CHAPTER X.—RADIO TELEGRAPHIC RECEPTION

E.M.F. AND CURRENT IN A RECEIVING AERIAL

1. In the preceding chapters we have discussed the production of electromagnetic radiation of frequencies such as are actually employed for radio-communication, without reference to the means employed to detect the presence of such radiation at the receiving station. The principles involved in the latter process will be the subject of the present chapter. We have already seen (Chapter VII) that the radiation from a transmitting aerial consists of a travelling electrical field, the strength of which varies sinusoidally both in space and time, or alternatively of a magnetic field having similar characteristics. These fields are in phase with each other, and if the wave is normally polarised, the direction of the electric field is vertical and that of the magnetic field horizontal, the plane of polarisation being perpendicular to the direction of propagation of the wave. This electromagnetic field travels with a velocity of 3×10^{10} centimetres per second, which is generally denoted by the symbol c. Consider the effect of the electromagnetic wave upon any electric circuit in its path. If at any point in the field two metal plates are suspended one above the other, d centimetres apart (fig. 1a), the passage of the electromagnetic disturbance through the volume of ether enclosed by them is equivalent to the existence of a P.D. between the plates, and we may find the magnitude of this P.D. quite simply. If the peak electric field strength is $\hat{\Gamma}$ electrostatic units, the peak P.D. is equal to $\hat{\Gamma}d$ E.S. units or 300 $\hat{\Gamma}d$ volts, because 1 E.S. unit of P.D. is 300 volts. Instead of suspending this condenser in mid-air, consider a single vertical wire d centimetres in length, as in fig. 1b. A magnetic field of strength $\mathcal{H}$ travelling with a velocity of c centimetres per second in the region in which the wire is situated, will set up an induced E.M.F. in this wire

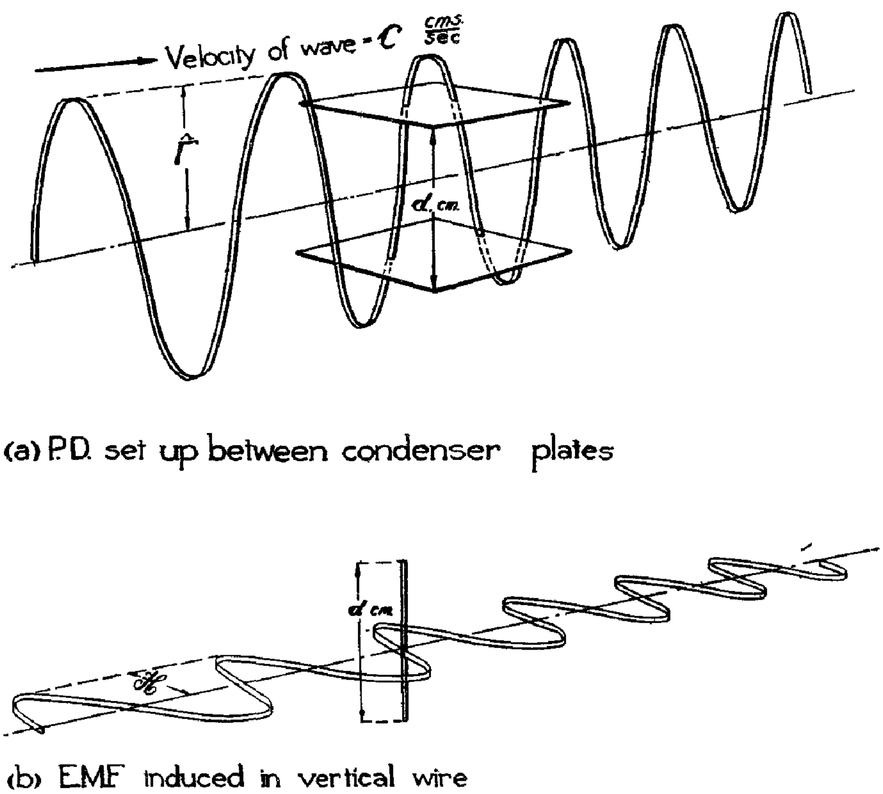


FIG. 1, CHAP X.—Induced voltage due to electromagnetic field.

in accordance with Faraday's law, and again its magnitude can be easily calculated, from the relation $\mathscr{E} = \frac{c\mathscr{H}d}{10^8} = 300\mathscr{H}d$ volts. As previously shewn (Chapter VII) the magnetic field strength $\mathscr{H}$ and the electric field strength $\hat{F}$ of the wave are equal numerically although expressed in different units, and therefore, whether we chose to consider the wave as an electrical or as a magnetic phenomenon, the magnitude of the E.M.F. set up in a given region is the same. It must be carefully noted that the voltage at any point in the field is not the sum of the two voltages derived above, for these are merely different aspects of the same thing. The electric field is identical with the moving magnetic flux, while the magnetic field is identical with the moving electric flux, and the peak P.D. between two points in space, their vertical distance apart being d centimetres, is either $300\,\hat{F}d$ or $300\,\mathscr{H}d$ volts. At the distances over which radio communication is generally used, the electric field strength is only of the order of from 10^{-7} to 10^{-9} E.S. Units. It is therefore more conveniently expressed in millivolts (or microvolts) per metre. Since 1 E.S.U. = 300 volts per centimetre, 1 millivolt per metre $= \frac{1}{3 \times 10^7}$ E.S.U.

Example.—At Cranwell, the peak value of the electric field strength due to the London Regional transmitter of the B.B.C. was found to be 10^{-8} E.S.U. Express this in millivolts per metre and find the peak E.M.F. induced in a vertical aerial 10 metres in height.

$$1 \text{ E.S.U.} = 300 \text{ volts per centimetre}$$
$$\therefore 10^{-8} \text{ E.S.U.} = 3 \times 10^{-6} \text{ volts per centimetre}$$
$$= 3 \times 10^{-4} \text{ volts per metre}$$
$$= \cdot 3 \text{ millivolts per metre.}$$

The total E.M.F. acting in the aerial circuit will therefore be $\cdot 3 \times 10 = 3$ millivolts.

2. As the vertical wire must possess distributed capacitance, inductance and resistance, the induced E.M.F. is able to establish a current in the wire, and the latter is then said to act as a receiving aerial. The current may be considered to be a conduction current in the wire, and a corresponding displacement current in the surrounding medium, the circuit consisting of the wire itself and the capacitance existing between different parts of the conductor. If the induced voltage has an R.M.S. value of E volts, and the total impedance of the aerial circuit is Z ohms, the R.M.S. value of the current is given by the usual equation,

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

and will attain its greatest value if the receiving aerial circuit is in resonance with the frequency of the distant radiant circuit, i.e., the transmitter. The receiving aerial will offer no reactance at this frequency and the value of the current will be $\frac{E}{R}$. In order to obtain maximum current, therefore, the inductance and capacitance in the receiving aerial circuit must be adjusted to such values that

$$\omega L = \frac{1}{\omega C}$$

where L and C are the effective inductance and capacitance of the whole circuit. The principles involved in tuning receiving aerial to a given frequency may be simplified by considering only the earthed aerial, and assuming also that its effective capacitance C and inductance L are constant for all frequencies. Thus a certain small receiving aerial is found to have an effective inductance of 60 microhenries, an effective capacitance of 170 micro-microfarads, and an effective resistance of 50 ohms. With neither inductance nor capacitance added, therefore, its resonant frequency is

$$f_r = \frac{1}{2\pi\sqrt{LC}},$$

$$= \frac{1}{2\pi\sqrt{\frac{60}{10^6} \times \frac{170}{10^{12}}}}.$$

$$= 1{\cdot}57 \times 10^6 \text{ cycles per second (1,570 k.c/s.).}$$

Aerial tuning

3. (i) Now suppose it is required to adjust this aerial to receive a signal on a frequency of 8×10^5 cycles per second. As the signal frequency is lower than the resonant frequency of the aerial, the desired result is obtained by adding inductive reactance in series between the aerial and earth. To find the reactance required, we observe that the reactance of the aerial alone is

$$X_E = \omega L - \frac{1}{\omega C}$$

$$\text{and } \omega = 2\pi \times {\cdot}8 \times 10^6 = 5{\cdot}025 \times 10^6$$

$$X_E = (5{\cdot}025 \times 10^6 \times 60 \times 10^{-6}) - \left(\frac{10^{12}}{5{\cdot}025 \times 10^6 \times 170}\right)$$

$$= 301{\cdot}5 - 1168$$

$$= -866{\cdot}5 \text{ ohms.}$$

The negative sign confirms that the reactance of the aerial circuit at the particular frequency is capacitive, and an inductive reactance of $+ 866{\cdot}5$ ohms must be added to bring the aerial circuit into resonance with the distant transmitter. This corresponds to an inductance of 172 microhenries, although (as shown in Chapter V) the added reactance may be constituted by an inductance of smaller value than this, in parallel with a condenser of a certain value. The cardinal point to be remembered is that if the distant transmitter has a frequency higher than the natural frequency of the aerial, capacitive reactance must be interposed between the

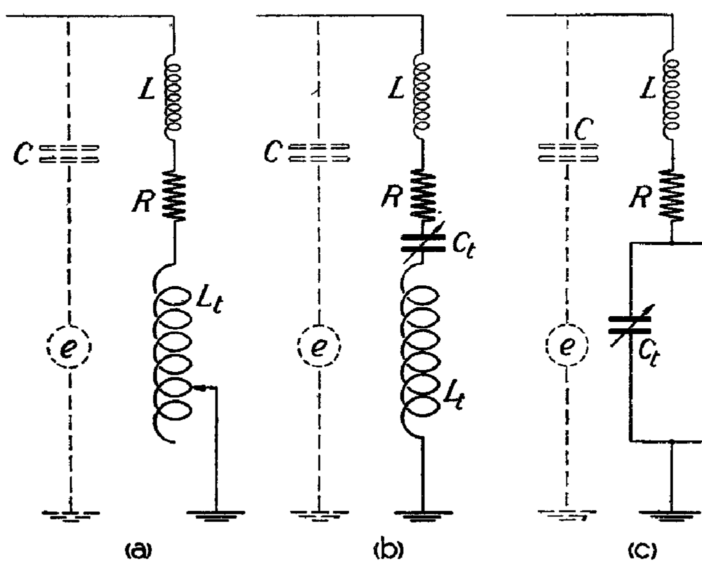


FIG. 2, CHAP. X.—Tuning devices for receiving aerial.

aerial and earth, while if the frequency of the transmitter is lower than the natural frequency of the aerial, inductive reactance must be inserted. The necessary tuning reactance may be obtained by a combination of inductance and capacitance, either or both being variable in order that the receiver may be adjusted to cover a given frequency range, but no matter how complex the aerial circuit may appear, the aerial circuit as a whole always operates as an acceptor circuit for the frequency to which it is tuned. Three possible arrangements of the receiving aerial circuit are shown in fig. 2, in which L, C, R are the constants of the aerial, e the effective E.M.F. induced in the aerial by the incoming signal, and L_t, C_t the tuning inductance and capacitance.

(ii) The arrangement shown in fig. 2a has already been illustrated by a numerical example; it should be noted that if it is desired to receive frequencies above the resonant frequency of the aerial, the total tuning reactance must be capacitive, and it will be necessary to insert a series condenser, resulting in the circuit shewn in fig. 2b.

Example.—In fig. 2b if the aerial inductance is 60 μH, its capacitance 170 $\mu\mu F$, and the added inductance 1080 μH, find the frequency range which will be covered if C_t is variable between 30 and 300 $\mu\mu F$.

The total effective capacitance C_e is that of C and C_t in series, or $C_e = \frac{C\,C_t}{C + C_t}$.

When $C_t = 30\ \mu\mu F$,

$$C_e = \frac{30 \times 170}{30 + 170} = 25{\cdot}5\ \mu\mu F.$$

When $C_t = 300\ \mu\mu F$,

$$C_e = \frac{300 \times 170}{300 + 170} = 108{\cdot}5\ \mu\mu F.$$

The lowest frequency will be

$$f_l = \frac{10^9}{2\pi\sqrt{(1080 + 60) \times 108{\cdot}5}}$$

$= 451{,}000$ cycles per second (451 k.c/s.),

and the highest frequency

$$f_h = \frac{10^9}{2\pi\sqrt{(1080 + 60) \times 25{\cdot}5}}$$

$= 930{,}000$ cycles per second (930 k.c/s.).

(iii) In the arrangement shown in fig. 2c it is easily demonstrated by methods explained in Chapter V that if L_t is very much larger than L the resonant frequency is approximately

$$f_r = \frac{1}{2\pi\sqrt{L_t\,(C + C_t)}}$$

i.e., for tuning purposes we must regard the tuning condenser to be in parallel with the aerial capacitance. It must particularly be noted that no " rejector " action is involved in the parallel combination of L_t and C_t since it is not in resonance with the signal frequency.

Example.—If the aerial inductance is 60 μH, the aerial capacitance 170 $\mu\mu F$, the added inductance 1080 μH and the added capacitance is variable from 30 to 300 $\mu\mu F$, find the tuning range.

The highest frequency will be

$$f_h \doteqdot \frac{10^9}{2\pi\sqrt{1080\,(170 + 30)}}$$

$= 334{,}200$ cycles per second (334 k.c/s.), and the lowest frequency

$$f_1 \doteqdot \frac{10^9}{2\pi\sqrt{1080\ (170 + 300)}}$$

$$= 224{,}000 \text{ cycles per second (224 k.c/s.).}$$

(iv) In obtaining the above results, it was assumed that the aerial capacitance is constant at all frequencies, but this is not strictly true ; nevertheless, the approximations are sufficiently close to enable one to predict the probable tuning range of a given circuit when used with a particular aerial. Other arrangements of the aerial tuning system are discussed in later paragraphs; and immediate attention must be devoted to the means whereby the reception of a signal is made perceptible to the human senses. In order to appreciate this problem it is essential to bear in mind that the strength of the field radiated by a transmitter is rapidly attenuated as the distance from the transmitter increases and it is often necessary to detect the presence of a signal having a field strength of the order of one microvolt per metre. If the height of the receiving aerial is 10 metres and its resistance, including that of the tuning devices and earth connection, 50 ohms, a field of this intensity would establish an aerial current of only $\frac{10 \times 1 \text{ microvolt}}{50 \text{ ohms}} = \cdot 2$ microampere. It is quite impossible to detect an alternating current of this magnitude by any direct-reading instrument such as a hot-wire ammeter and it is necessary to employ some form of detector which possesses the required degree of sensitivity.

RECTIFICATION

Necessity for rectification

4. The telephone receiver described in Chapter II can be designed in such a manner that it is sensitive to extremely small variations of current, i.e. of the order of one-tenth of a microampere. At first sight, therefore, it might be inferred that the presence of current in the receiving aerial could be detected by connecting a telephone receiver (or a pair of such receivers) in series between the aerial proper and earth. This simple solution is not effective for several reasons which must be fully appreciated, and therefore merit a somewhat detailed discussion. It is convenient to refer to the physiological processes by which the sensation of sound is produced in the human brain as " hearing," while the sound may be defined as that which is heard. The process of hearing is extremely complicated and, like all other phenomena connected with the nervous system, cannot be said to be fully understood. It is however known that when the drum of the ear is set into vibration by sound, the presence of the latter is signalled to the brain. The sound consists of mechanical vibration of the medium with which the ear-drum is in contact, which is generally air at atmospheric pressure, and the sensations produced by the sound depend upon three characteristic properties of the vibration. These are first the frequency, second the intensity and third the wave form, but when dealing with C.W. or I.C.W. reception we are chiefly concerned with the first of these characteristics, the frequency. The ear and brain perceive as sound only such vibrations as possess frequencies lying between a lower and an upper limit ; these limits cannot be sharply defined, for they vary in different individuals, and even in the same individual according to the circumstances existing at the time. Direct detection of a radio signal by the telephone receiver, then, is not possible for the following reasons :—

(i) In normal individuals the extreme lower limit is about 16 cycles per second, and the upper about 20,000 cycles per second. The upper limit is therefore lower than the highest frequency used for radio communication, and consequently, if a telephone receiver were connected in the manner suggested above, the vibration of the telephone diaphragm at the frequency of the signal would not convey to the brain any sensation of sound.

