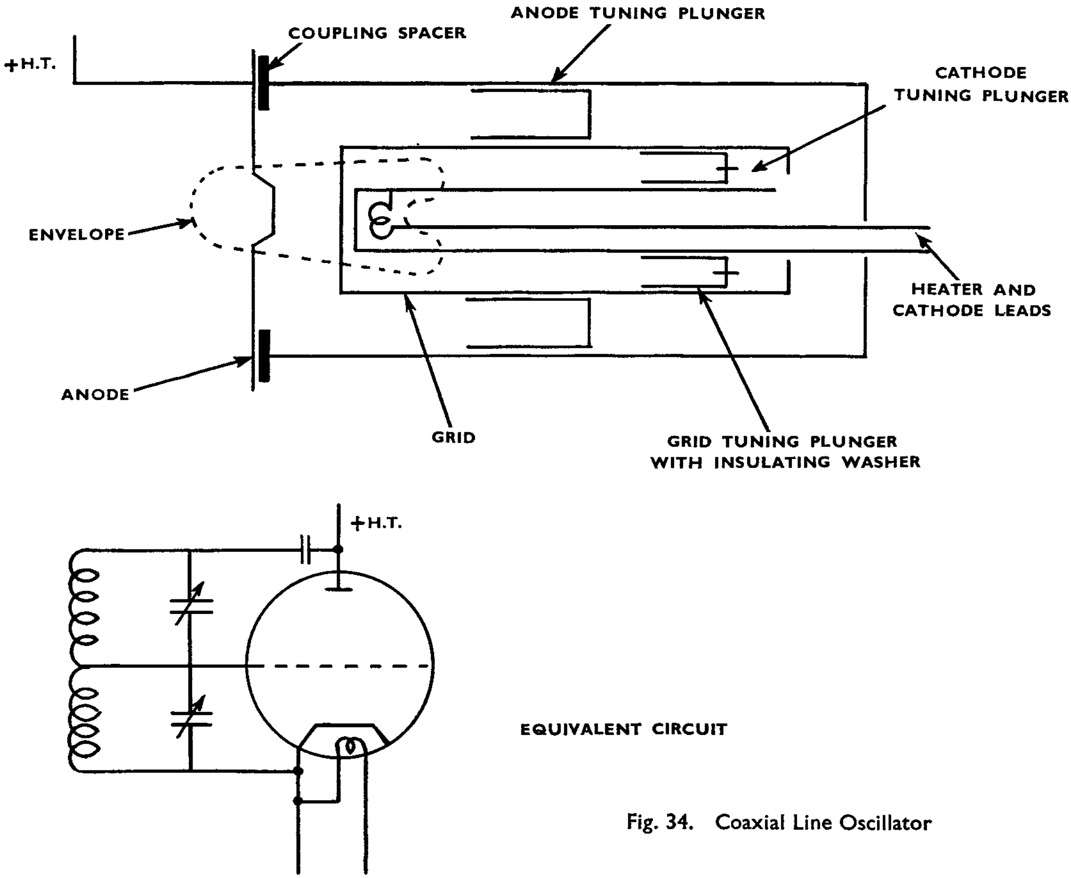


Fig. 34. Coaxial Line Oscillator

inside a ceramic holder, having external metallic contacts. By careful adjustment of the contact during manufacture, the internal resistance is arranged so that the electron flow from the whisker to the silicon crystal is much greater than in the opposite direction. In actual fact crystals will pass current in the opposite direction, but provided that the "back to front" ratio is greater than 10 : 1 the crystal will function satisfactorily.

58. A characteristic curve showing current plotted against the applied voltage for a typical crystal is shown in Fig. 36. It should be noted that the crystal will not stand currents of more than 500 micro-amps. for very long before burning out. For this reason, and to indicate the back to front ratio, crystals are usually colour coded. They may be tested with an Avometer Model 7 (100,000 ohms range) and great care should be exercised in handling them.

The Crystal Mixer Chamber

59. When used at centimetric wavelengths, the mixing chamber is usually a section of waveguide into which the crystal is fitted. To compensate for the presence of the crystal, some form of tuning plunger is provided which corrects the waveguide matching. The signal input from the scanners is fed down the waveguide and the output from the local oscillator is introduced by a probe at a suitable point. The crystal will rectify the signal and local oscillator voltages, producing a difference voltage, which is fed to the I.F.

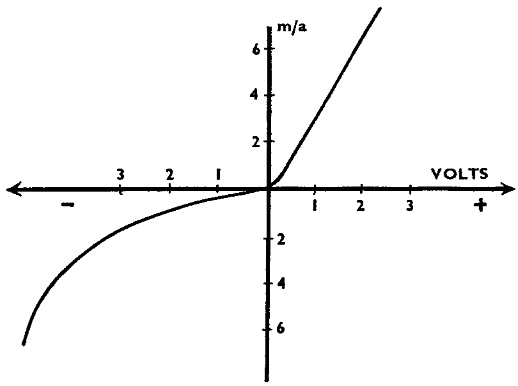


Fig. 36. Characteristic Curve of a Crystal

amplifiers. The dielectric washer C in Fig. 37 acts as a low capacitance, effectively by-passing the R.F. and oscillator voltages, and allowing only the lower I.F. voltages (usually 45 mc/s) to be fed to the I.F. amplifiers ; exact positioning of the probe, crystal, and tuning plunger, is essential to prevent a mismatch in the waveguide which may result in reflection and double echoes.

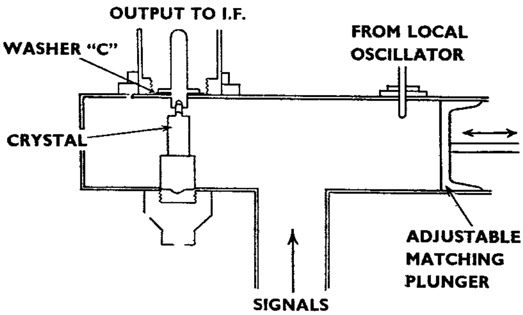


Fig. 37. Mixer Bridge

KLYSTRONS

The Klystron Oscillator

60. The local oscillator in a centimetre mixer is required to work at a high frequency and to produce only a low power output. These requirements can be met quite easily by a special form of oscillator valve called a klystron. This consists simply of a resonant cavity or rhumbatron with its centre lips close together. Across these lips is directed a stream of electrons from an electron gun, comprising a heater, cathode, and shield (see Fig. 38). The large potential difference

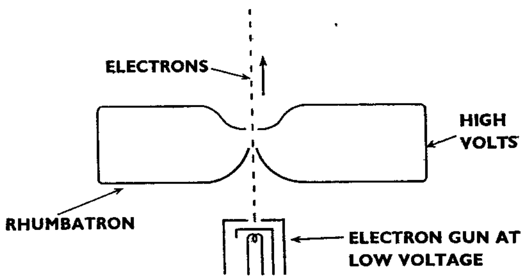


Fig. 38. Basic Klystron

between the gun and the rhumbatron will shock excite the klystron into oscillation. This produces an oscillating field across the lips which will alternately attract and repel the electrons. Thus some electrons will be accelerated, others will be decelerated, while some passing through the lips at the instant when the field is changing from positive to negative will be unaffected. This is known as velocity modulation and results in the electrons bunching together at certain points where the faster electrons have caught up with the slower ones. These bunching points will be repeated, but with progressively decreasing intensity as the electrons are diffused again (see Fig. 39).