(ii) In a telephone receiver of ordinary design, the passage of a radio-frequency current would not set up an appreciable vibration of the diaphragm, which owing to its stiffness and inertia possesses a natural frequency of the order of only 1,000 cycles per second. The resonance is not very sharp in the normal designs, and a fairly even response can be attained over a frequency range of say 200 to 2,000 cycles per second, but the response of the diaphragm falls off rapidly as the latter frequency is exceeded, and above about 5,000 cycles per second practically no response can be obtained. A typical response characteristic for a commercial instrument is shewn in fig. 3.

(iii) The windings and connecting leads of the telephone receiver possess considerable inductance and distributed capacitance. The inductance of a telephone winding of ordinary design may be of the order of 1 henry, which is very much greater than is required in the aerial circuit for tuning purposes. This inductive winding is however shunted by the distributed capacitance which may be of the order of $100\mu\mu F$ and consequently will offer very much less opposition to an alternating current of radio frequency, e.g. if $\omega = 5 \times 10^6$ the capacitive reactance of the shunt path is only 2×10^4 ohms, while an inductance of 1 henry offers a reactance of 5×10^6 ohms. Hence only a small portion of the current will flow through the windings, and very little response would be obtained even if the mechanical characteristics of the diaphragm could be modified to allow it to vibrate at higher frequencies.

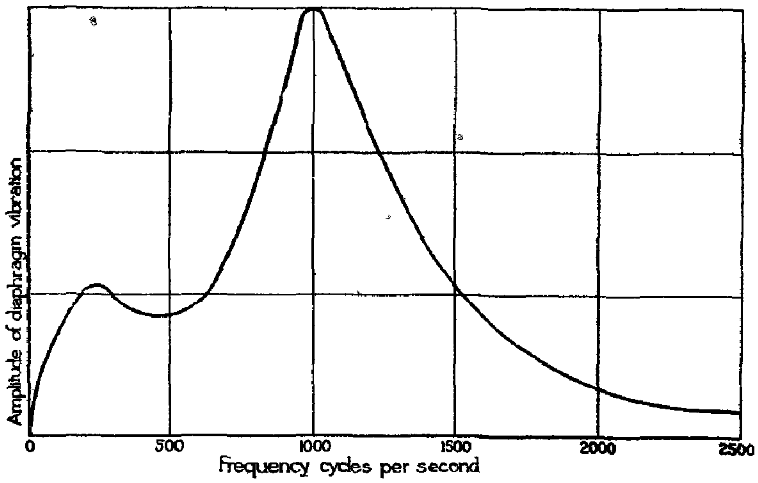


FIG. 3, CHAP X.—Frequency response of telephone receiver.

Rectification by ideal diode

5 (i) It may appear that the impossibility of direct employment of the telephone receiver for radio reception has been given more consideration than is merited by its importance, but experience shows that operators frequently fail to appreciate the necessity for the inclusion of other apparatus in the receiver. The telephone receiver can be, and is, almost universally used as a receiving device in radio-telegraphy, in conjunction with other devices which cause the current through the telephone to vary in amplitude at a frequency which is within its responsive capability. The necessary steps are first, rectification of the radio-frequency currents and second, variation of their amplitude at a rate which is within the limits of efficient response of the telephone, e.g. from 200 to 2,000 times per second. A rectifier has already been defined as a conductor which does not obey Ohm's law, or which has a non-linear current/voltage characteristic, and the rectification of an alternating voltage in order to provide direct current H.T. supply for the C.W. transmitter has been described in the previous chapter. Now suppose that owing to the operation of a distant C.W. transmitter a radio-frequency current is established in a receiving aerial circuit which is tuned to the transmitter frequency by means of an added inductance; as shewn in Chapter V, the P.D. across the ends of this inductance may be much greater than the E.M.F. induced in the aerial. A rectifier and a telephone receiver, in series, may be connected across the ends of the inductance, the circuit being then as shown in fig. 4, in which the rectifier is a two-electrode valve or diode. A

reservoir condenser C_r is connected in parallel with the telephones. This serves not only as a reservoir but also to reduce the radio-frequency impedance of the path between the points A and B to a negligible value.

(ii) The action of this circuit may be studied with the aid of the characteristic curve of the rectifier. The general shape of the diode characteristic has been discussed in Chapter VIII, but it will simplify the present explanation if we assume the diode to possess the ideal characteristic shown in fig. 5, i.e. a linear relation between anode voltage (V) and anode current (I) for all positive valves of V, and zero current for all negative values of V. When no oscillatory P.D. exists between the ends of the inductance the anode-filament P.D. of the diode is zero, and no anode current will flow. During the reception of an electro-magnetic wave an oscillatory aerial current will be established, causing a difference of potential between the ends of the tuning inductance. This P.D. is applied to the rectifying circuit, that is, to all intents and purposes, to the anode-filament path of the diode, for as already pointed out, the presence of the reservoir condenser ensures that no appreciable radio-frequency P.D. will exist between the points A and B.

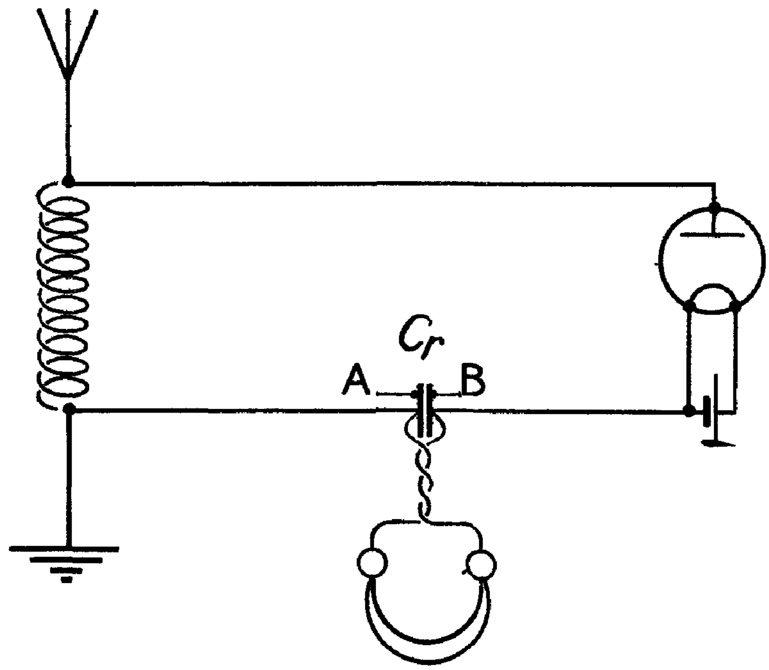


FIG. 4, CHAP X.—Simple receiver with diode rectifier.

During those half-cycles of oscillatory anode-filament P.D. in which the anode is positive with respect to the filament, an anode current will be established, which will flow through the tuning inductance and charge the reservoir condenser. Electrons reaching the plate A set up a displacement current in the dielectric and repulsion of electrons from the plate B, which therefore becomes positively charged. During the half-cycles in which the anode is negative to the filament, the anode filament path of the diode is non-conductive and no such anode current can exist. The electron current flowing into the reservoir condenser at the point A thus consists of a series of unidirectional impulses as shown in the diagram.

6. (i) So far the presence of the telephones has been ignored, for as previously stated no appreciable portion of the radio-frequency currents will pass through them. The windings however constitute a path by which the reservoir condenser is free to discharge, and therefore the charge introduced into it by the impulses of electron current will leak away at the average rate at which it is received, in the form of a unidirectional current through the windings. With

the ideal form of rectifier characteristic postulated, if the peak voltage applied to the rectifier is $\mathcal{V}$, and the anode A.C. resistance of the valve is r_a, the peak value of the anode current is $\frac{\mathcal{V}}{r_a}$, and the average value of anode current over a complete cycle is $\frac{\mathcal{V}}{\pi r_a}$. This is the value of the steady current which will be established through the windings of the telephone receiver, during the first cycle of the oscillatory voltage. If the impedance of the telephone receiver is negligible compared to the anode A.C. resistance of the valve, each successive positive half-cycle will give rise to a current of this value, so that during the whole of the period in which the oscillatory P.D. is applied, a steady current of $\frac{\mathcal{V}}{\pi r_a}$ amperes will flow through the telephone windings.

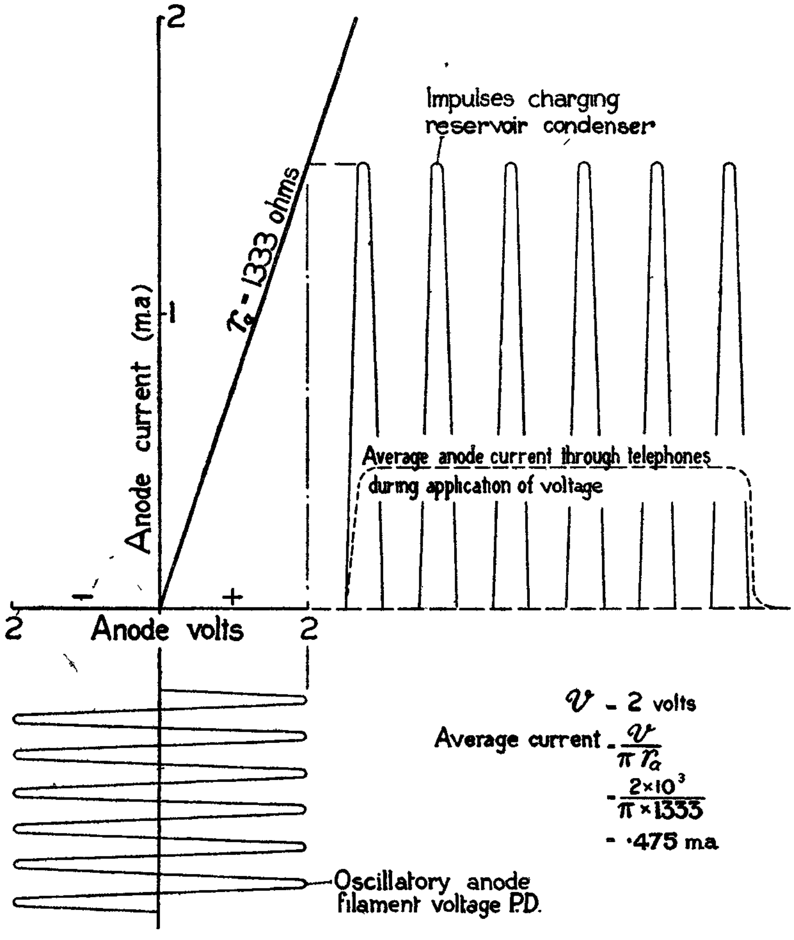


FIG. 5, CHAP. X.—Rectification of oscillatory voltage of constant amplitude by ideal rectifier.

(ii) The effect of this current on the telephone magnets will depend upon the direction of the current, for if in one direction round the winding it will increase the pull on the diaphragm, in the contrary direction it will weaken the magnets slightly and tend to release the diaphragm. In either event, no vibration of the diaphragm ensues, and little if any indication of the presence of the aerial current will be given although if the transmitter is very close to the receiver, a single click may be heard when the transmitting key is pressed, and another when it is released. If however, a high resistance microammeter were inserted in place of the telephones the pointer would be deflected, rising to some mean value, e.g. under the operating conditions of fig. 5, to 475 microamperes.

Approximate rectified current with resistance load

7. The value $\frac{\mathscr{V}}{\pi r_a}$ which has been obtained above assumes that the impedance of the circuit (external to the diode itself), is zero. Since this cannot be true in practice, owing to the presence of the telephone receivers and reservoir condenser, the rectifier current will be less than this, because the P.D. across the reservoir condenser causes the anode to become more and more negative with respect to the filament, during the time that the radio-frequency voltage is applied. The value $\frac{\mathscr{V}}{\pi r_a}$ for the rectified current must therefore be regarded as an upper limit which cannot be exceeded.

An exact derivation of the correct value involves somewhat heavy mathematics and is purely of academic interest, since no rectifier possesses the ideal characteristics postulated. Since, however, it is found experimentally that on the application of a radio-frequency voltage of constant amplitude, the counter-E.M.F. of the reservoir condenser reaches a mean steady value in the course of the first few cycles, continuing then to receive during each successive positive half-cycle a charge just sufficient to maintain a practically steady current through the load, we may obtain an approximation to the load current and the counter-E.M.F. of the condenser as follows. As before, let $\mathscr{V}$ be the peak value of the applied voltage, C_r the capacitance of the reservoir condenser, r_a the anode A.C. resistance of the valve, R the load resistance and e the counter-E.M.F. of the reservoir condenser. Then the charging current during any positive half-cycle will be

$$I = \frac{\mathscr{V} - e}{\pi r_a}$$

flowing for nearly $\frac{1}{2f}$ second. The charge received by the condenser will be

$$Q = \frac{I}{2f} = \frac{\mathscr{V} - e}{2\pi f r_a} = \frac{\mathscr{V} - e}{\omega r_a}$$

and the counter-E.M.F. developed, if the load resistance were infinitely high, would be

$$e = \frac{Q}{C_r} = \frac{\mathscr{V} - e}{\omega C_r r_a}$$

Owing to the presence of the load resistance, the condenser charge leaks away during the negative half-cycles, the average current through the resistance being $\frac{e}{R}$ amperes. During one half-cycle, the charge lost will be $\frac{e}{2fR}$ coulombs, leading to a fall of P.D. equal to $\frac{e}{2fC_rR}$ or $\frac{\pi e}{\omega C_r R}$ volts. Hence

$$e = \frac{\mathscr{V}}{\omega C_r r_a} - \frac{e}{\omega C_r r_a} - \frac{\pi e}{\omega C_r R}$$

$$e\left(1 + \frac{1}{\omega C_r r_a} + \frac{\pi}{\omega C_r R}\right) = \frac{\mathscr{V}}{\omega C_r r_a}$$

$$\text{or } e = \frac{R\mathscr{V}}{\pi r_a + R + \omega C_r R r_a}$$

The current I_r through the load resistance is $\frac{e}{R}$, and

$$I_r = \frac{\mathscr{V}}{\pi r_a + R + \omega C_r R r_a}$$

Actually, the load current will be rather less than this, because the condenser may charge for appreciably less than $\frac{1}{2f}$ second. The average input resistance of the rectifier is also of interest. To the degree of accuracy of the above derivation, if R_0 is the input resistance, since the average value of the applied voltage during one half-cycle is $\frac{2\mathcal{V}}{\pi}$, it follows that

$$\frac{2\mathcal{V}}{\pi R_0} = \frac{\mathcal{V} - e}{\pi r_a}$$

$$\therefore \quad R_0 = \frac{2 r_a}{1 - \frac{e}{\mathcal{V}}}$$

The average input resistance is of importance in a particular service application of the diode (*see* paragraph 49).

Detection of I.C.W. signals

8. To produce an audible response in the telephone receiver, it is necessary to interrupt or vary the current at a rate to which the diaphragm will respond. This variation or interruption may be performed either at the transmitter or at the receiver, but if performed at the transmitter

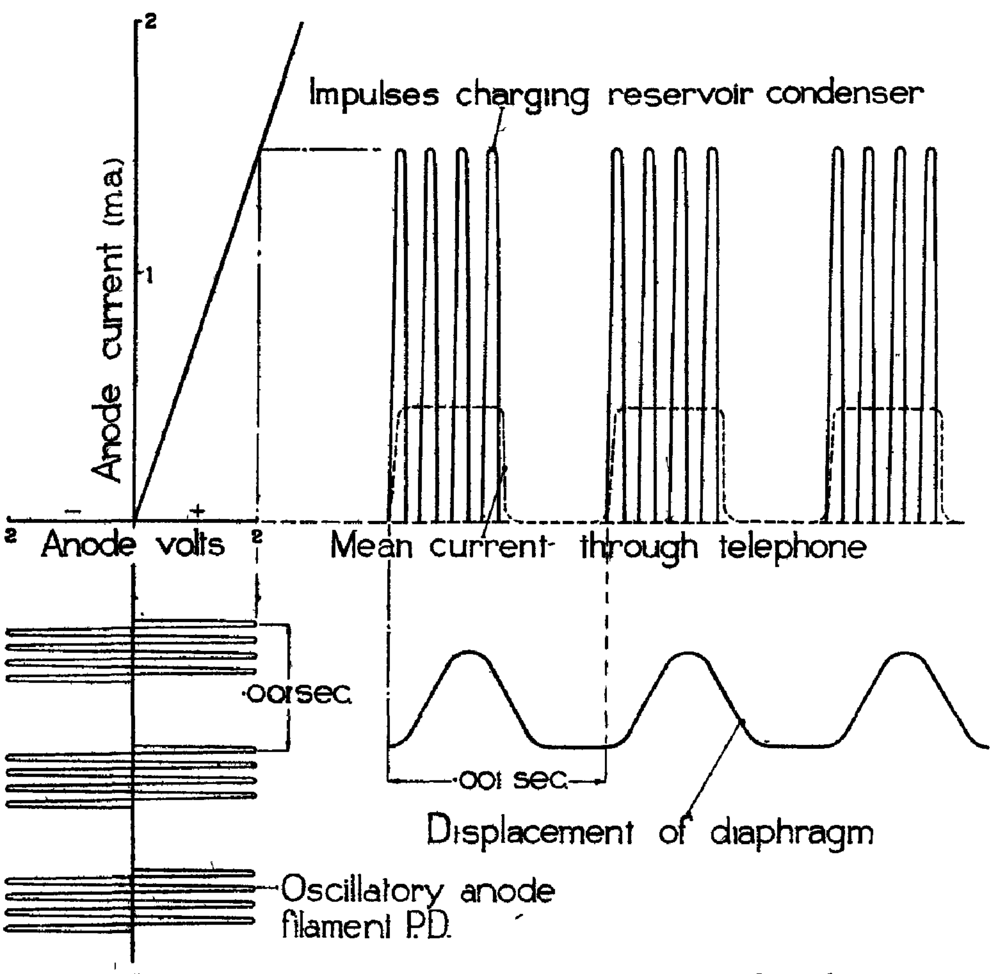


FIG 6, CHAP. X.—Rectification of I.C.W. signal by ideal rectifier.

the emission is no longer a continuous wave, but some form of modulated wave, i.e., I.C.W., M.C.W., or radio-telephony depending upon the nature of the variation. The receiver action in the case of I.C.W. transmission is shewn in fig. 6, which is similar to fig. 5 except that the voltage applied to the rectifier has a different wave form. The transmission may consist of radio-frequency waves which are interrupted 1,000 times per second; if the radio frequency is 1 megacycle per second, one group of 500 complete cycles will occupy $\frac{1}{2000}$th of a second, while an interval of similar duration will occur between successive groups. As a morse "dot" lasts for about one-twentieth of a second (at 20 words per minute) the number of groups comprising a single "dot" is $\frac{1}{20} \div \frac{1}{1000} = 50$. It will be appreciated therefore that neither the number of waves per group, nor the duration of individual waves and complete groups respectively, can be drawn to scale. During every group of waves, a negative charge will be established upon the plate A of the reservoir condenser, and a corresponding positive charge on the opposing plate B, the condenser however discharging through the telephones at the average rate at which it is charging. The telephone current therefore rises to a value of $\frac{\mathscr{V}}{\pi r_a + R}$ (approximately) during each group of waves and falls to zero when the group ceases; as each group of waves lasts only about $\frac{1}{2000}$th of a second and is followed by an interval of about the same duration before the commencement of the next group, the telephone current will rise and fall at the same rate, and the telephone diaphragm will be set into vibration at a fundamental frequency equal to the number of groups per second, producing a musical note which is easily distinguished from other noises which may be present (*see* paragraphs 5 *et seq.*). Actually the vibration will contain higher harmonics, but this is of no importance in telegraphic reception.

Square law rectification

9. Having established the general nature of the process of rectification it must now be pointed out that the effect produced by a diode rectifier differs in one important respect from that which would be produced by the ideal rectifier hitherto considered. If the rectifier characteristic were truly a straight line sloping upward from the origin for all positive values, and a straight line of zero slope for all negative values of applied voltage, the charge introduced into the telephone condenser would be directly proportional to the peak value of the applied voltage. Such a rectifier is said to be a linear one. The term linear is often thought to refer to the fact that the characteristic curve is represented by straight lines, but actually it signifies that the output voltage, i.e. e, is directly proportional to the peak signal voltage $\mathscr{V}$ and can be expressed algebraically thus

$$e = K\mathscr{V}$$

where K is a constant of proportion. No such ideal rectifier is known. Referring to the characteristic curve of an actual diode, it is found by trial that for small values of anode voltage, the anode current varies approximately with the square of the anode voltage. This implies that for small applied signal voltages, the diode will give a rectified current which is proportional to the square of the input voltage. Fig. 7 shows the actual characteristic of a diode, and the peak current obtained by applying voltages of various peak values. An alternating E.M.F. of peak value 2½ volts gives a peak current of ·5 milliamperes, while 5 volts gives a peak current of 2 milliamperes, that is, doubling the input voltage gives four times the rectified current. Similarly, 7½ volts input gives a current of 4·5 milliamperes peak value. If however, the input voltage is further increased this "square law" is not maintained, for an E.M.F. of 10 volts peak only causes a current of 7·5 milliamperes peak value, whereas if the square law were applicable the current would be 8 milliamperes, while a further increase of input voltage to 12·5 volts gives only 11 milliamperes instead of 12·5 milliamperes which would be obtained if the square law continued to represent this portion of the characteristic. These effects are generally expressed by the statement that the characteristic of a diode rectifier follows the square law ($I_a \propto V_a^2$) over the lower portion, and the linear law ($I_a \propto V_a$) over the upper portion. There is no hard and fast line of demarcation, but a few trial values as given above will decide in what region either law may be assumed to hold. This law of variation between input voltage and resulting current has been explained with specific reference to the diode, but it is found that practically all rectifiers in general use possess such characteristics that for input voltages below a certain value the square law may be assumed, while for higher input voltages the linear law is more nearly correct.

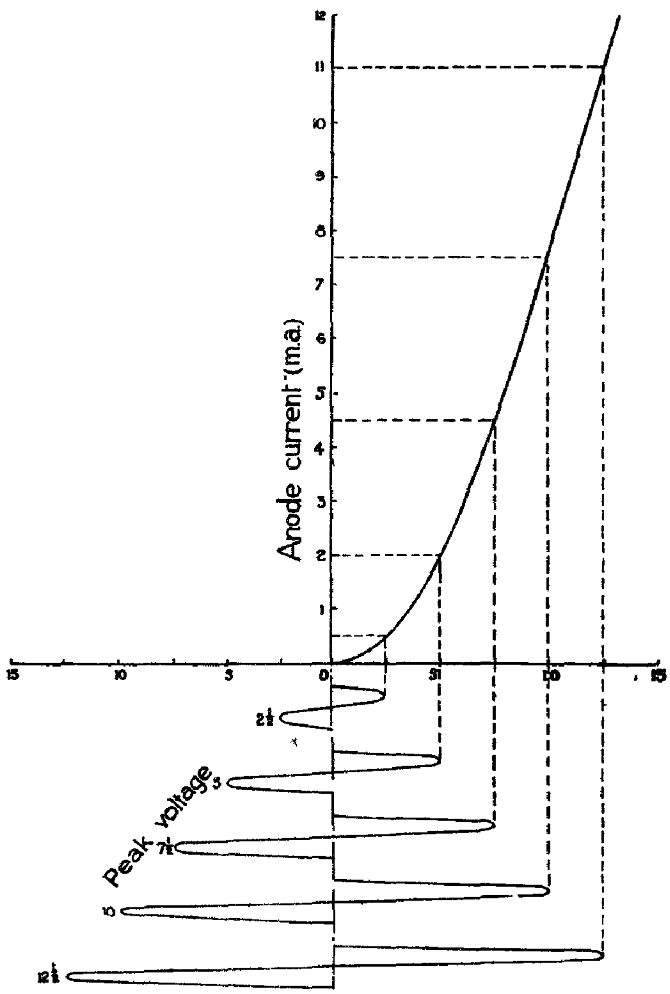


FIG. 7, CHAP. X.—Relation between peak input voltage and peak anode current in actual diode.

10. In the foregoing discussion it was assumed that in the absence of a signal the anode and filament of the diode were at the same potential. This condition is not necessary and in practice it is generally found advantageous to apply a small positive potential to the anode of the valve in order to obtain the greatest rectified current for a given signal voltage. The rectification of a single cycle is then as shown in fig. 8. Under no-signal conditions, the anode voltage is E_a and the anode current I_0. During the positive half-cycle the anode current gradually increases to I_1 and falls to I_0, while during the negative half-cycle it falls to I_2, returning to the value I_0 at the end of the cycle. As the increase of anode current $(I_1 - I_0)$ is greater than the decrease $(I_0 - I_2)$ the average current during the cycle is not I_0 but I_m, where

$$I_m = \frac{I_1 + I_2}{4} + \frac{I_0}{2}$$

In the diagram, $I_1 = 4 \cdot 5$ milliamperes, $I_2 = 0 \cdot 5$ milliamperes and $I_0 = 2$ milliamperes, hence

$$I_m = \frac{4 \cdot 5 + 0 \cdot 5}{4} + \frac{2}{2}$$
$$= 2 \cdot 25 \text{ milliamperes.}$$

11. The increase of anode current due to the application of a signal voltage is the rectified current. It is equal to $I_m - I_0$ or to $\frac{I_1 + I_2}{4} - \frac{I_0}{2}$; in the present example this is equal to $0 \cdot 25$ milliamperes. In fig. 8 this result has also been derived graphically. The construction is as follows :—Join I_1, I_2 by a straight line, intersecting the voltage ordinate E_a at I_3. Bisect the straight line I_0, I_3. The bisecting line corresponds to the current ordinate I_m, and the rectified current is the difference between I_m and I_0 as previously stated. The point I_0 on the

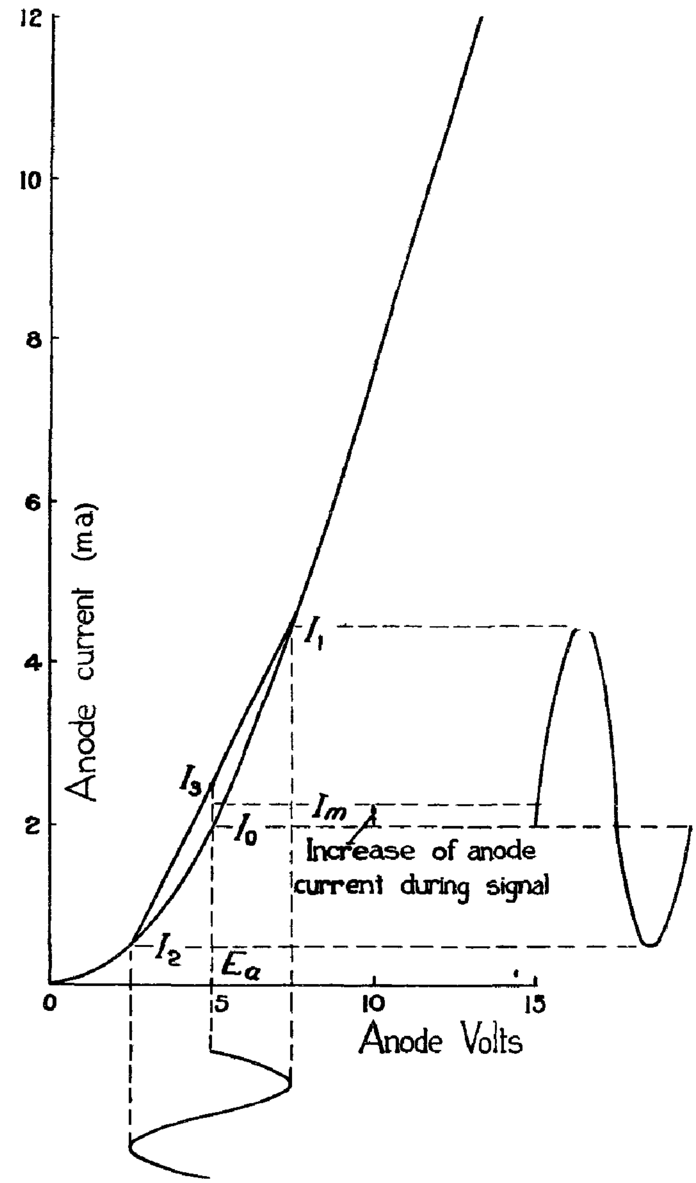


FIG. 8, CHAP. X.—Rectified current, square law rectification.

characteristic curve, which gives the anode current under no-signal conditions, is called the operating point and it can be proved that to obtain maximum rectified current the operating point should be located where the curvature of the characteristic is greatest. In this connection curvature may be explained as follows. Any characteristic curve may be considered to be built up of a series of arcs of circles, these arcs having different radii and the arcs themselves being very small. Then the arc having the smallest radius is the one having the greatest curvature, and the operating point should be situated at the midpoint of this arc. In many practical cases, the position of this point can be determined approximately by inspection of the characteristic. This rule, namely that the operating point should be located at the point of greatest curvature, is applicable to all rectifiers when the applied E.M.F. is small, i.e. less than about one volt.

C.W. RECEPTION

12. It has already been shown that if the radio-frequency voltage applied to the rectifier is of constant amplitude, as it would be during the reception of continuous wave signals, the output of the rectifier will take the form of a direct current, and will cause no vibration of the telephone diaphragm. A simple expedient which achieves the desired result is to introduce some form of interrupter in series with the telephones, preferably operated by an other than electrical means (fig. 9). The operation of this device is as follows. In the absence of a signal E.M.F. no anode current flows through the telephone windings and no sound is produced, in spite of the fact that the interrupter is in operation. When a signal is received, the voltage applied to the rectifier introduces a charge into the reservoir condenser in the manner previously

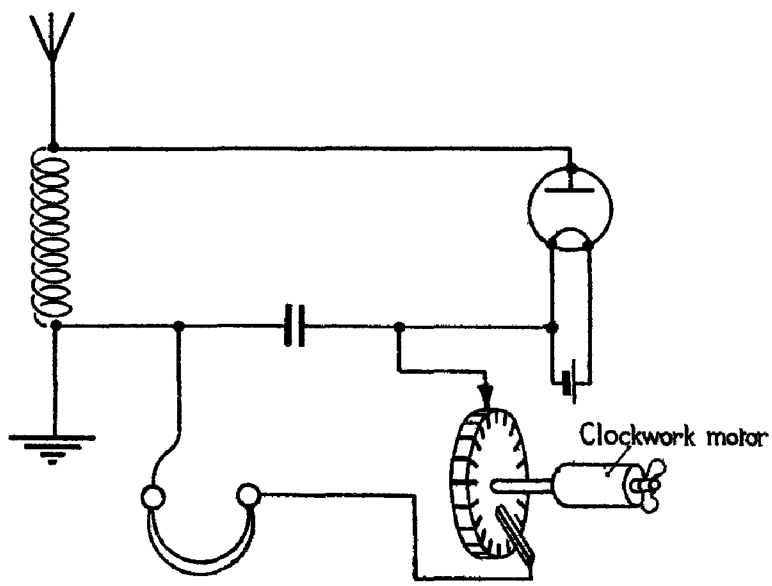


FIG. 9, CHAP. X.—Principle of tikker reception of C.W. signal.

described, and a discharge occurs whenever the telephone circuit is completed by the interrupter. The current through the telephone windings consists of a series of undirectional pulses and the diaphragm is thrown into vibration at a rate corresponding with the number of interruptions per second ; a device of this nature is called a " tikker ". This was the first practical method of C.W. reception, and in an emergency might still prove to be of value, but it has been entirely supplanted by a much more effective method which is known as beat reception or heterodyne reception.