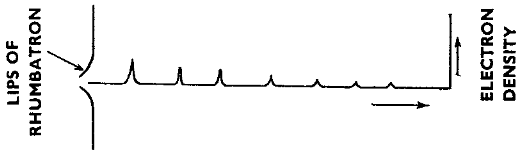


Fig. 39. Velocity Modulation

The Reflector Klystron

61. To maintain self-oscillation in the rhumbatron it is necessary to impart energy into it at the correct moment. For example, the electrons that were originally retarded by the rhumbatron virtually gave up some of their energy to it, but those that were accelerated actually took away energy. In the reflector klystron, a reflector plate with a large negative potential is just beyond the rhumbatron lips and repels the electrons. By careful adjustment of this variable potential and the natural frequency of the rhumbatron, the electron stream is caused to bunch on its return journey at the lips of the rhumbatron just when the field reaches a maximum in that direction. Thus the electrons are made to give up enough energy to maintain oscillation.

62. A simple analogy can be found by considering a number of stones thrown into the air at different velocities. Gravity will cause all to return to earth in the same way as the electrons are returned by the reflector. Those going upwards faster will travel further than the slower ones, but if they can all be made to strike a downward moving see-saw at the same instant, sufficient energy will be given to the see-saw at the right moment to keep it moving.

Construction of a Reflector Klystron

63. The rhumbatron is usually in the form of a shaped cavity having a resonant frequency which is adjustable by mechanically varying the pressure on one side of it. Alternatively, the reflector voltages and heater are all fed in through the standard low capacity valve base. Reflector volts are usually adjustable externally. The output is taken from a short loop connected inside the cavity and positioned at right angles to the magnetic field for maximum output. In some klystrons the loop can be rotated to vary the output level. High-power outputs are not possible from this type of klystron, so its use is restricted to local oscillators in a test set, or in the receiver

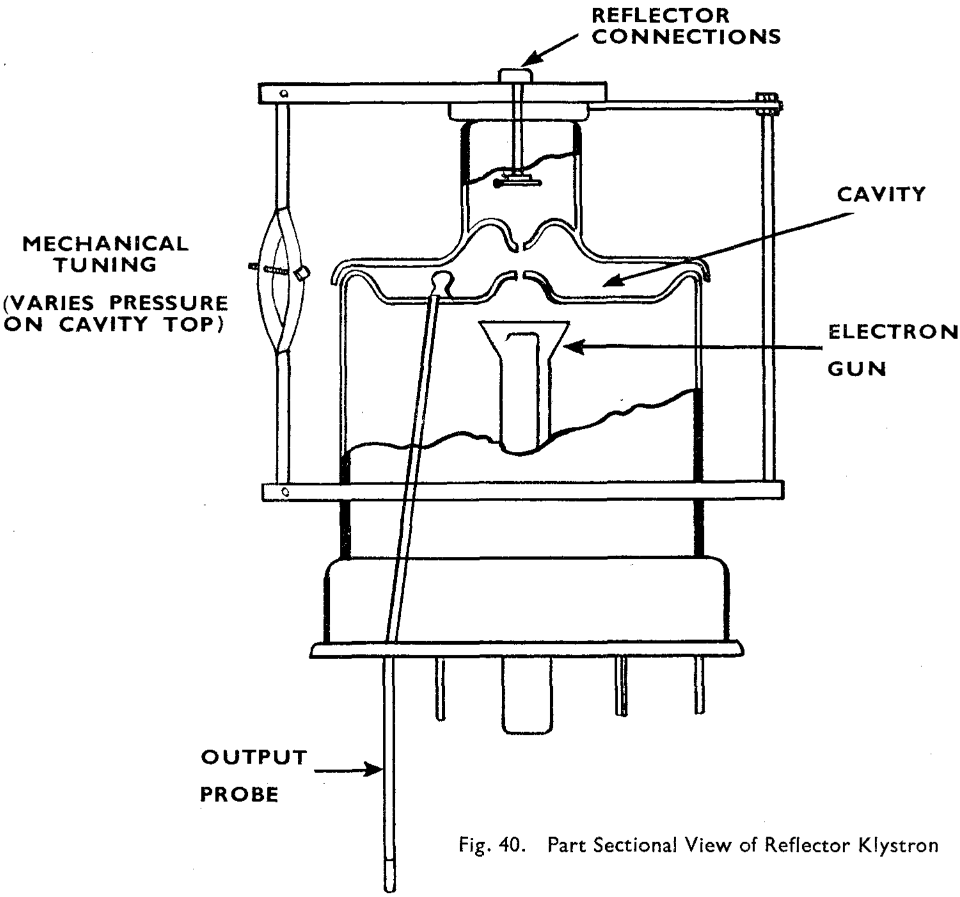


Fig. 40. Part Sectional View of Reflector Klystron

chain. The main advantage of the low-voltage reflector klystron is its ability to oscillate over a band of frequencies. It is therefore suitable for circuits having automatic frequency control in which the local oscillator frequency is being continually adjusted to compensate for any slight drift in transmitter frequency.

MAGNETRONS

64. The magnetron was developed to function as a high-power oscillator for centimetre transmitters. R.F. amplification being impossible, the oscillator acts as the main output stage. The R.F. output is in the form of short-duration pulses; thus peak pulse power outputs of several hundred kilowatts are possible from magnetrons.

Operation

65. The cathode is centrally fixed inside a cylindrical anode, across which a steady electric field is formed by the high potential between anode and cathode. At right angles to this field, *i.e.* going in to the paper, is a magnetic field produced by a powerful magnet. The effect on electrons leaving the cathode will vary according to their initial velocity and the relative field strengths. In general they will all follow a curving path (see Fig. 41). Some will turn so far as to return to the cathode causing heat (A); others will turn so little that they strike the anode and are lost (B); the remainder, (C), those that help the oscillation, will follow a path that takes them near the anode and cathode, but they do not actually strike either. The speed with which they pass near the anode will depend on the energy given to them by the steady electric field.

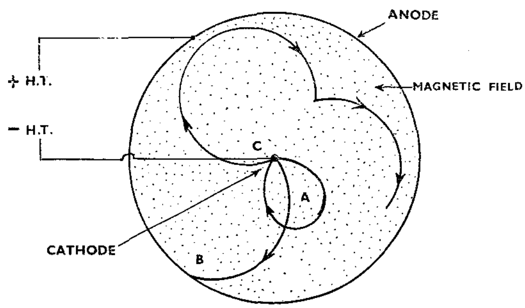


Fig. 41. Electron Path in Magnetron

(60638)

66. By replacing the single anode by a number of segments across which are connected oscillatory circuits tuned to the same frequency, the circuits are shock-excited into self-oscillation by the fast moving electrons.