Heterodyne reception

13. The importance of the phenomenon known as the " beat effect " has for long been recognised in the study of sound. An example familiar to every airman is found in the sound produced by a twin-engined aeroplane when the engine speeds differ slightly. If one engine is running at 2,000 r.p.m. while the other is running at 2,060 r.p.m. the combined sound of the engines will rise and fall in intensity once per second, and this variation in loudness is termed the beat effect. As the vibrations in this example are very complex, consider two bodies which when set into vibration will set up sinusoidal sound waves in the surrounding air, for example two tuning forks which have been individually adjusted to emit a sound having the pitch of first lower C, corresponding to a frequency of 128 cycles per second. If both are sounded together, the aural impression gained by an observer is that of a single clear note, but if a small piece of wax is attached to each prong of one fork, so that its mass is increased, this fork will now have a natural frequency slightly lower than the other, e.g. 126 cycles per second. On sounding both

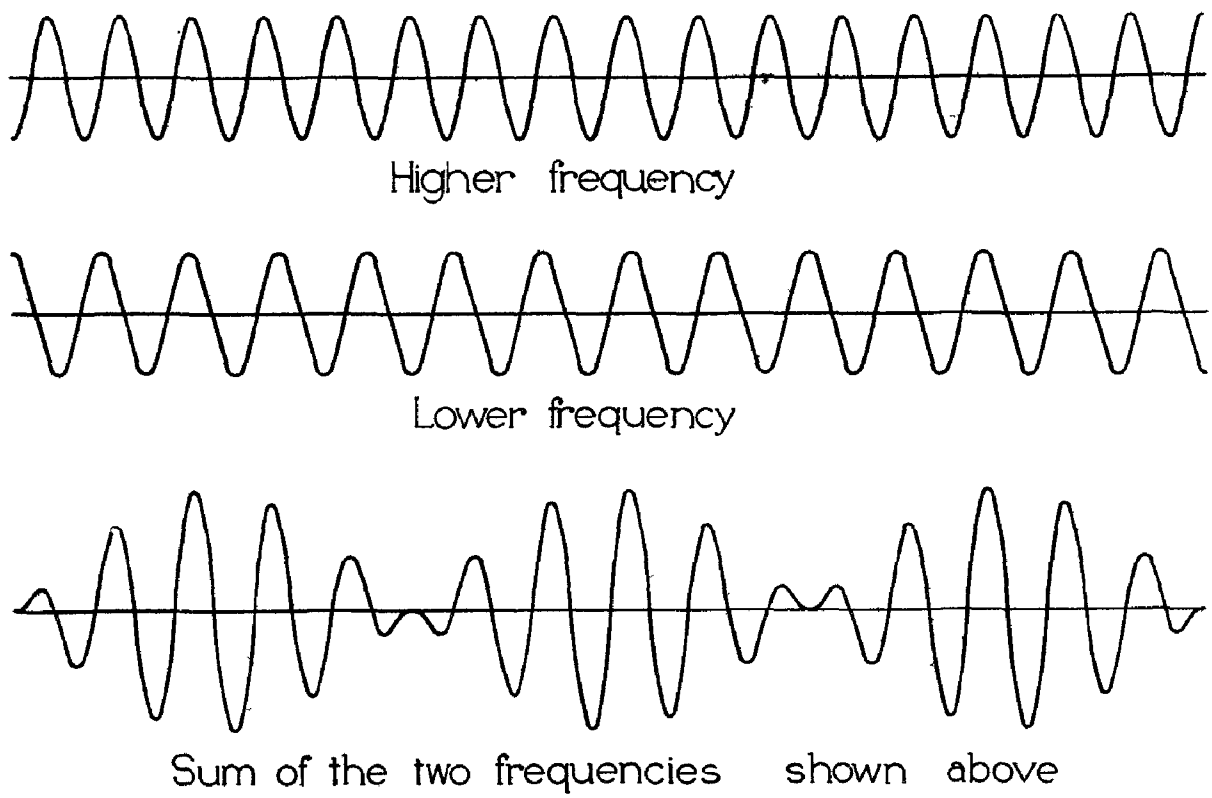


FIG. 10, CHAP. X.—Beat effect between waves of different frequencies and equal amplitude.

simultaneously, it will be observed that the emitted sound waxes and wanes in intensity twice per second; the explanation is as follows. The intensity of the sound at any instant is the sum of the intensities due to the two separate sources. The sound waves are both sinusoidal in form but of different frequency, and this instantaneous sum can be found by plotting the two curves showing the instantaneous intensity due to each source over a period of one or more seconds, subsequently finding the sum of the two curves at a large number of points on the " time " axis, and plotting this sum to form a new curve. This process has been performed in fig. 10 in which are shown the two component sine curves, the latter being of equal amplitude in this particular example. The curve obtained by adding the instantaneous values of each curve is also shown, this curve being called the resultant of the other two. The individual half-cycles of this resultant are approximately sinusoidal, but the amplitude of each successive half-cycle varies in value, growing from zero to a maximum, falling again to zero, again rising to a maximum and so on, so long as the two sources continue to produce their characteristic sound. The maximum amplitude of the resultant is twice the amplitude of either component curve and the number of beats per second is equal to the difference between the two component frequencies.

14. The laborious process of graphical addition can be replaced by mathematical addition of the two equations representing the component sine waves. Let us assume that these equations are

$$v_1 = \mathscr{V} \sin \omega_1 t, \ \omega_1 = 2\pi f_1$$

$$v_2 = \mathscr{V} \sin \omega_2 t, \ \omega_2 = 2\pi f_2$$

$(f_1 - f_2)$ being small compared with f_1 and f_2. It will be convenient to denote the mean frequency $\frac{f_1 + f_2}{2}$ by f, and $2\pi f$ by ω ; then $\omega = \frac{\omega_1 + \omega_2}{2}$. The equation representing the resultant wave will then be

$$v = v_1 + v_2 \text{ or}$$

$$v = \mathscr{V} (\sin \omega_1 t + \sin \omega_2 t)$$

The sum of the sines of two angles, say P and Q, is given by the equation

$$\sin P + \sin Q = 2 \sin \frac{P + Q}{2} \cos \frac{P - Q}{2}$$

Hence

$$v = 2\mathscr{V} \sin \frac{\omega_1 + \omega_2}{2} t \cos \frac{\omega_1 - \omega_2}{2} t$$

$$= \left. 2\mathscr{V} \cos \frac{\omega_1 - \omega_2}{2} t \right\} \sin \omega t.$$

The expression has been bracketed in such a way as to emphasise that the resultant is a sinusoidal quantity of frequency $\frac{f_1 + f_2}{2} = f$, the maximum amplitude of which is $2\mathscr{V}$. As shown in fig. 10, the amplitude varies between zero and $2\mathscr{V}$, a complete cycle of this variation occurring $f_1 - f_2$ times per second. The number $f_1 - f_2$ is often termed the " beat frequency," but it is desirable to avoid the use of the term " frequency " when referring to the number of beats per second, reserving its employment to express the number of cycles per second of an alternating quantity.

15. When the amplitudes of the two component vibrations are not equal, the resultant is of somewhat more complicated form, in that the periodic time of the individual waves composing a complete beat varies slightly during each beat, while the amplitude of the vibration varies between two values which are the sum and difference of the amplitudes of the constituent quantities, e.g. if the latter are represented by A and B, the amplitude of the resultant varies between $A + B$ and $A - B$. The resultant beats caused by the super-position of two vibrations of different amplitude is shown in fig. 11. Prior to the rectification of a C.W. signal it is necessary to cause an audio-frequency variation in amplitude of the voltage which is to be rectified, in order to produce an audio-frequency change in the telephone current, and the phenomenon just described is easily adapted to this end. The method is generally referred to as " heterodyne reception," the term heterodyne having been coined to denote the " mixing " of power from different sources. There are two methods of applying the heterodyne principle, which are termed (i) " separate heterodyne " and (ii) " autodyne " or " self-heterodyne." The latter cannot be used with a diode detector, and will be explained later.

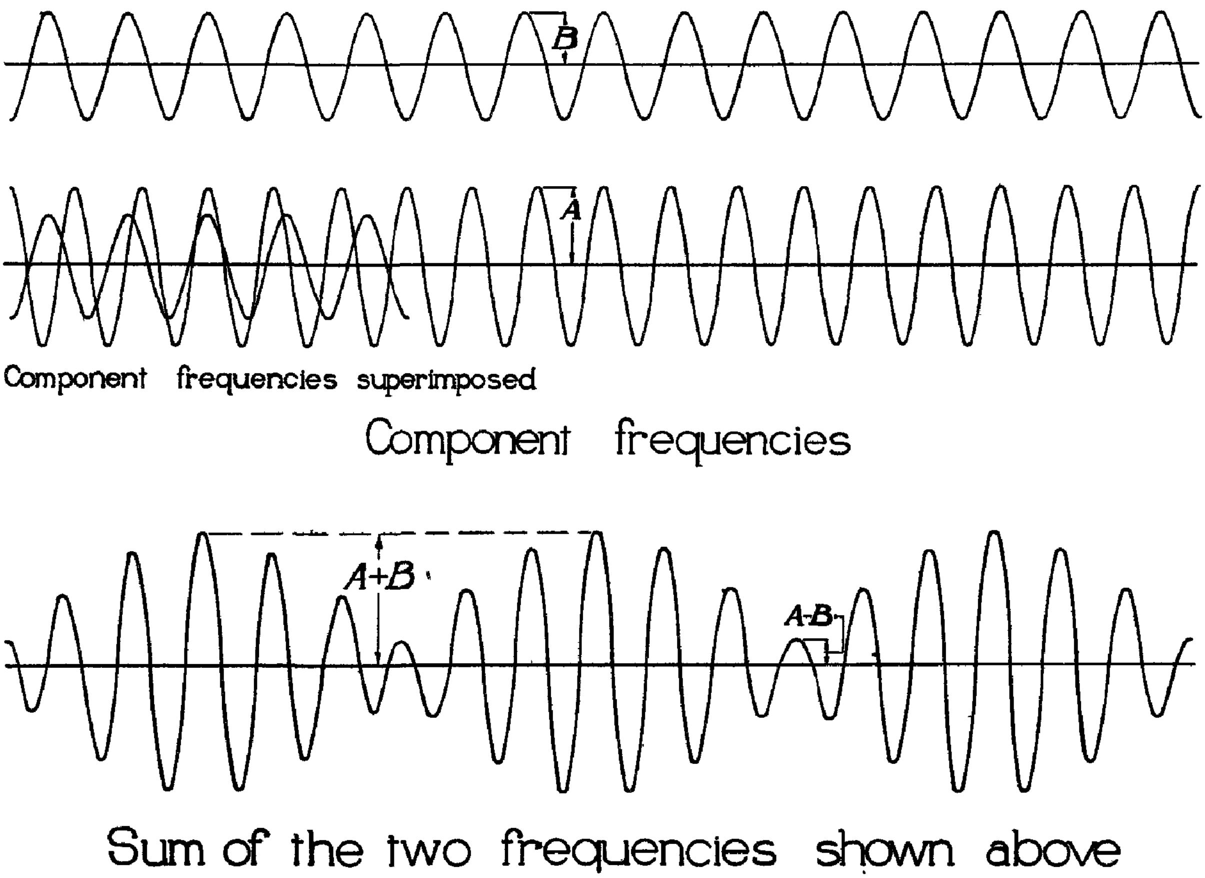


FIG. 11, CHAP. X.—Beat effect between waves of different frequencies and unequal amplitude.

The separate heterodyne

16. In this system we may consider the receiver proper to consist of the tuned aerial circuit, the diode and its ancillary battery, and the telephone receiver. We have seen that this apparatus alone will not cause the telephone diaphragm to vibrate at an audible frequency on the arrival of a C.W. signal. In separate heterodyne reception, a small oscillator of extremely low power is located near to the receiving aerial circuit. This oscillator generates a radio-frequency current in an oscillatory circuit which is tuned to within about 2,000 cycles per second of the signal to be received, and is coupled to the receiver aerial system. A radio-frequency E.M.F. of the local oscillator frequency is consequently set up in the aerial circuit, but this E.M.F. alone will produce no variation of telephone current, for reasons already explained. On the receipt of a C.W. signal, however, an E.M.F. of the signal frequency is also induced in the aerial circuit, and the oscillatory current in the latter is the sum of two currents of different frequencies, i.e. those of the C.W. signal and local oscillator respectively. Beats of the nature shown in fig. 10 or 11 are therefore produced, and the voltage induced in the aerial inductance has a similar waveform. This voltage is applied to the anode-filament path of the diode and its rectification will result in a pulsating current in the anode circuit and an audio-frequency variation of telephone current, hence the action upon the diaphragm is as shewn in fig. 12. The simplest form of receiver using the separate heterodyne system is given in fig. 13; the receiver proper is similar to that given in fig. 4, and the circuit of the local oscillator identical with that of the simple oscillator described in Chapter IX. The aerial circuit is tuned to the frequency of the distant transmitter by means of the inductance L and condenser C, and the local oscillator to some frequency differing from that to be received by from 200 to 2,000 cycles per second. The local oscillator is said to be detuned from resonance by this amount, and the degree of detuning is

often of great assistance in achieving freedom from interference due to the operation of other transmitters. To understand this, imagine the transmitter from which reception is desired to emit a continuous " dash," and the receiving aerial circuit to be correctly tuned for its reception. If the local oscillator is adjusted to generate a frequency 20,000 cycles above the desired frequency, the interaction of the two frequencies will give rise to 20,000 beats per second; although the detector valve will operate in such a manner that the current flowing in the telephones undergoes a practically sinusoidal variation in amplitude at the same rate, no appreciable sound is perceived owing to the small response of the telephone diaphragm and the insensitivity of the ear to such a high-pitched note. As the frequency of the local oscillation is brought near that of the distant transmitter the number of beats per second is reduced, for example, when the frequency difference is about 5,000, a very high note of feeble intensity will be perceived. This note is too highly pitched and of too small amplitude to be suitable for morse code operation, and is generally said

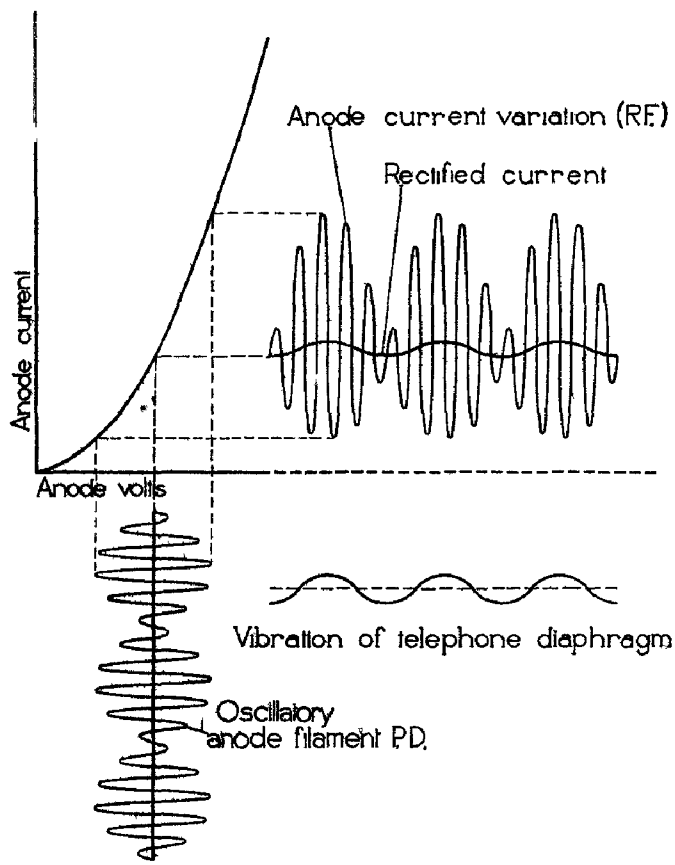


Fig. 12, Chap. X.—Rectification of heterodyne beat voltage by diode.

to have " no body." On bringing the local oscillator more nearly into resonance with the signal frequency, e.g. differing only by 2,000 cycles per second, the note becomes lower pitched and possesses more " body " because the telephone diaphragm vibrates with greater amplitude and the ear is more sensitive to sound of this frequency. If the local oscillator is left at this point and actual reception of morse code performed for a few minutes, this note will be found tiring to the ear. A further approach to resonance between local oscillator and distant transmitter will give a lower-pitched note with (apparently) still more sound energy; most operators usually prefer a note which is in the neighbourhood of 800 to 1,000 cycles per second, although of course the setting is done entirely without reference to any scale either of frequency of local oscillation or pitch of note. The operator simply varies the adjustment of the local oscillator (usually the capacitance of the local oscillatory circuit) until the note suits him.