67. In addition to the steady electric field from cathode to anode, there are now oscillatory fields around the anode segments which also affect the electrons. Those passing through the oscillatory field in its positive phase will be accelerated and will hit the anode. Those passing through the field in its negative phase will be slowed down and, as a result, part of the energy they obtain from the steady field is passed into the oscillatory circuit in correct phase to make good its losses. In practice, more energy is given to the oscillations by the decelerated electrons than is taken by the accelerated electrons, and self-oscillation is maintained ; this condition depends on the critical adjustment of field strength and anode/cathode potential.

The Cavity Magnetron

68. In one form of magnetron the oscillatory circuits consist of resonant cavities or slots cut into the anode block (see Fig. 43(b)).

69. As in the rhumbatron, the hole and slot act as inductance and capacitance at these ultra-high frequencies. A loop of wire projecting into any one of the holes will act as an output coupling. Reference to Figs. 43(a) and (b) will simplify this point. Each cavity cannot be regarded as an oscillation on its own ; the whole series of resonant cavities are interdependent in the action. Therefore, as the cavities cannot be manufactured to resonate at exactly the same frequency, they are strapped together to oscillate at a common frequency. The power-handling capability of a magnetron is increased by this system of strapping, and by the same means the efficiency is also improved. In spite of the improved efficiency a large amount of heat is produced in the magnetron. The excessive heat is dissipated by wide cooling fans which maintain the magnetrons at a constant operating temperature ; this prevents frequency drift. After the initial warming up period, the heat generated by electrons returning and bombarding the cathode is enough to keep it hot with the heater switched off.

TRANSMIT/RECEIVE DEVICES

Common Aerials

70. For compactness and mechanical simplicity, it is preferable to have only one aerial for both transmitting and receiving. This system also ensures that the receiver aerial is pointing in the same direction as that taken by the transmitted pulse.

71. The major difficulty in using a common aerial system is that the high peak transmitter output is liable to damage seriously the first stages in the receiver. Another difficulty is that the transmitter absorbs a proportion of the returning echo, giving rise to weak signals. A protective device is therefore necessary to cut off the receiver from the aerial during the period of the transmitter pulse, and also to cut off the transmitter from the aerial at other times.

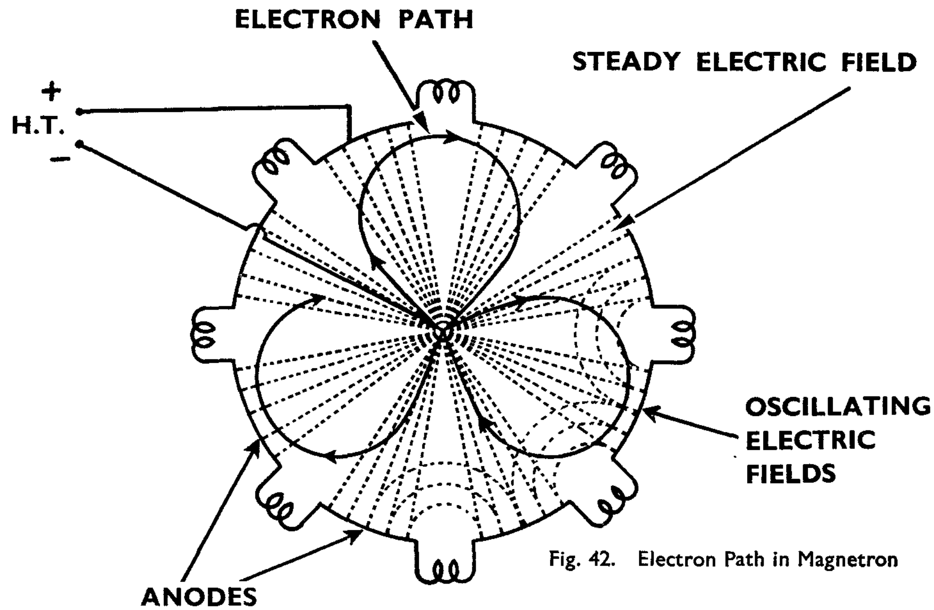


Fig. 42. Electron Path in Magnetron

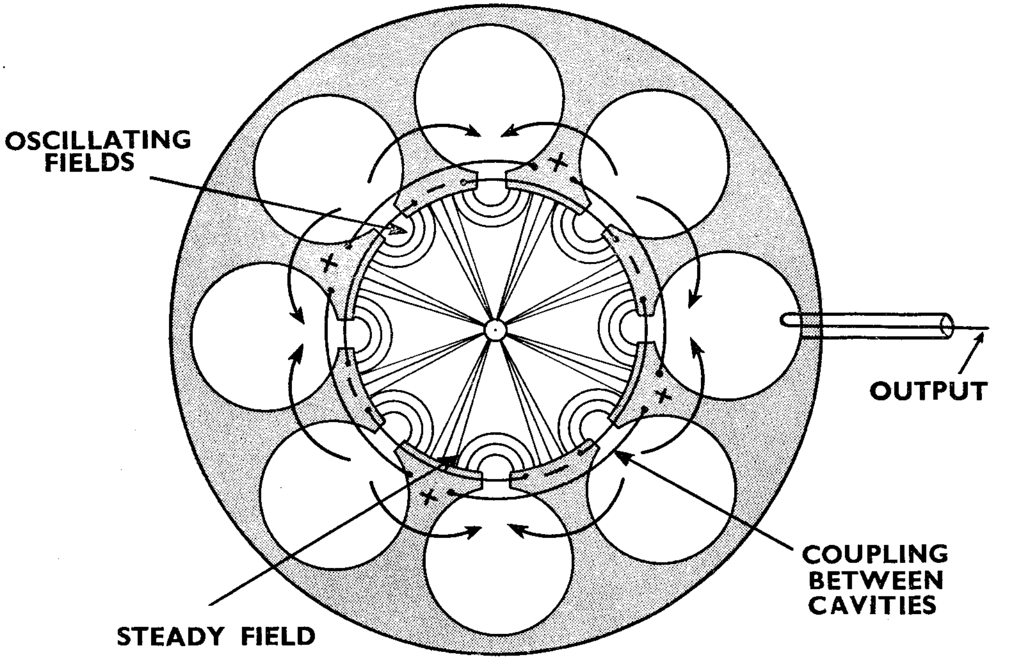


Fig. 43 (a). Cavity Magnetron

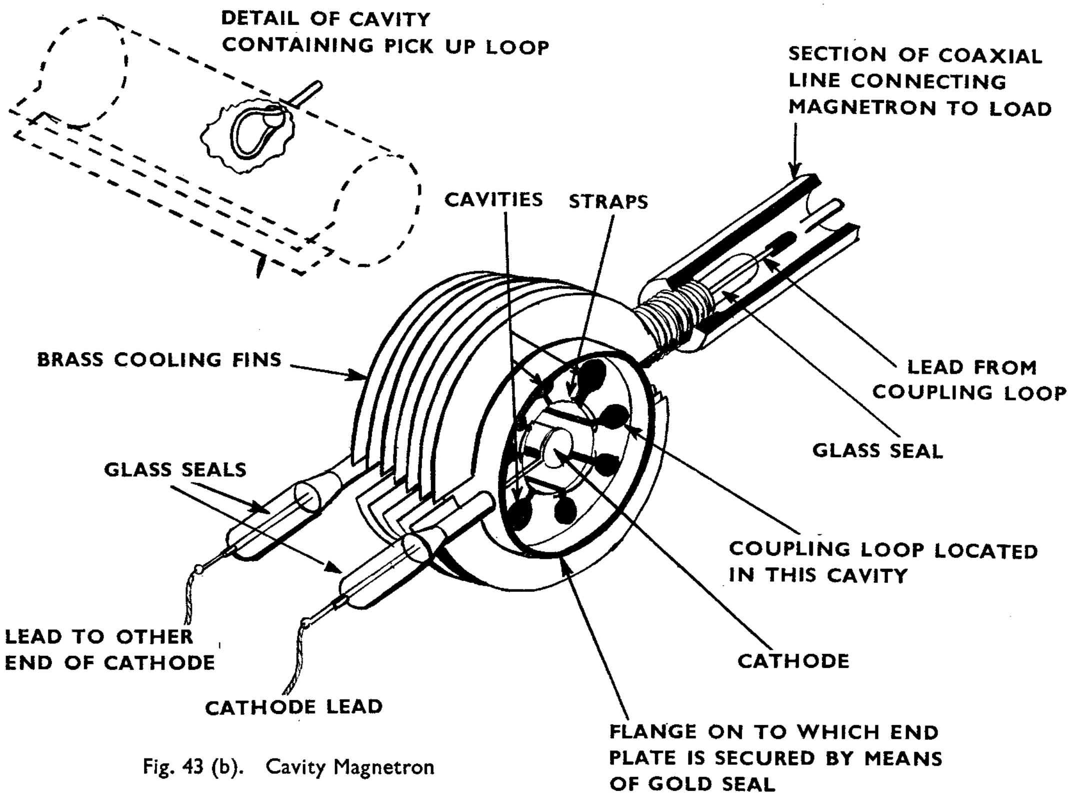


Fig. 43 (b). Cavity Magnetron

Basic T/R System

72. The device which prevents transmitter power from reaching the receiver is generally known as the T/R cell, and is in the feed to the first stage of the receiver. An anti-T/R cell is inserted in the main transmitter line to prevent energy from the returning echo being wasted in the transmitter (see Fig. 44.)

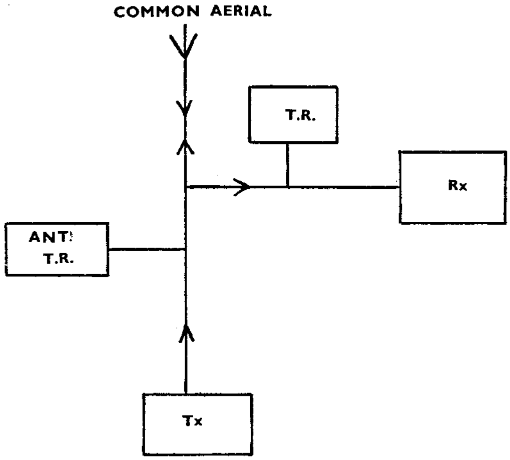


Fig. 44. Basic T/R System

73. The principle of operation is the same whichever type of cell is used. When the transmitter fires, the energy path from transmitter to receiver is closed, leaving a clear path from transmitter to the aerial. When the transmitter is not firing, the energy path from the aerial to the receiver is open, whereas that to the transmitter is closed.

Soft Rhumbatron

74. Centimetre T/R cells employ a resonant cavity with provision for short circuiting the cavity, usually by a spark gap. To reduce the voltage required for sparking, the cap is surrounded by some readily "ionizable" gas within a sealed glass envelope; this device is called a soft rhumbatron.

75. The electrodes forming the gap are enclosed within a glass envelope, the whole unit fitting inside a circular rhumbatron. Metal discs which pass through the gas-filled envelope complete the walls of the rhumbatron. The "keep-alive" electrode is fed with a high potential almost to breakdown point to ensure that the gas is permanently ionized, and only a small increase in voltage (from the transmitter pulse) is required to break down the gap and cause a short circuit.

T/R Device for Waveguide Systems

76. Use is made of the quarter-wave short-circuited line principle to open or close an energy path in the waveguide. With energy travelling inside the walls of the waveguide, a hole or break in the side will effectively prevent energy passing down the guide. A short placed across that hole then allows energy to pass. The rhumbatrons are coupled to the waveguide by holes in the side. The T/R cell is in the feed to the receiver and is fixed one half-wavelength from the waveguide. When the transmitter fires, the short produced across the gap is reflected as a short across the hole in the waveguide and the receiver path is blocked. Provided that the rhumbatron is tuned in resonance, its high impedance during the receiving period is across the receiver path and therefore has no effect. Energy from the returning echoes passes to the receiver without loss.