Dead space

17. If the frequency of the local oscillator is brought within about 200 cycles per second of the transmitter frequency, the beat effect generally ceases. This is due to two causes, first, the insensitivity of the telephone receiver at low audio-frequencies, and second, a phenomenon

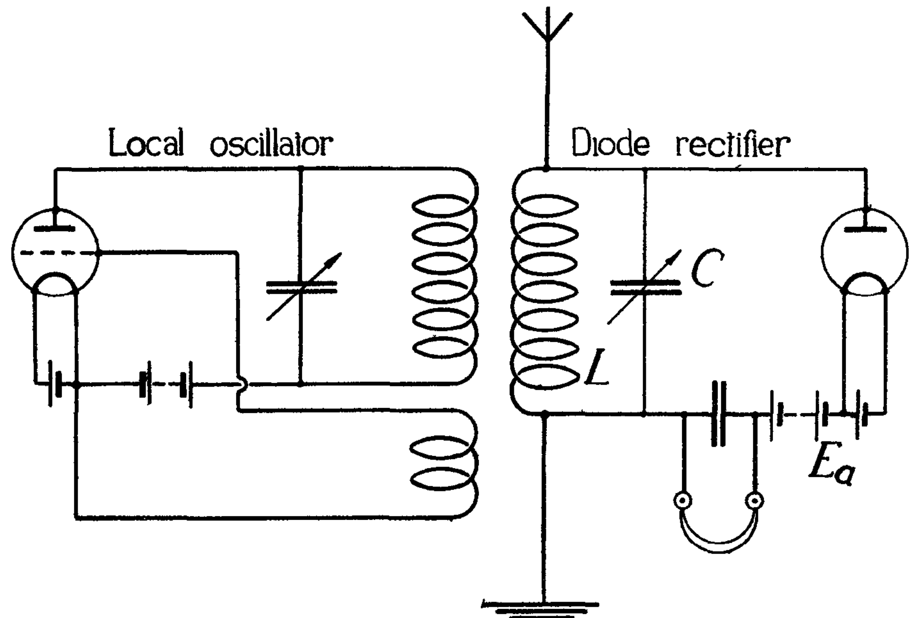


FIG. 13, CHAP. X.—Separate heterodyne receiver using diode detection.

called automatic synchronization. When the tuned circuit of the local oscillator becomes nearly resonant with the distant transmitter, it is forced to oscillate at the frequency of the transmitter instead of at its own natural frequency, and under this condition no heterodyne beats are produced. Under practical conditions it will be found that this usually occurs over a

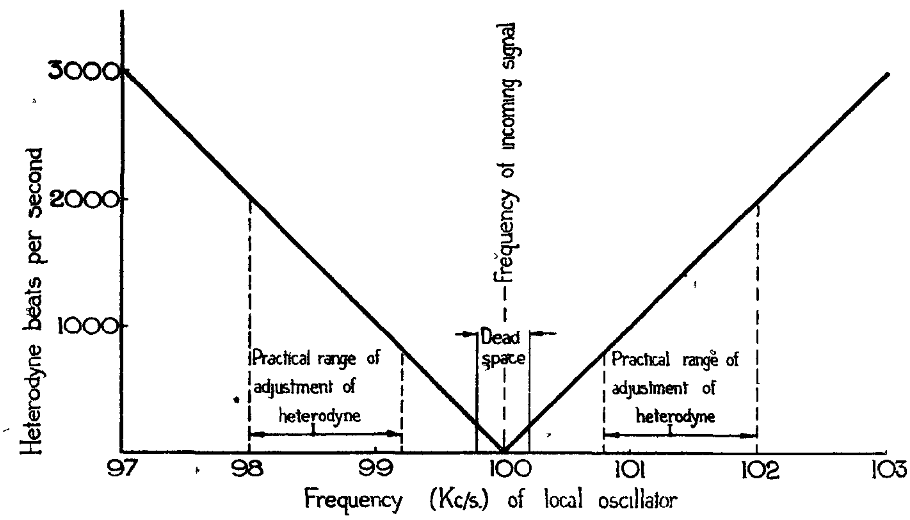


FIG. 14, CHAP. X.—Variation of beat note with frequency of local oscillation.

frequency band of about 200 cycles per second above and below the frequency of the transmitter, and this zone is known as the "dead space" of the heterodyne. If the adjustment of the heterodyne is continued through the dead space, the beat effect is again perceived, first giving a very low pitched note having a frequency in the region of 200 cycles per second, and increasing to a pitch above the limit of audibility as the frequency difference is increased. The change of pitch of the heterodyne beat-note is illustrated in fig. 14 for a particular instance, in which the incoming signal is assumed to have a frequency of 10^5 cycles per second, and the frequency of the local oscillator is continuously varied between 97,000 and 103,000 cycles per second. The straight sloping lines represent the number of beats per second which are formed by the interaction of the two frequencies, while the dotted lines show the practical limits between which the frequency of the local oscillator can be varied, observing the limitations caused by the lack of sensitivity of the ear and telephone diaphragm at frequencies much over 2,000 cycles per second.

Advantages of heterodyne reception

18. The fact that the pitch of the telephone signals is entirely under the control of the operator is one of the advantages of C.W. over I.C.W. operation, the note in the latter case being fixed by apparatus at the transmitter. In addition to allowing (under normal conditions) the use of a pitch which is agreeable to the ear of each particular operator, thus enabling him to handle traffic with less fatigue, it gives a certain degree of what may be termed "note selectivity." Thus the operator receiving a signal on a frequency of 10^6 cycles per second may experience interference on a frequency adjacent to this, say 1,001,000 cycles per second. If the operator sets his local oscillator to 998,500 cycles per second, the desired signal will, after rectification, give a note of frequency 1,000,000–998,500 or 1,500 cycles per second, a rather high note not very difficult to read, in fact one which may be preferred by some operators. The interfering signal will, after rectification, give a note of 1,001,000 — 9,985,000 = 2,500 cycles per second, which is of higher pitch and will also be of reduced strength owing to the comparatively inferior response of the telephone at this frequency. Alternatively, the operator may adjust his local oscillator to within 200 cycles per second of the interfering signal, which then falls in the zone referred to above as the dead space; no beat note is then caused by the interfering signal, while the desired signal gives a beat note of between about 800 and 1,200 cycles per second according to the exact point tuned to in the dead space. For this expedient to be entirely successful, it is necessary for the transmitter frequencies to be controlled in such a manner that a high degree of constancy is maintained. A further advantage of heterodyne reception is that if the rectifier obeys the square law ($I_a \propto V_a^2$) as is always the case for small input voltage, the rectified current is not proportional to the signal voltage but to the strength of the local oscillation, hence a C.W. signal received in this way will give a much louder response than an I.C.W. or tonic train signal. This can be shown as follows.

19. Let the input voltage of the signal be $v_1 = \mathscr{V}_1 \sin \omega_1 t$ and the local oscillator voltage be $v_2 = \mathscr{V}_2 \sin \omega_2 t$. The total input voltage will then be $v = v_1 + v_2$ or

$$v = \mathscr{V}_1 \sin \omega_1 t + \mathscr{V}_2 \sin \omega_2 t.$$

The characteristic of the rectifier is given by the equation

$$i_a = K\, v_a^2$$

Therefore
$$i_a = K \{ \mathscr{V}_1 \sin \omega_1 t + \mathscr{V}_2 \sin \omega_2 t \}$$
$$= K \{ \mathscr{V}_1^2 \sin^2 \omega_1 t + 2\, \mathscr{V}_1 \mathscr{V}_2 \sin \omega_1 t \sin \omega_2 t + \mathscr{V}_2^2 \sin^2 \omega_2 t \}$$

The expression in braces may be divided into two groups of terms :—

(i) $\mathscr{V}_1^2 \sin^2 \omega_1 t + \mathscr{V}_2^2 \sin^2 \omega_2 t$

$$= \frac{\mathscr{V}_1^2}{2} + \frac{\mathscr{V}^2}{2} - \frac{\mathscr{V}_1^2}{2} \cos 2\, \omega_1 t - \frac{\mathscr{V}_2^2}{2} \cos 2\, \omega_2 t.$$

These terms cause a mean rise of anode current, and also radio-frequency variations of twice the frequency of the incoming and local oscillation respectively; these do not affect the telephone windings but are by-passed by the reservoir condenser.

(ii) $2\, \mathscr{V}_1 \mathscr{V}_2 \sin \omega_1 t \sin \omega_2 t$

$$= \mathscr{V}_1 \mathscr{V}_2 \{ \cos (\omega_1 - \omega_2) t - \cos (\omega_1 + \omega_2) t \}$$

The second term within the braces is also a radio frequency having no effect on the telephone windings, but the first corresponds to the number of heterodyne beats per second, and will result in an audio-frequency component of anode current, its amplitude being $K\mathcal{V}_1\mathcal{V}_2$. The strength of the signal is therefore not proportional to $\mathcal{V}_1$ but to the product $\mathcal{V}_1\mathcal{V}_2$. The amplitude of the signal voltage, i.e. $\mathcal{V}_1$, is not under control, but that of the local oscillator, i.e. $\mathcal{V}_2$, is variable within wide limits by adjustment of the coupling between local oscillator and receiver proper. The signal strength due to the voltage $\mathcal{V}_1$ may therefore be increased by an increase in the voltage $\mathcal{V}_2$. The notion somewhat prevalent among wireless operators that optimum conditions are obtained when the signal and local oscillator voltages are equal, is thus shown to be fallacious; the amplitude of the local oscillation may profitably be increased provided that the characteristic follows the law $i_a = Kv_a^2$ over the operating range, but a further increase in the amplitude of local oscillation will not result in a louder response from the telephones. In certain circumstances such an increase in the amplitude of the local oscillation will cause the signal to become weaker.

THE TRIODE RECTIFIER

20. Although the principles of rectification exemplified by the diode are of general application, this type of valve is not in common use as a rectifier in receivers designed to deal with very small input voltages. It has however, a considerable field of employment in broadcast reception, in which the signal voltage is considerably amplified before rectification. (*See* Chapters XI and XII.) Where it is desired to obtain the strongest signal in the telephone receivers for a given input voltage, the triode valve is almost universally employed. It has previously been stated that this type of valve functions primarily as a voltage amplifier, and when operated under conditions in which rectification is also obtained, a more powerful response can be obtained than by the process of rectification alone. As before, it is desirable to consider the reception of I.C.W. or tonic train signals in the first place, in order to avoid the complications caused by the necessity for beat reception of C.W. The triode is usually employed as a rectifier either by making use of (i) the curvature of the grid current/grid volts curve, giving rise to what is termed cumulative grid rectification, or (ii) the curvature of the anode current/grid volts curve,

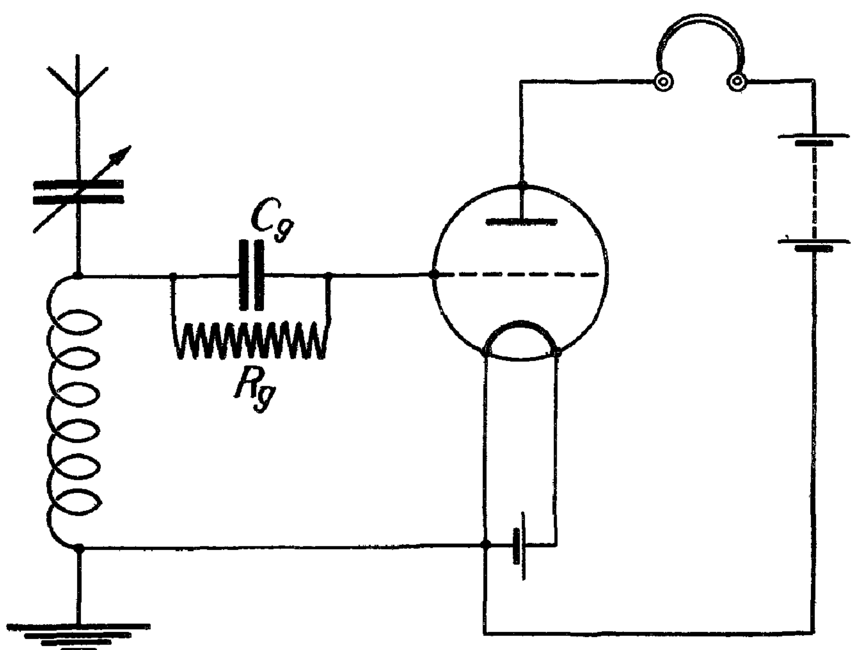


FIG. 15, CHAP. X.—Cumulative grid rectification.

a method generally known as anode bend rectification. Each method has several alternative methods of circuit connection and operating conditions, but these do not affect the general principles.

Cumulative grid rectification

21. The simplest form of circuit for use with this form of rectification is given in fig. 15. The aerial circuit is tuned to the frequency of the desired signal as usual, and the voltage developed in the inductance is applied to the grid and filament of the triode. In series between the inductance and the grid of the valve is interposed a condenser C_g, called the grid condenser, the reactance of which is negligible at the signal frequency. In parallel with this is a resistance R_g, called the grid leak, which may be one or more megohms; the factors which determine the values of the capacitance C_g and resistance R_g will receive consideration later. The anode circuit of

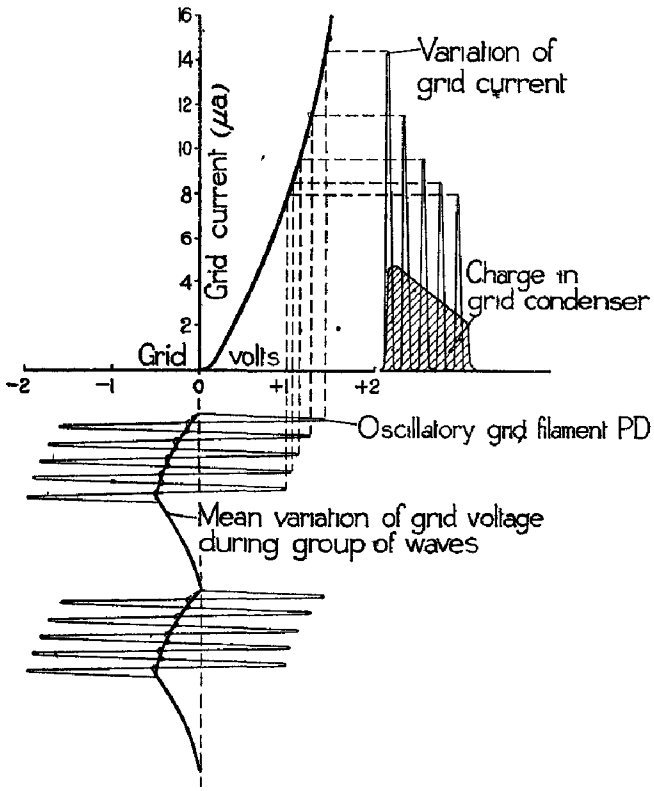


FIG. 16, CHAP. X.—Action in grid circuit of cumulative grid rectifier.

the valve consists of the anode-filament path of the latter, a pair of telephones and the anode H.T. battery; in discussing the initial stages of the action we may ignore the anode circuit altogether and confine our attention to the grid circuit. The presence of a signal E.M.F. will set up in the aerial circuit an oscillatory current of the same frequency, and consequently a counter-E.M.F. is developed in the inductance L. This E.M.F. is applied to the circuit consisting of the grid condenser (with its leak resistance) in series with the grid-filament path of the valve, and as the impedance of the latter path is very large compared with that of the parallel combination of grid leak and condenser, practically the whole of the oscillatory voltage is applied between grid and filament of the valve.