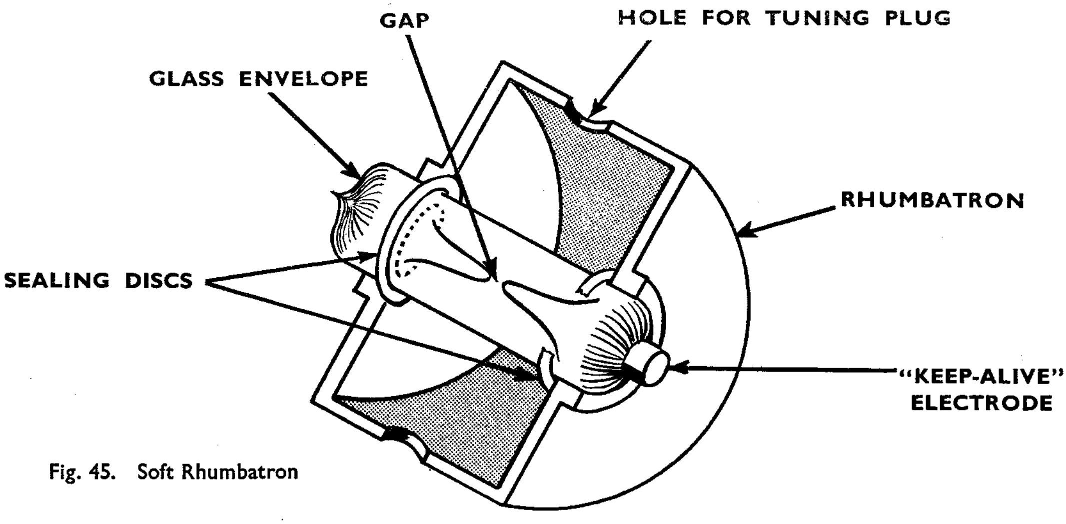


Fig. 45. Soft Rhumbatron

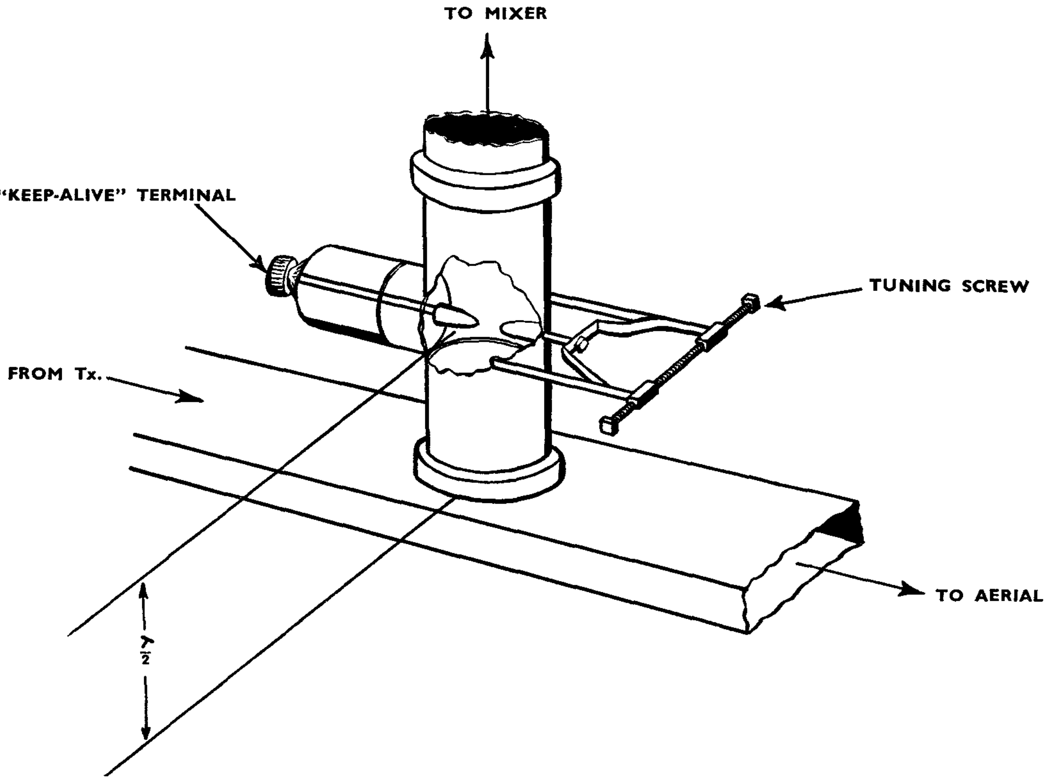


Fig. 46. T/R Cell

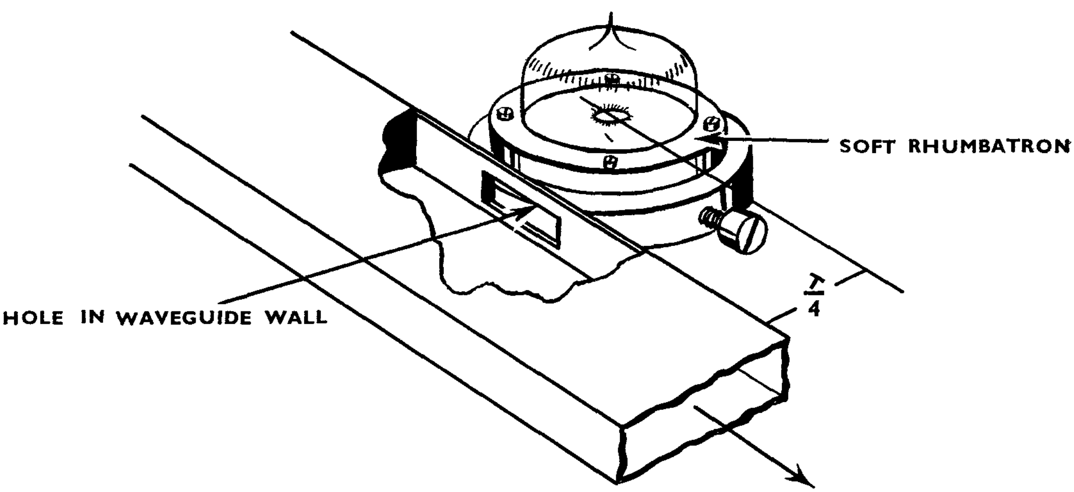


Fig. 47. Anti-T/R Cell Affixed to Waveguide

Anti-T/R Cell

77. Without the T/R cell, energy from the echoes would pass to the transmitter and be wasted. To prevent this, the transmitter path is closed during receiving periods by the non-closing of the hole in the waveguide. During the transmitting period the anti-T/R cell shorts the hole in the waveguide and plays no other part. No "keep alive" voltage is necessary for the anti-T/R cell, as delay in closing the hole is of no importance.

Typical 3 cm. Waveguide T/R System

78. Fig. 48 is a diagrammatic drawing of a typical T/R system showing the magnetron output probe feeding into a matched waveguide.

79. Between the magnetron output probe and the aerial is the anti-T/R cell and the receiver branch, with the T/R cell effectively in parallel. The first stage of the receiver being the mixer, the output from the klystron is local. Oscillation is mixed with the echo signals in the crystal, and the difference frequency is fed to the first I.F. stages. Matching is achieved by mechanical adjustment, and tuning by mechanical and electrical adjustments.

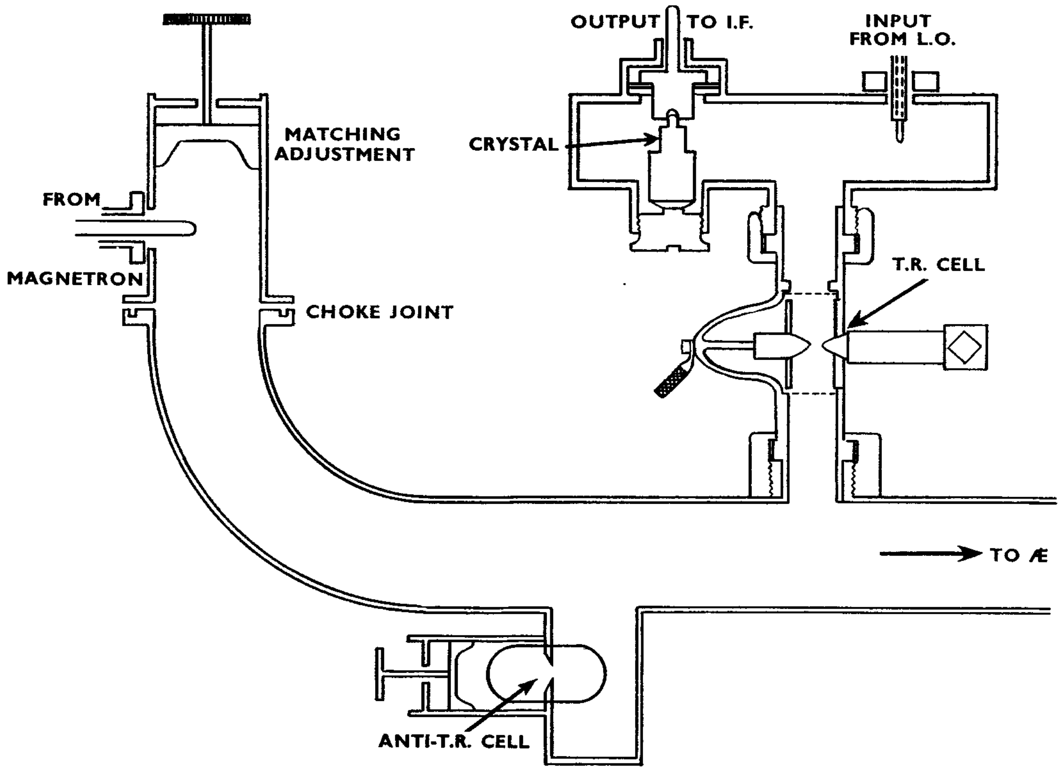


Fig. 48. Typical T/R System

CHAPTER 17

AIRCRAFT RADAR POWER SUPPLIES

POWER SUPPLY REQUIREMENTS

Need for Various Power Supplies

1. Some idea of the varied power supplies that are required by radar equipments has been given in the preceding chapters. Supplies to certain equipment must be stable, whilst accurate stability in others is unimportant. Besides D.C. at 28 volts for motors, relays, etc., there is a need for 200, 300, 400, and 500 H.T. voltages. Extra high tension (E.H.T.) up to 5,000 volts, either positive or negative with respect to earth, is used for the cathode ray tube. To energize the magnetron, and at the same time keep the anode and the waveguide at earth potential, a negative voltage pulse of some 14,000 volts is required. In addition the valve heaters require 5 and 6·3 volts A.C.

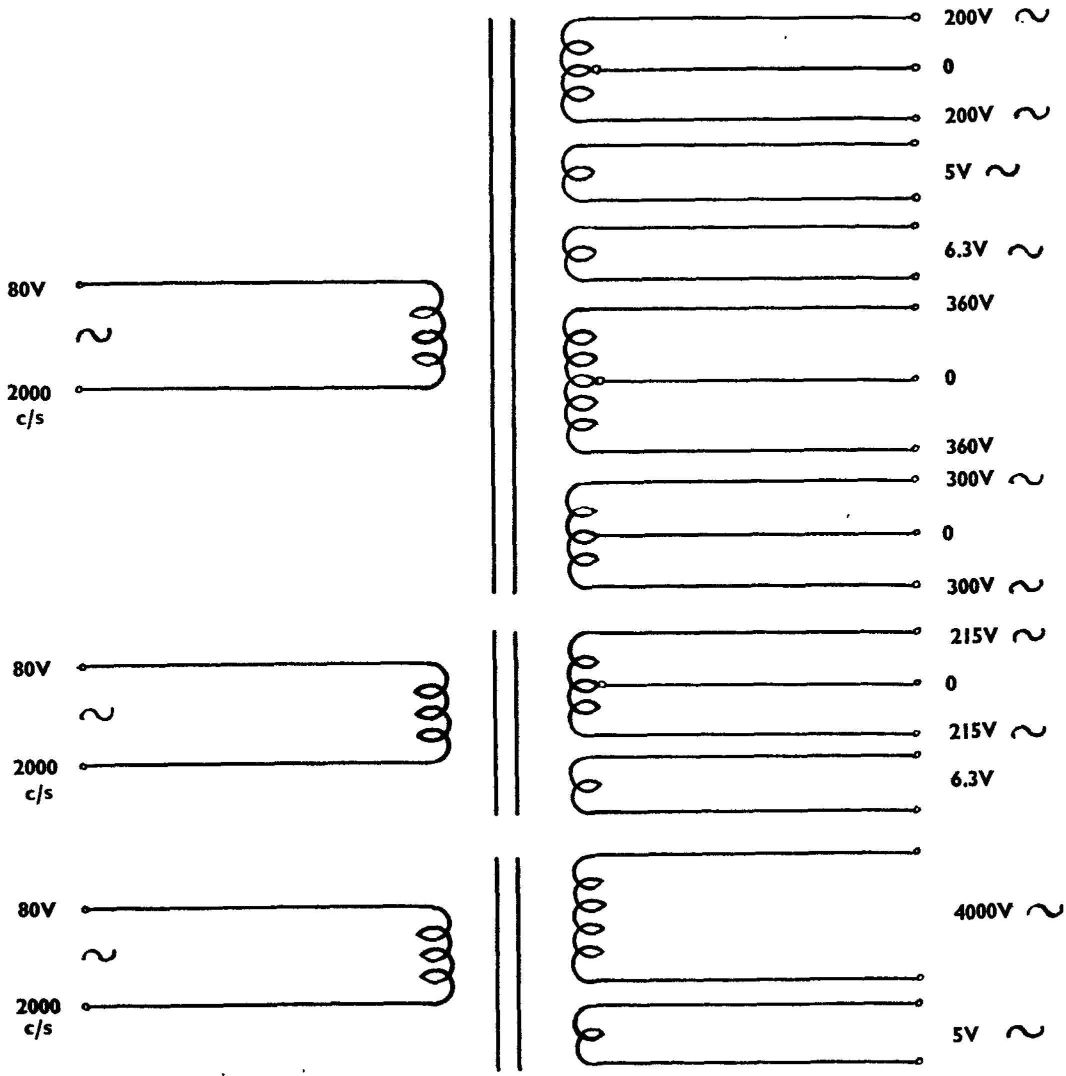


Fig. 1. Typical Power Unit Values

Source of Supply

2. To obtain these high voltages directly from D.C. sources is difficult, so an alternator, driven by the aircraft engine, or a D.C. motor, provides an A.C. output. This is later stepped up or down by transformers to the required voltage and rectified into D.C.

3. Generally speaking, for the same power rating and efficiency a transformer working on a high frequency can be made lighter and smaller than one designed for a low frequency. This also applies to smoothing chokes, etc. Weight and size being of primary importance in aircraft equipment, standard radar equipment is designed to operate from a supply of 80 volts at 2,000 cycles per second. This output, together with a connection from the aircraft's 28 volt D.C. supply, is normally applied to the power units forming part of each individual radar installation.

Typical Output Voltages

4. The incoming A.C. supply to a power unit is invariably fed to the primary of one or more transformers. The outputs, contained in the secondary windings, are at the voltage levels required for the particular equipment. For example, a typical equipment uses :—

(*a*) A.C. at 5 and 6·3 volts to heat the valve filaments.

(*b* A.C. at 200–0–200, 215–0–215, 300–0–300, 360–0–360 volts, with centre tappings to rectifiers for H.T. supply.

(*c*) A.C. at 4,000 volts rectified to supply the E.H.T. to the transmitter.

In addition to the output so far mentioned it may be necessary to provide outputs accurately stabilized at a particular voltage. They may be obtained from additional secondary windings, or tapped down from an existing output and subsequently stabilized.

TYPES OF RECTIFIERS

Half-Wave Rectifier

5. The simplest valve rectifier found in radar power units is the half-wave rectifier employing only one diode.

6. In Fig. 2 an alternating voltage applied via the capacitor C across the diode V will produce a charging current only on alternate half-cycles. This is because the diode will not conduct when the anode is negative with respect to the cathode. The resultant output is in the form of short pulses of current which maintain a fairly steady charge in the capacitor C. A serious disadvantage is that if a heavy current load is required the output voltage will vary considerably during the period of each cycle. This type of rectifier is satisfactory for circuits requiring a high voltage with low or intermittent current, and where perfect stability of the supply is unimportant. The plate supply for a cathode ray tube is an example.