22. In order to predict the current which will flow under the influence of this voltage, the characteristic grid current/grid volts curve of the particular valve must be consulted. Fig. 16

shows the $I_g - V_g$ curve of a suitable receiving valve, and it will be observed that when the grid and filament are at the same potential, no electron current flows from filament to grid. Below the $I_g - V_g$ curve are shown the grid-filament voltage variations corresponding to two groups of waves which are assumed to be part of, say, a morse " dot," as in the explanation of the diode rectifier. When the grid is positive with respect to the filament a grid current will be established, but the grid-filament path is perfectly non-conductive during those half-cycles of grid voltage in which the grid is negative to the filament. On the first positive half-cycle therefore, electrons will be attracted by the grid, and will pass into the right hand side of the grid condenser charging it negatively, and causing a displacement current in the dielectric with the consequent repulsion of electrons from the left hand plate, which thereupon becomes positively charged. During the succeeding half-cycle, in which the grid becomes negative to the filament, no electrons are attracted to the grid, but the grid condenser becomes partly discharged owing to the presence of the grid leak resistance R_g. At the end of the first complete cycle the grid potential is

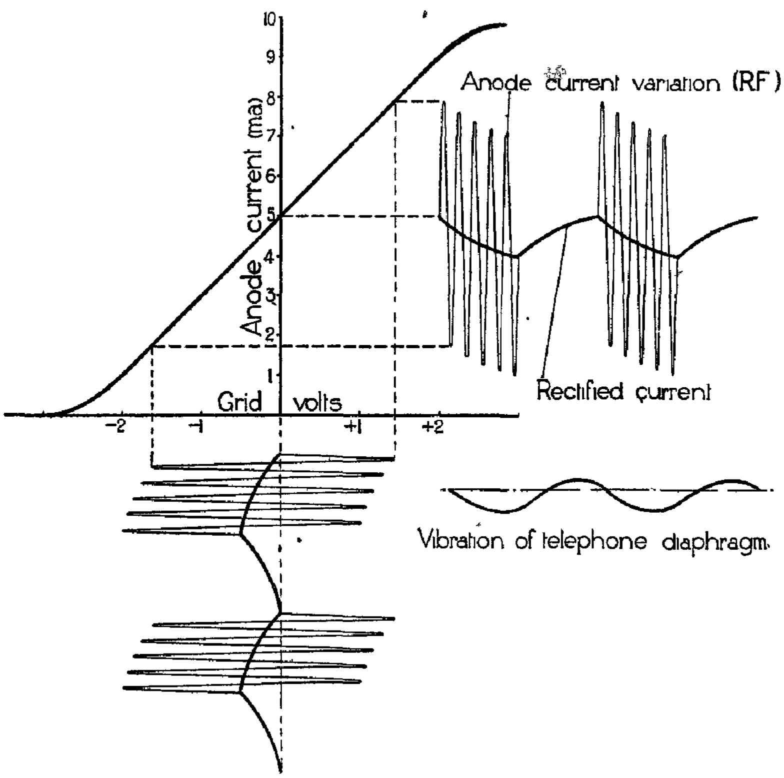


FIG. 17, CHAP. X.—Action in anode circuit of cumulative grid rectifier.

slightly negative compared with its potential at the beginning of the cycle. During the next positive half-cycle, the grid condenser will again receive a negative charge on its right hand plate, and will lose a portion of this charge during the negative half-cycle owing to the conductive property of the resistance R_g; the net effect is that at the end of the second cycle, the grid has acquired a still further negative potential with respect to the filament, and so on until the end of the group of waves. When no further oscillatory voltage is applied between grid and filament the grid condenser continues to maintain a current through the grid leak until its charge has been completely dissipated, and during this time the grid gradually returns to its original potential, namely, that of the filament. This sequence of operations is shown graphically in fig. 16. The group of waves has thus caused the introduction of a charge into the grid condenser C_g in exactly the same manner as into the reservoir condenser in diode rectification, the resistance R_g acting as the load resistance. If the latter were absent, the grid condenser would retain its charge at the end of the group of waves, and the succeeding group would cause the grid to become still further negative and so on. In consequence, after the first few groups of waves, the grid would become so negatively charged that the grid current would be reduced to zero and further rectification would become impossible.

23. (i) The effect upon the anode current of this gradual accumulation of charge in the grid-condenser may now be considered, with the aid of the $I_a - V_g$ curve, fig. 17. Before the oscillatory voltage is applied, the anode current has a steady value of 5 milliamperes; but during the group of waves the grid voltage becomes more and more negative and the anode current gradually falls to 4·2 milliamperes, an anode current change of ·8 milliamperes. At the end of the group the anode current resumes its original value of 5 milliamperes as the charge in the grid condenser leaks away and the grid voltage returns to normal. This variation of anode current will cause a single variation of flux acting upon the diaphragm and a corresponding inflection of the latter, or more crudely, a single "click." Since however the groups of waves must be assumed to occur about 1,000 times per second, the diaphragm is set into vibration at this rate and gives rise to the emission of a musical note by the telephone receivers. In addition to this audio-frequency variation of anode current, the latter will also vary at the frequency of the applied signal voltage. This variation does not enter into the process of rectification, but nevertheless may be made to perform a useful function, as explained later.

(ii) As in the case of the diode detector previously described, most efficient rectification of weak signal voltages is obtained when the operating point is located where the curvature of the rectifying characteristic is greatest. With most triodes in use at the present time, this necessitates the application of a small positive potential (generally about ·2 to ·3 volt) to the grid of the valve. This potential can be obtained by connecting the grid leak to the positive terminal of the filament battery instead of to the negative as shown in fig. 18a. In the following explanation the valve is assumed to require a filament battery of 2 volts, such valves being in general service use. It must not be supposed that this method of connecting the grid leak resistance will cause the grid potential to be 2 volts positive to the negative end of the filament, for the fact that the grid is at positive potential implies that grid current will be established, and the grid-filament conductance of the valve will be of some finite value. Let us suppose that this is $\frac{1}{200000}$ siemens (mho), i.e. that the effective resistance r_g (for direct current) of the grid-filament path inside the valve is 200,000 ohms, while the grid leak resistance is 2 megohms. In addition to supplying the filament heating current, the filament battery then causes a current to flow in the circuit comprised by the grid-filament path and the grid leak. In the present circumstances this current will be $\frac{2 \text{ volts}}{(2{,}000{,}000 + 200{,}000) \text{ ohms}}$ or ·91 microamperes. As a result of this current a potential difference will be established between the grid and filament, and the grid will be positive with respect to the negative end of the filament by an amount equal to $r_g I_g = 200{,}000 \times \frac{2}{2{\cdot}2 \times 10^6} = \frac{{\cdot}4}{2{\cdot}2}$ or ·18 volts.

24. The reader may reasonably object that this value is obtained by an unwarranted assumption as to the value of r_g, for in the $I_g - V_g$ characteristic of fig. 16 measurement of the slope of the curve shews that r_g varies from infinity to about 2×10^5 ohms as the grid voltage varies from zero to $+{\cdot}18$ volt. For any value of grid leak resistance R_g, and any valve for which the $I_g - V_g$ characteristic is given, however, the operating point can be located by a graphical method from the above principles, for the resistance R_g can be treated as a "load line" (*see* Chapter VIII) and drawn upon the characteristic. To explain the process, consider the $I_g - V_g$ curve of fig. 18b, and let $R_g = 2 \times 10^6$ ohms; this resistance may be represented by a line having a slope of ·5 microampere per volt. With the connections made as in fig. 18a, with no current flowing in the grid leak, there will be no IR drop in the latter and the grid will be 2 volts positive to the filament. Hence one end of the load line will rest at the point $V_g = +2$, $I_g = 0$. If 1 microampere were to flow in the grid leak, the IR drop in the latter would be 2 volts, and the grid potential would be 2 − 2 or zero volts, hence another point on the load line is that corresponding to $V_g = 0$, $I_g = 1$ microampere, and the line may be drawn with a

straightedge to connect the two points so found. This line intersects the $I_g - V_g$ curve at a point at which the grid current through the valve is equal to the current through the leak, and the point of intersection gives (i) the mean value of grid current when no signal E.M.F. is applied and (ii) the mean potential of the grid under these conditions.

Damping due to grid current

25. Having stated that the application of a small positive potential results in greater rectified current for a given grid-filament voltage, it may appear paradoxical to state that the effect of such positive grid bias may be to reduce the strength of signals. That this is so will be appreciated when it is remembered that the E.M.F. applied between grid and filament depends partly upon the opposition offered by the path. In the absence of grid current, the path may be considered to consist only of a very small capacitance having no losses and consequently causing

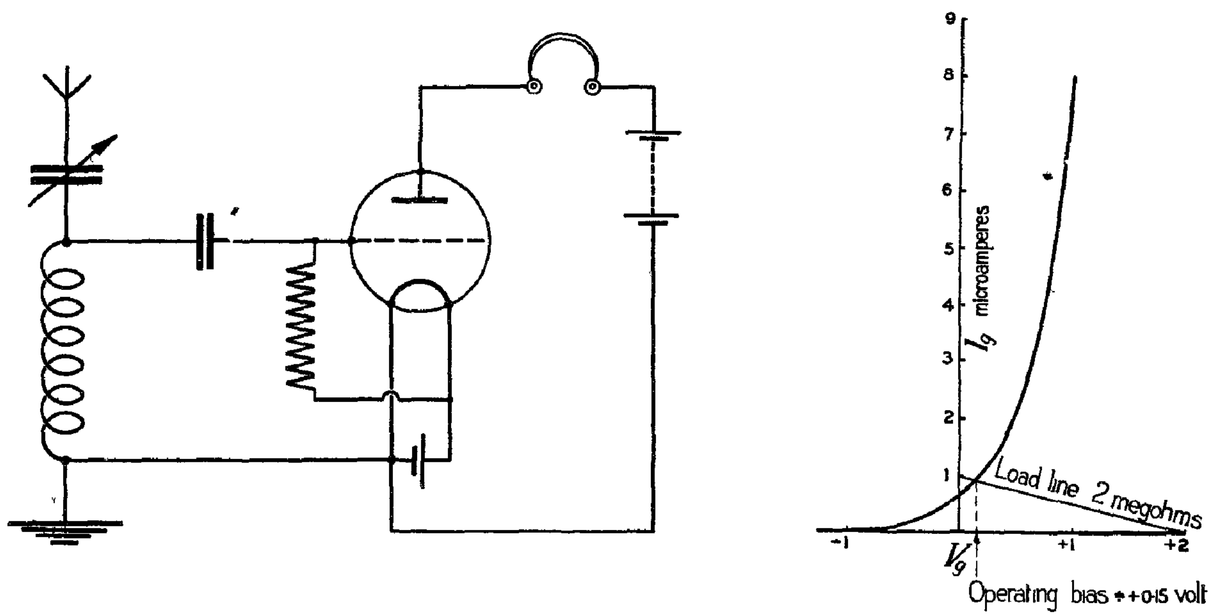


FIG. 18, CHAP. X.—Alternative connection of grid leak resistance.

no waste of energy. When electrons flow from filament to grid, passing round the external circuit back to the filament, the electrons inside the valve can be urged into oscillatory motion by an applied alternating E.M.F. just as if they were enclosed in a conductor. Hence the impedance of the grid-filament path, instead of being purely due to the small inter-electrode capacitance, consists of this capacitance in parallel with a resistance r'_g—the A.C. resistance of the grid-filament path. The shunting effect of the resistance r'_g reduces the circuit magnification and therefore, for a given induced E.M.F. in the aerial, the voltage actually applied to the grid-filament path is reduced. This effect will receive further consideration in Chapter XI.

Factors influencing the values of grid condenser and leak

26. The values of capacitance and resistance chosen for these components is of great importance. Attention must be given to four considerations. First the time constant of the circuit (consisting of grid condenser and the parallel combination of grid leak resistance R_g and the internal grid-filament path r_g) should be of such a value that the charge in the condenser has time to leak away in the interval between consecutive groups of waves. Second, the capacitance of the grid condenser must be small in order that a small accumulation of electrons

may charge it to as high a potential as possible. Third, the reactance of the grid condenser at the signal frequency should be small compared with the impedance of the grid-filament path of the valve, in order that the voltage drop between the condenser terminals shall not be an appreciable fraction of the signal voltage. This consideration points to a large value of C_g and is directly opposed to the second requirement. Fourth, the resistance of the grid leak should be as large as possible in order that the accumulation of electrons on the grid condenser may build up a considerable potential between the terminals of the latter; if too large a value is adopted, however, the first requirement will not be fulfilled. In addition to these four requirements for maximum signal strength, the question of selectivity is also involved. The large number of variable quantities renders it advisable to settle the capacitance of the grid condenser and resistance of the grid leak by direct experiment, bearing in mind the service for which any particular receiver is designed; in most cases a capacitance of from ·0001 to ·0003 μF and a resistance of from ·5 to 2 megohms are found suitable.

Damping due to anode circuit load

27. The effect of grid current in decreasing the magnification of the input circuit of the triode has already been pointed out. It is perhaps not quite so obvious that, even if no grid current flows, the valve and its associated anode circuit will impose a load upon the effective voltage of the tuned circuit. This phenomenon is generally called the Miller effect after the physicist who

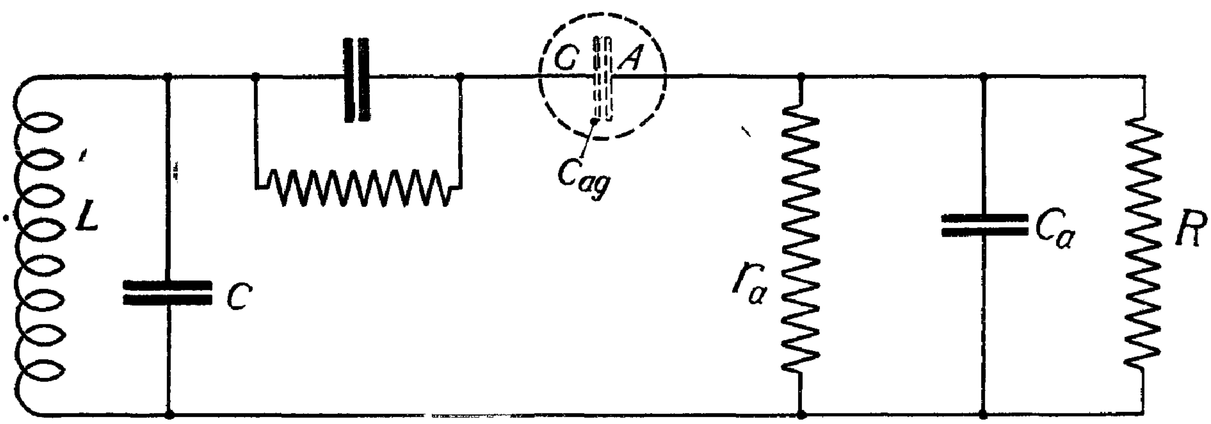


FIG. 19, CHAP. X.—Damping of input circuit owing to anode load and grid-anode capacitance.

first analysed its cause. The Miller effect is due to the electrostatic coupling which exists between the anode and grid circuit. This coupling may be, and in practice generally is, only that caused by the capacitance between the grid and anode of the valve, including of course the leading-in wires at the " pinch ", which is of the order of 10 $\mu\mu F$ in ordinary triodes. The effect is illustrated in fig. 19, in which the anode circuit is assumed to consist of a resistance R and capacitance C_a in parallel, and is effectively coupled to the tuned circuit L C by the grid-anode capacitance C_{ag}. It has already been shown that when circuits are coupled together by a common reactance, an effective resistance is transferred from the secondary to the primary, and this is so in the circuit shown, but the effect is more complex than is apparent from the diagram owing to the amplifying properties of the valve. Further consideration of the Miller effect will therefore be found in Chapter XI. For the present it is sufficient to realise that in extreme cases, the total damping imposed upon the tuned circuit by the valve, including both the effects of grid current and the anode circuit load, may be equivalent to the insertion into the tuned circuit of a series resistance of the order of several hundred ohms. The damping effect of the anode load can be reduced by the employment of a telephone condenser of large capacitance, but this solution leads to a reduction of telephone current and consequently to weaker signals. A more practical expedient will now be discussed.

Reduction of damping by regenerative amplification

28. When no signal voltage is applied between grid and filament of the rectifying valve, the anode current is constant, but during the reception of an I.C.W. or T.T. wave group, it varies in a complex manner. In the simplest instance this complex variation may be considered to consist of the sum of two variations superimposed upon the steady or no-signal anode current, viz. a variation which takes place at a rate corresponding to the number of groups radiated per second, and a variation at the frequency of the applied E.M.F., i.e. the true signal frequency. It has already been stated that the latter component plays no part in the mechanism of rectification proper, and it is now proposed to explain how this component can be beneficially employed. When the grid and anode circuits of a triode are inter-coupled, any variation of grid voltage, by causing a change of anode current, will cause a corresponding E.M.F. to be induced in the grid circuit. Let us therefore suppose that the receiving circuit has been arranged as shown in fig. 20 which is similar to fig. 18a except that an inductance L_a has been inserted in series between the anode of the valve and the telephones. This coil is inductively coupled to the inductance L in the aerial circuit, as indicated by the arrow linking the two coils. Now suppose that the actual

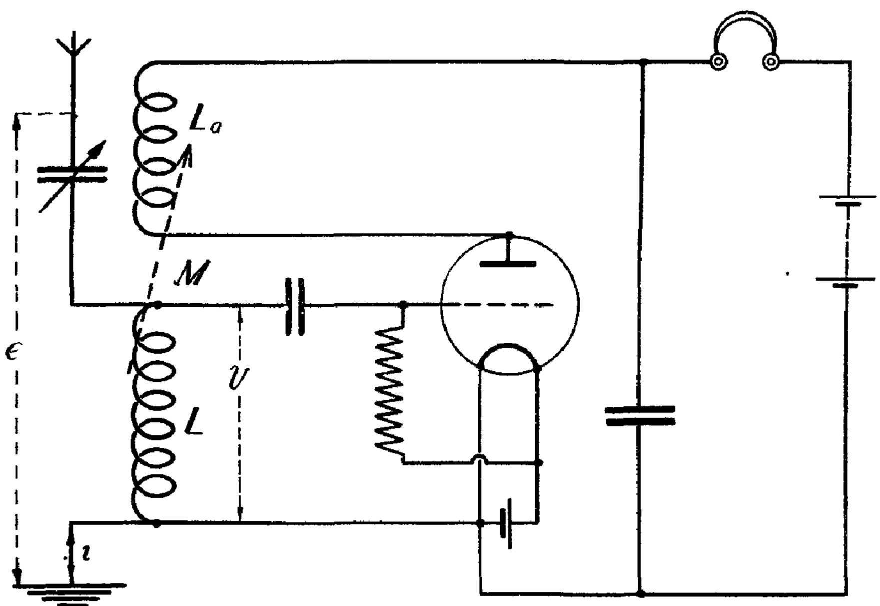


FIG. 20, CHAP. X.—Cumulative grid rectifier with reaction.

E.M.F. induced in the aerial (indicated by e in the diagram) causes grid-filament voltage variations as shown in fig. 17; the resulting anode current variations will then also be the same as in this diagram, and will flow through the coil L_a. We are now only concerned with the radio-frequency component shown by the thinner line. Owing to the coupling between the two coils, the radio-frequency variation of anode current will set up a corresponding flux in and around the coil L_a which links with the coil L, and an oscillatory E.M.F. of the same frequency as the original signal, will be induced in the aerial circuit. The oscillatory grid-filament P.D., v will now be the vector sum of the original P.D. and that due to the coupling between anode and grid; if they are very nearly in phase with each other, v will be equal to their sum and the rectified current will be much greater than in the absence of the coupling arrangement. On the other hand if the two components of the grid-filament P.D. are nearly 180° out of phase, v will be approximately equal to their difference and the rectified current will be smaller than if the signal E.M.F. alone were operative. The coil L_a is referred to as the reaction coil, and the process by which an increase of grid-filament P.D. is achieved as regenerative amplification. The effect of regenerative amplification upon an incoming signal voltage is shown in fig. 21. The upper curve shows the grid-filament P.D. due to a tonic train signal without regenerative amplification and the lower curve the grid-filament P.D. with regeneration. It should be noted that in addition to an increase in the amplitude of the successive waves, the oscillation takes longer to reach its maximum amplitude, and dies away more slowly, so that the duration of the wave train is increased. This signifies that the effect of reaction is to reduce the damping (or increase the magnification), of the aerial circuit and therefore, as shown in Chapter V, to increase the selectivity. Instead of stating that the total resistance is decreased, it is convenient to consider that the effect of reaction is to introduce a " negative resistance " into the oscillatory circuit.

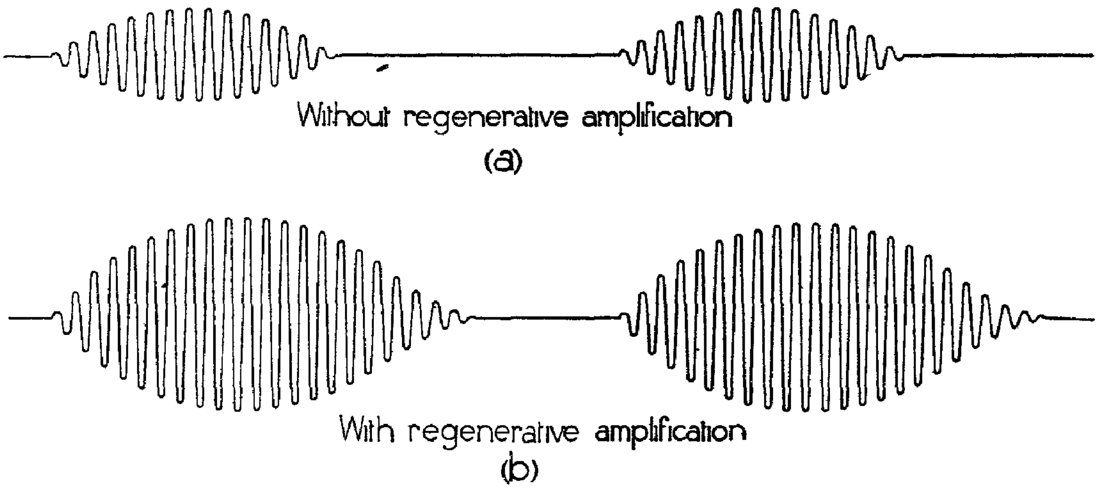


FIG. 21, CHAP. X.—Effect of reaction on grid voltage due to tonic train signal.

Approximate mathematical treatment

29. The effect just explained can be traced out step by step with the aid of fig. 20. The effective voltage set up in the aerial by the distant transmitter is e volts, and we may assume that in conjunction with the E.M.F. due to reaction, this gives rise to a current of i amperes. The counter-E.M.F. set up in the inductance L will be $v = \omega Li$ volts, and this is the signal voltage to be rectified; ignoring the latter process which does not affect the result in any way, this voltage will cause a radio-frequency component of anode current, equal to $\frac{\mu v}{Z_a} = \frac{\mu \omega Li}{Z_a}$ volts, where Z_a is the impedance of the whole anode circuit. The latter consists of the anode A.C. slope resistance r_a, the reactance of the coil L_a and the impedance of the telephones and telephone condenser in parallel. The capacitance of this condenser is purposely adjusted to a value which offers no appreciable reactance at radio frequencies, while the reactance of L_a will be negligible compared to r_a, hence the radio-frequency component of the anode current is approximately equal to $\frac{\mu\omega Li}{r_a}$ amperes. In addition to this, however, by ordinary transformer action an induced E.M.F. is set up in the reaction coil by the aerial current, its value being ωMi volts, consequently the total radio-frequency E.M.F. in the anode circuit is $(\omega M + \mu\omega L)\, i$ volts and the current caused by the latter is $i_a = \frac{(\omega M + \mu\omega L)\, i}{r_a}$ amperes. This current reacts into the aerial circuit, setting up an E.M.F. $- \omega Mi_a$ volts, and therefore the total voltage acting in the aerial circuit is not e alone, but $e - \omega Mi_a$ or $e - \frac{\omega M\, (\omega M + \mu\omega L)\, i}{r_a}$. Hence if Z is

the impedance of the aerial circuit the aerial current is given by the equation

$$i = \frac{e - \dfrac{\omega Mi\,(\omega M + \omega L\mu)}{r_a}}{Z}$$

$$\frac{e}{Z} = \left\{1 + \frac{\omega M\,(\omega M + \omega L\mu)}{r_a Z}\right\} i$$

$$\text{and } i = \frac{e}{Z + \dfrac{\omega M\,(\omega M + \omega L\mu)}{r_a}}$$

30. The effective impedance added to the aerial by the circuits connected thereto is therefore $\frac{\omega^2 M^2}{r_a} + \frac{\omega^2 LM\mu}{r_a}$. It must be noticed that this result is in no way dependent upon the tuning of the aerial, although of course if the aerial circuit is in resonance with the transmitter, its impedance becomes purely resistive and may then be denoted by R, in which circumstances

$$i = \frac{e}{R + \dfrac{\omega^2 M^2}{r_a} + \dfrac{\omega^2 LM\mu}{r_a}}$$

and obviously will be greater than $\frac{e}{R}$, the value in the absence of reaction, if M is negative in sign and does not exceed the value μL. The term $\frac{\omega^2 LM\mu}{r_a}$ is then inherently negative in sign and is the negative resistance introduced into the circuit by the regenerative action. This decrease of total resistance results in an increase in the magnification of the circuit, and consequently the aerial circuit is more selective when used with reaction than in the absence of the latter. To illustrate this, consider the aerial circuit to be tuned to a frequency $\frac{\omega}{2\pi}$ where $\omega = 5 \times 10^6$, e.g. $L = 160\ \mu H$, $C = \cdot 00025\ \mu F$, and $R = 50$ ohms. The resonance curve for this circuit is given

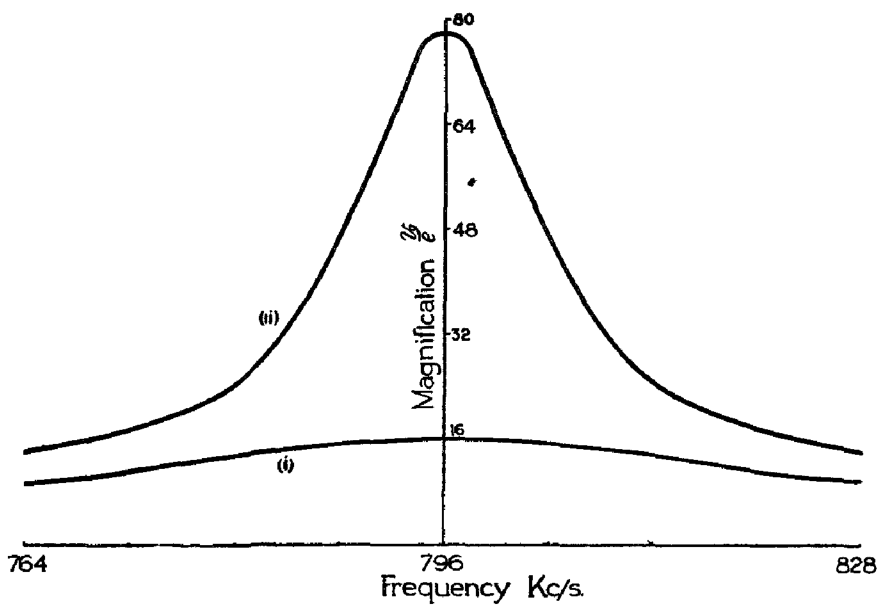


FIG. 22, CHAP. X.—Resonance curve of aerial circuit, with and without reaction.

in fig. 22 curve (i). Now if coupled to a triode of $r_a = 10{,}000$ ohms, $\mu = 10$, by a negative mutual inductance of 10 μH between the aerial and reaction coils, the additional resistance added to the aerial will be

$$\frac{\omega^2 M^2}{r_a} = \frac{25 \times 10^{12} \times 100 \times 10^{-12}}{10^4} = \cdot 25 \text{ ohm.}$$

While the amount by which the resistance is reduced, i.e. the negative resistance, is

$$\frac{\omega^2 M L \mu}{r_a} = \frac{25 \times 10^{12} \times 10 \times 10^{-6} \times 160 \times 10^{-6} \times 10}{10^4}$$

$$= 40 \text{ ohms.}$$

Hence the effective resistance of the aerial circuit is reduced from 50 to 10·25 ohms, and the resonance curve under these conditions is shown in curve (ii) of fig. 22.

31. The effect of such a reduction in aerial resistance is two-fold. In the first place, as the circuit magnification is increased, the grid-filament voltage due to the signal will be much greater than in the absence of reaction, and in the second, the persistency of the train of oscillations comprising each group of waves will be greater. These effects have already been illustrated in fig. 21. There is a limit to the amount of regenerative amplification thus obtainable, for when the effective resistance of the aerial is decreased below a certain amount the circuit becomes unstable in the following manner. As the reaction coupling is increased the dynamic load in the anode circuit changes, and this causes a shift in the operating point on the $I_a - V_g$ curve, which connotes some slight change in the value of r_a. An alteration in the effective damping of the input circuit follows, giving rise to a further change in the operating point, and so on. The ultimate result is that the anode A.C. resistance, r_a, and oscillatory anode current i_a tend to assume values at which the damping of the input circuit is exactly neutralised and the circuit becomes a form of oscillation generator.. Some such process invariably takes place if an attempt is made to reduce the damping nearly but not quite to zero by critical adjustment of the reaction coupling.

The auto-heterodyne

32. The fact that oscillations can be maintained in this circuit without detriment to its rectifying properties suggests a means of dispensing with the use of a separate heterodyne for C.W. reception. In practice, the circuit given in fig. 20 is frequently employed for this purpose, by increasing the reaction coupling so that oscillations occur. As it is necessary for the frequency of the local oscillation to differ from the signal frequency by about 500 to 2,000 cycles per second, the aerial circuit must be detuned by this amount, for the frequency of the generated oscillation is practically equal to the natural frequency of the aerial circuit. This results in a slight reduction of aerial current due to the distant transmitter and of induced E.M.F. in the inductance L, consequently the oscillatory grid-filament voltage is slightly reduced, but at the frequencies employed in modern communication this effect is negligible. At the very low radio frequencies formerly employed for long distance communicaton however, the effect was of such magnitude that the autodyne receiver could not be usefully employed. As an example, consider the reception of a transmitter operating on 30 k.c/s., the telephone note to be 1,000 cycles per second. The autodyne receiver would then be tuned to 30,000 $\pm$ 1,000 cycles per second, and would be 3·3 per cent. out of resonance. If, however, the transmitter frequency is 1,000 k.c/s., the local oscillator is required to generate 1,000,000 $\pm$ 1,000 cycles per second and is detuned only 0·1 per cent. Autodyne reception is therefore mainly used for frequencies higher than about 300 k.c/s. When receiving C.W. signals by the autodyne method it is found that for maximum telephone response the reaction coupling must be adjusted to a critical value somewhat closer than that required to maintain the circuit in oscillation, while for I.C.W. or T.T. reception the point of optimum telephone response is just off the point of oscillation.

33. As in any other form of oscillator, oscillations are produced when the energy transfer is just sufficient to reduce the effective resistance of the oscillatory circuit to zero, i.e. when

$$\frac{\omega^2}{r_a} M^2 + \frac{\omega^2 L\mu}{r_a} M + R = 0.$$

Solving this as a quadratic equation to find the critical value of M,

$$M = -\frac{\mu L}{2} \pm \sqrt{\left(\frac{\mu L}{2}\right)^2 - \frac{R\, r_a}{\omega^2}}$$

Taking the same constants as in the previous example, i.e. $L = 160\ \mu H$, $\omega = 5 \times 10^6$, $R = 50$ ohms, $r_a = 10{,}000$ ohms,

$$M = -\frac{160 \times 10}{2 \times 10^6} \pm \sqrt{\left(\frac{160 \times 10}{2 \times 10^6}\right)^2 - \frac{50 \times 10^4}{25 \times 10^{12}}}$$

$$= -\frac{8}{10^4} \pm \sqrt{\frac{64}{10^8} - \frac{2}{10^8}} \quad \text{(henries)}$$

$$= (-800 \pm 786)\ \mu H$$

$$= -1586 \text{ or } -14\ \mu H.$$

Thus any value of negative mutual inductance between 14 and 1586 μH will maintain the circuit in oscillation. If M exceeds the larger value the positive resistance $R + \frac{\omega^2 M^2}{r_a}$ becomes larger than the negative resistance $\frac{\omega^2 L\mu}{r_a} M$ and no oscillations are produced, while if the connections to the reaction coil are reversed so that the sign of M is positive, both these terms contribute to the damping of the input circuit. It may here be noted that it is usual to speak of " positive reaction " as that which reduces damping, so that positive reaction is obtained with negative mutual inductance and vice versa.