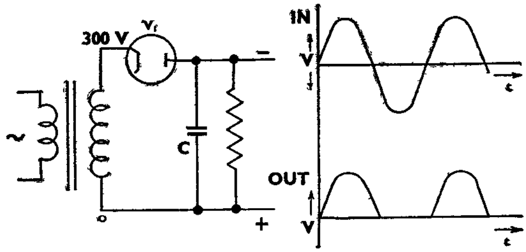


Fig. 2. Half-Wave Rectifier

Full-Wave Rectifier

7. The full-wave rectifier, as its name implies, rectifies both halves of the input sine wave. Two diodes are used, but are generally enclosed within one envelope, forming a *double diode.*

8. In Fig. 3 alternate half cycles of the input voltage are rectified by a particular diode, and their outputs commoned. There are twice as many charging pulses to capacitor C than were given by only one valve, therefore a higher load current may be taken without appreciable variation in the output voltage. Notice that the secondary winding has twice as many turns as those required for half-wave rectification, which represents a large increase in weight if used for high voltage supplies. This type of rectifier is used extensively for H.T. supplies up to 1,000 volts, especially where stability of supply is essential.

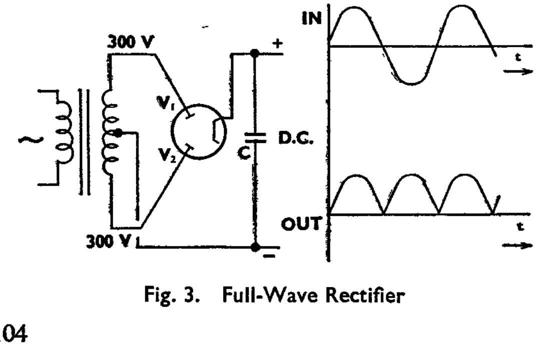


Fig. 3. Full-Wave Rectifier

Bridge Rectifiers

9. To obtain full-wave rectification from a single (untapped) secondary winding, bridge connections are used. Four rectifier valves are needed to achieve this object. One double diode may be used in place of V_2 and V_4 (Fig. 4).

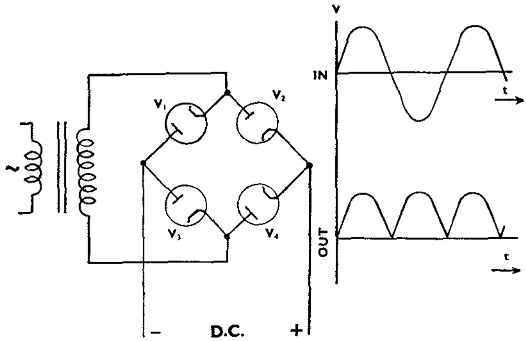


Fig. 4. Bridge Rectifier

10. When the top end of the secondary winding is made positive, diodes V_2 and V_3 conduct, completing a closed circuit via the load. On the other half cycle diodes V_1 and V_4 conduct, so that the direction of current round the load circuit remains the same.

Copper Oxide Bridge Rectifier

11. Where a lightweight compact power unit is essential for a low voltage supply the thermionic valves may be replaced by metal rectifiers. These consist essentially of a number of discs alternatively of copper and copper oxide. They are bolted together, in quite a small unit, the size depending on the current required from the rectifiers. Four of the units are used in the bridge circuit already described, and although a very small current will pass from the oxide to the copper the current is virtually unidirectional, *i.e.* from copper to oxide.

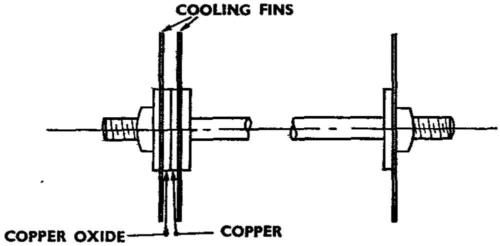


Fig. 5. Copper Oxide Bridge Rectifier

12. Comparing the metal rectifiers with the corresponding valves in the previous bridge circuit, the direction of the rectifier symbols represents the direction of the current (see Fig. 6).

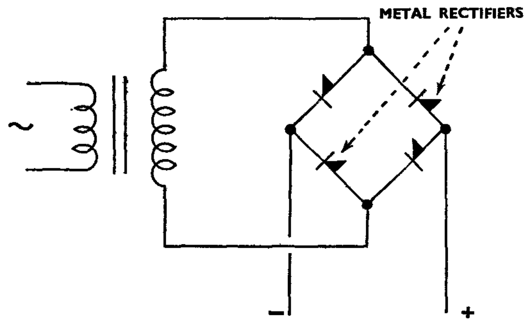


Fig. 6. Metal Rectifier Bridge Circuit

Voltage Doubler Rectifier Circuits

13. Where a high voltage, low current, low stability supply is required, the voltage doubler circuit may be used. The output voltage is twice that from the transformer secondary, because the circuit virtually consists of two half-wave rectifiers with their output capacitors in series. In Fig. 7, V_1 charges up C_1 on the positive half cycle, and V_2 charges up C_2 on the other half cycles. The output from C_1 and C_2 in series is the sum of the output voltages from each half-wave rectifier.

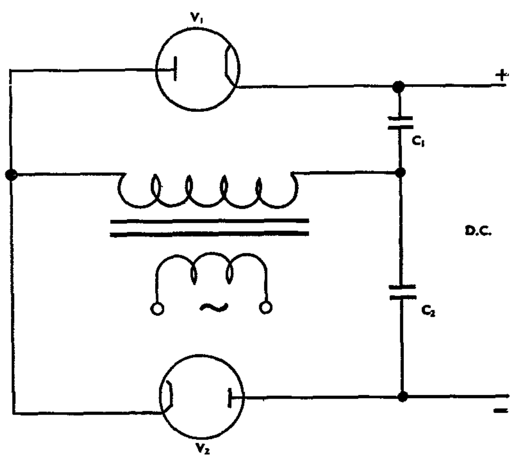


Fig. 7. Voltage Doubler Rectifier Circuit

SMOOTHING CIRCUITS

Composition of Output Voltage

14. The D.C. output obtained from the rectifier circuits so far discussed will not be a steady voltage. On analysis, the output is found to be made up of a steady voltage with an alternating voltage "ripple" superimposed on it. The frequency and amplitude of the ripple will vary for different rectifiers and for various load conditions. For example, the ripple frequency from a full-wave rectifier will be twice the supply frequency.

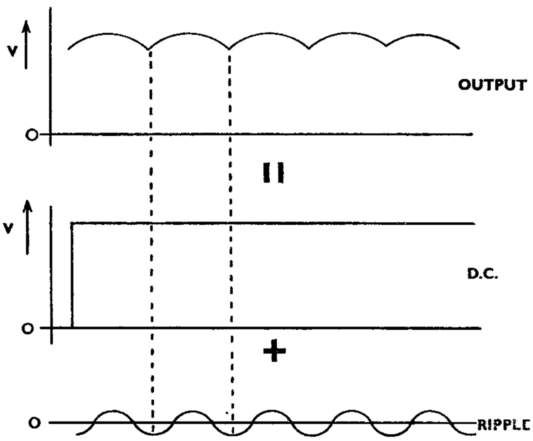


Fig. 8. Rectifier Output

This ripple is unimportant in certain radar functions, but in all other cases, especially when a stabilized supply is required, it must be entirely removed or reduced to a very low level.

L-C Filters

15. If the elimination of the whole ripple voltages is not essential, a simple inductance capacitance filter circuit is sufficient.

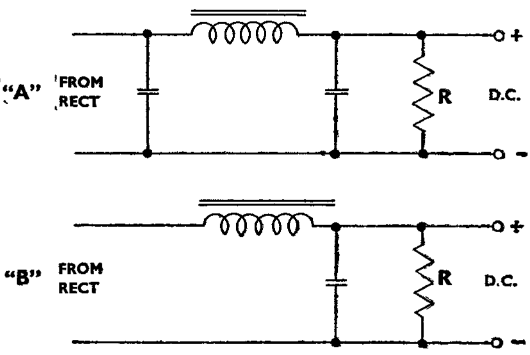


Fig. 9. L-C Filters

The circuit in Fig. 9 is called a *capacitor input*, or a *choke input filter*, depending on whether capacitance or inductance is used as the first element. The action is the same in both instances, for the capacitor offers a high impedance to the steady D.C. component and a very low impedance to the ripple voltage. The inductance, on the other hand, offers negligible impedance to the steady D.C., but a high impedance to the ripple. As current will take the easiest path in a circuit, the steady current will be maximum at the D.C. output terminals, and the ripple will pass through the capacitor.

16. The resistor R (Fig. 9) is usually included in a filter circuit, and particularly in a high voltage supply, to discharge the capacitors when the load is disconnected. To prevent a heavy drain on the capacitors during normal operation the resistor should have a high value, depending on the output voltage, *e.g.* 1 megohm across a 200 volt supply.

17. For additional smoothing, another section of inductance and capacitance may be added, and high values of L and C chosen (see Fig. 10).

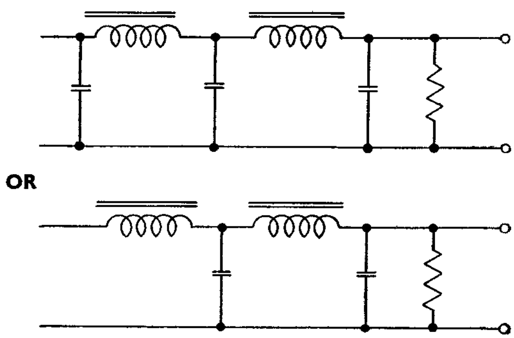


Fig. 10. L–C Filters with Additional Smoothing

18. A simple resistance capacitance smoothing circuit may occasionally be used if the loss of D.C. voltage across the resistor is acceptable. Its main advantage is the lower weight of a resistor, but excessive heat is generated if the circuit passes a high current.

VOLTAGE STABILIZERS

Need for a Stable Output

19. As already mentioned in para. 1, certain circuits in a radar equipment require a stable voltage supply. A regulator is necessary to maintain a constant voltage output irrespective of the load taken, even though the voltage supply is obtained by tapping off an existing smoothed supply, or by a separate rectifier.

Soft Valve Stabilizer

20. The neon valve is the basis of this type of stabilizer, relying for its operation on the constant voltage drop across the valve once the gas inside has ionized. The neon valve, consisting of two electrodes inside a gas filled envelope, is connected in series with a resistor across the supply. The load is connected to the output terminals directly in parallel with the valve (see Fig. 11).

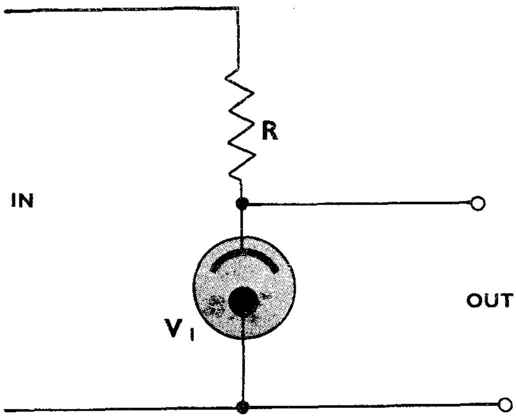


Fig. 11. Neon Stabilizer

So long as the input voltage is higher than that required to ionize the gas, any further rise in output voltage will cause an increased current through R and V. As an increase in current through the valve only causes a decrease in resistance, the increased voltage from the supply is dropped across R, leaving the output voltage constant.

21. Similarly, an increase in load current will be reflected as a decreased current through the valve. Its ionization tends to decrease, raising its internal resistance proportionally ; thus the output voltage remains at its previous level. This simple type of stabilizer is satisfactory only for low voltages and currents, and its output is stable only for a small variation of load.

Hard Valve Stabilizer

22. For circuits requiring a supply stabilized at a particular voltage, and constant for wide variations of load, the soft valve stabilizer is useless. The stabilized output must be at or around the ionizing voltage, unless of course two or more neon valves are used to obtain the required output.

23. A more satisfactory system uses hard valves. The high gain pentode is used as a control valve to adjust the bias on a regular valve. The latter is in series with the supply, and a change in bias will change its resistance thereby altering the output terminal voltage.

24. In Fig. 12, valve V_1 is the pentode control valve whose bias is set by the potentiometer RV_1. The anode current for V_1 passes through resistor R to the H.T. line. V_2 is the regulator valve in series with the positive supply line, and its bias is obtained from resistor R. If, for example, the output voltage rises, the positive bias on V_1 will rise, so increasing its anode current. This results in an increase of current through R, and an increased negative bias on V_2. The internal resistance of the latter will rise, preventing the increase of output voltage. The action is the opposite for a fall in the output voltage corresponding to an increased load. Provided that the valves and the resistance values are correctly chosen, the output voltage can be maintained constant at a particular level. as set by the potentiometer RV_1, to within 0·1 per cent. The neon V_3 serves to keep the reference point constant by preventing any change in the fixed bias on V_1, due to changes in its anode current. Owing to the voltage drop across V_2 the supply must exceed the required output voltage by about 50 volts. The maximum current available from the stabilizer is also limited to about 100 m/amps.

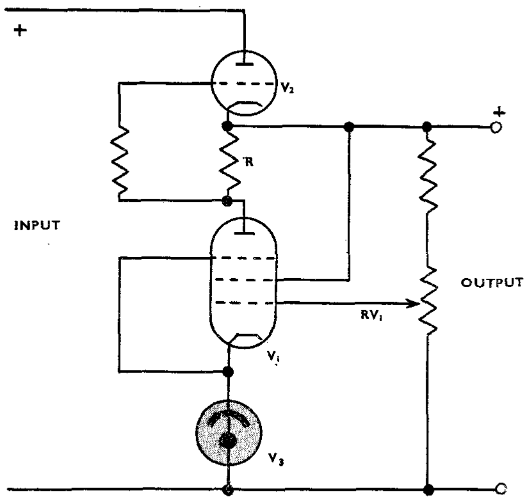


Fig. 12. Hard Valve Stabilizer

(60638) Wt. 29695/B/L. 3112 4,125 11/54 Hw.