Comparison of separate heterodyne and autodyne methods

34. (i) In comparison with the receiver using a separate heterodyne, the autodyne receiver has the important advantage that only one tuning adjustment is necessary, instead of two, but this is to some extent off-set by the necessity for keeping the reaction adjustment near the critical position as the tuning adjustment is varied. Nevertheless, searching for a signal on a frequency for which the aerial adjustments are only very approximately known is more easily carried out with an autodyne than with a local oscillator, unless the latter is accurately calibrated. The most sensitive type of C.W. receiver, which however requires very skilful handling, is one in which a local oscillator is used to produce the heterodyne beat, while the detector itself is operated with regenerative amplification. This will be best appreciated after some experience of C.W. reception, e.g. with a receiver of the type described in paragraphs 41–43, using a syntoniser (Stores Ref. 10A/3040) or wavemeter W.39 (Stores Ref. 10A/7156) as a local oscillator. The comparative simplicity of control of the autodyne receiver has in the past rendered it particularly suitable for use in aircraft, but it is now chiefly used where portability is a prime factor, e.g. in pack sets.

(ii) A further disadvantage of the autodyne system (when used in the manner outlined above) is the fact that the aerial circuit must radiate some energy at the frequency of the oscillation maintained by the valve. This is detrimental for two reasons, first it may cause interference in neighbouring receivers, and second, it may divulge the presence of the radiating receiver to an enemy. For these reasons, the modern form of autodyne receiver generally incorporates a radio-frequency amplifying stage, which also serves to prevent this radiation or at any rate to reduce it to a negligible amount. Such receivers are dealt with in Chapter XI.

(iii) While it is impossible to receive C.W. signals without either a mechanical interrupter or a local oscillator at the receiving station, I.C.W. signals and indeed any form of modulated wave may be received upon an oscillating receiver designed for C.W. reception. The effect of the local oscillation is to cause the total input voltage to the detector to be greater than in its absence, and the efficiency of rectification is increased, so that a stronger signal usually results. The characteristic note of the I.C.W. signal becomes distorted to such an extent that all indication of its original quality is eliminated, and the only advantage of I.C.W. over C.W. communication is lost. For this reason, as well as to avoid unnecessary interference with other stations by radiation from the receiving aerial, a receiver should never be used in this condition for the reception of other than C.W. signals.

Anode bend rectification

35. (i) Instead of making use of the curvature of the $I_g - V_g$ characteristic, the curvature of the $I_a - V_g$ characteristic may be utilised in order to achieve the desired rectification of a signal E.M.F. The $I_a - V_g$ characteristic of a tungsten-filament triode has two regions of

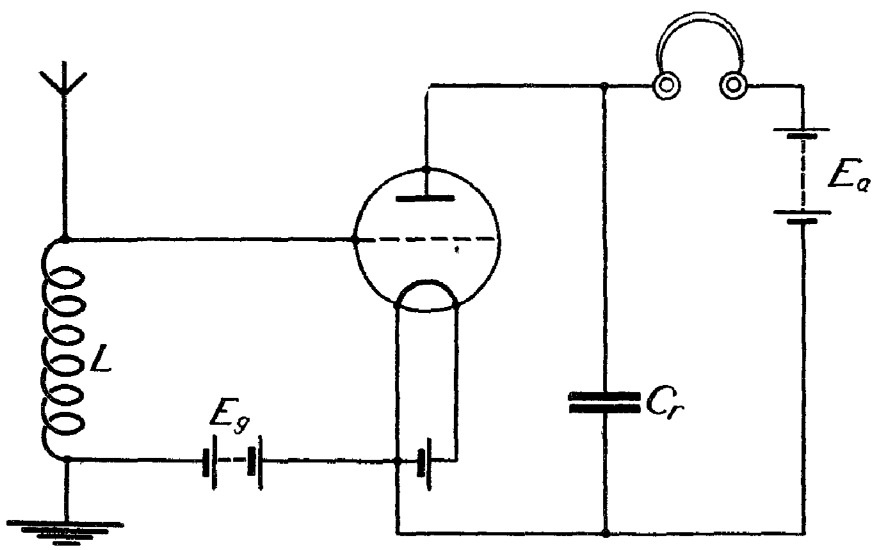


FIG. 23, CHAP. X.—Lower anode bend rectification.

well-marked curvature corresponding to low values of anode current and saturation current respectively; rectification will take place if the mean operating point is located in either region. Valves having oxide-coated filaments or indirectly-heated cathodes do not exhibit a marked saturation current, and as such valves are in almost universal use, it is proposed to consider first the form of rectification known as lower anode bend rectification. A suitable receiving circuit is shown in fig. 23 which may be compared with the circuit used for cumulative grid rectification. It differs from the latter in that the grid condenser and resistance leak are omitted, and a bias battery is provided, by which the normal potential of the grid may be made negative with respect to the filament. The value of this negative potential should be such that in the absence of a signal E.M.F. the anode current is maintained at a value near the point of greatest curvature of the $I_a - V_g$ characteristic. A typical I_a V_g curve is shown in fig. 24. The mean operating point P is maintained by the grid bias battery, which has an E.M.F. of 6 volts, and as no grid current flows, the grid will be maintained at a negative potential of 6 volts with respect to the negative end of the filament. In the absence of a signal the anode current is about ·2 milliamperes in the particular conditions illustrated.

(ii) Let us now consider the reception of a single group of an I.C.W. transmission, which sets the receiving aerial into oscillation, and will develop a corresponding oscillatory voltage in the aerial tuning inductance L, the peak P.D. being say **3** volts. On each positive half-cycle of grid oscillatory voltage, the anode current will increase to 2 milliamperes, and will fall to zero when the grid filament potential reaches some negative value, (about 7½ volts in fig. 24). The anode current will therefore vary at the frequency of the signal voltage, which is too high to cause vibration of the telephone diaphragm directly. The anode circuit of the valve consists of the H.T. battery, the telephones and the anode-filament path of the valve itself, the telephones and battery being shunted by the condenser C_r which is called the telephone condenser. This condenser fulfils exactly the same purpose as the reservoir condenser in diode rectification. Under pre-signal conditions, the P.D. between its plates is that of the H.T. battery, viz. 100 volts, for the battery charges it to this voltage as soon as the circuit is completed. The upper plate of the condenser is therefore 100 volts positive with respect to the lower.

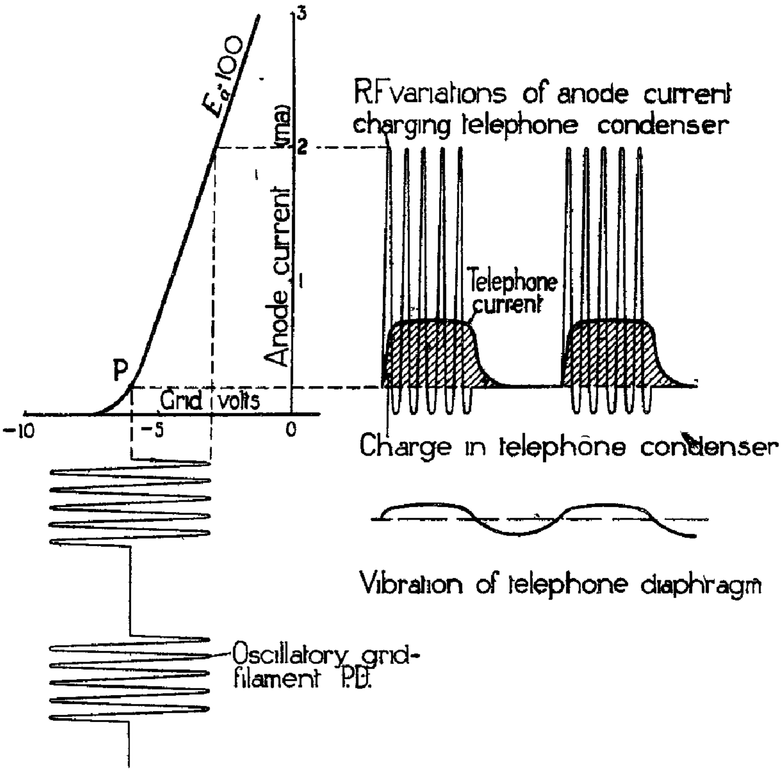


FIG. 24, CHAP. X.—Action of lower anode bend rectifier.

(iii) The opposition of the telephone windings to a steady current is merely the D.C. resistance, but to an oscillatory current the impedance offered is extremely high. During the positive half-cycles of oscillatory grid-filament P.D., the resulting increase of anode current will not flow through the windings, but will be forced to pass into the telephone condenser C_r. As an increase of anode current is equivalent to an increase in the rate at which electrons arrive at the anode, this implies an electron flow into C_r at its upper plate, and the P.D. between the plates is reduced. During negative half-cycles of grid-filament voltage the resulting decrease of anode current is less than the increase on the positive half-cycle, so that during a group of waves the P.D. across the telephone condenser C_r tends to fall below that of the H.T. battery. This cannot occur because the excess electrons in the upper plate of C_r flow steadily to the positive pole of the battery during the whole period, so that for each group of waves a unidirectional current is established in the telephone windings, causing a single inflection of the diaphragm, hence the latter is set in vibration at a frequency corresponding to the number of wave-groups per second. The variations of grid potential, anode current, and telephone current are shown in fig. 24.

36. If a reaction coil is included in the anode circuit, lower anode bend rectification may be combined with regenerative amplification as already described, while if the reaction coupling is sufficiently increased, autodyne reception of C.W. waves is possible. Owing to the fact that the valve is operated in a region where the anode A.C. resistance is higher than normal, the reaction coupling must be greater than in a similar circuit arranged for cumulative grid rectification. The reaction is also more difficult to control, because the degree of coupling necessary to cause oscillations to commence is much greater than that required to maintain them once they have started. This effect is often referred to as " overlap " or " back-lash " in the reaction control (paragraph 43). It is undesirable because it causes difficulty in ensuring that the receiver is adjusted for optimum conditions, i.e. just over the point of oscillation for autodyne reception or just " off " the point of oscillation for regenerative amplification. The sensitivity of anode bend rectification is generally only about one-half that of a similar receiver using cumulative grid rectification but, provided that the negative grid bias is sufficient to prevent the flow of grid current, and so avoid the damping it imposes, the selectivity is generally somewhat better.

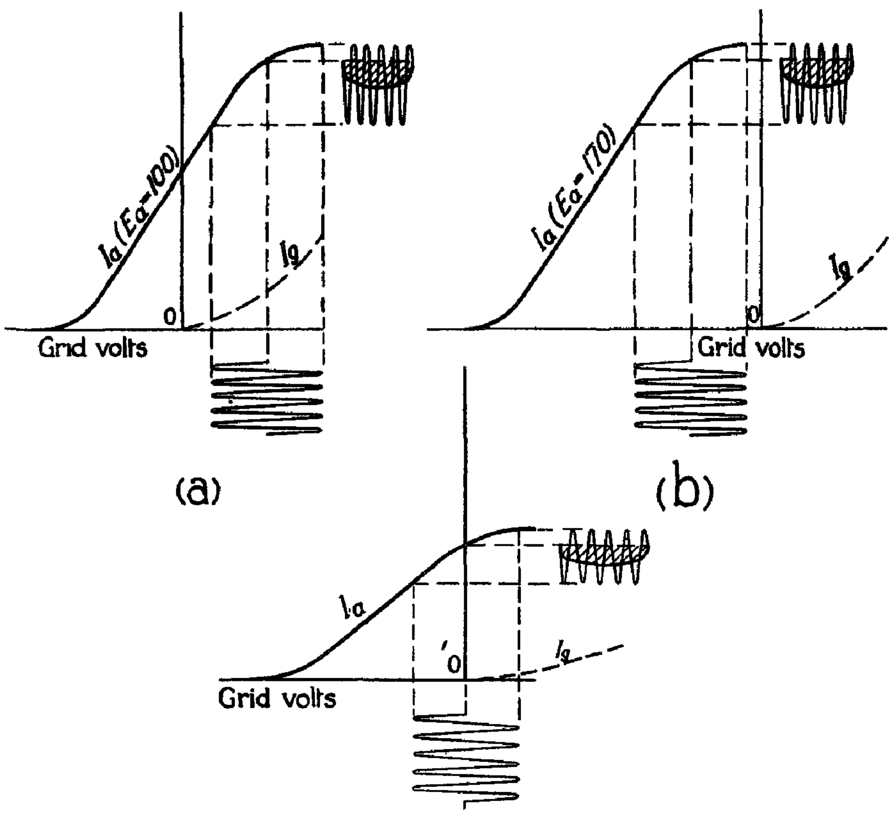


FIG. 25, CHAP. X.—Operating conditions with various types of upper anode bend rectifier.

Upper anode bend rectification

37. Little need be said about upper anode bend rectification. Its mode of operation follows from the previous discussion, observing however that instead of selecting an operating point near the foot of the characteristic by adjustment of grid bias, a point near the saturation bend is selected by one of several methods.

(i) Normal H.T. voltage being used, a positive bias may be applied to the grid, giving the operating conditions of fig. 25a. The disadvantage of this method is the heavy grid current which flows, and the resulting damping thrown upon the input circuit.

(ii) Using negative grid bias, an extra large H.T. voltage is applied, shifting the saturation bend of the curve to the left as shown in fig. 25b. The high value of H.T. voltage required for this method renders the system uneconomical.

In both the above schemes, normal emission is required from the filament.

(iii) Using normal H.T. voltage and zero grid bias, the filament emission is reduced by cutting down the filament current (fig. 25c). The drawback of this method is the reduced slope of the characteristic curve, which causes the rectifier to be even less sensitive than when operating on the lower anode bend.

Owing to the disadvantages of these methods they have fallen into practically complete disuse.

Comparison of cumulative grid and anode bend rectification

38. The relative merits of cumulative grid and anode bend rectification, so far as telegraphic reception is concerned, are briefly as follows. Bearing in mind that in the former type, rectification takes place in the grid circuit, the location of the mean anode current is on the straight and steepest portion of the $I_a - V_g$ curve, and the audio-frequency impulses set up in the grid circuit are magnified by the amplifying properties of the valve. The conditions in fact correspond to rectification followed by audio-frequency amplification, the latter process being efficiently performed owing to the operation taking place at a suitable point on the $I_a - V_g$ characteristic. The anode circuit impedance (i.e. the telephones in a simple receiver without A.F. amplification) is also easily matched to the internal impedance by the use of so-called high-resistance (really high inductance) telephones. In the anode bend rectifier, on the other hand, grid current need not occur, and the valve operates essentially as a radio-frequency amplifier having an unsymmetrical output voltage, which implies that the waveform contains a rectified component. As the location of the mean operating point on the $I_a - V_g$ characteristic is near one of the bends where the slope is comparatively small, the conditions are not favourable for efficient amplification, while the large value of the anode A.C. resistance in this region necessitates a very high impedance load in the anode circuit for correct matching, ordinary high-resistance telephones not being suitable. As a result, for small input voltages, say below 0·5 volts (peak value) the cumulative grid rectifier will give a much louder telephonic response than the anode bend rectifier, but as the input voltage is increased, this advantage becomes of less importance. In most practical receivers cumulative grid rectification is employed.

Simultaneous cumulative grid and anode bend rectification

39. In certain circumstances it is possible for both grid and anode rectification to occur simultaneously, but this is rarely an advantage. If in a cumulative grid rectifier the mean operating point is situated at a point of curvature of the $I_a - V_g$ characteristic as shown in fig. 26a, bottom anode bend rectification must occur to some extent. Now the effect of grid

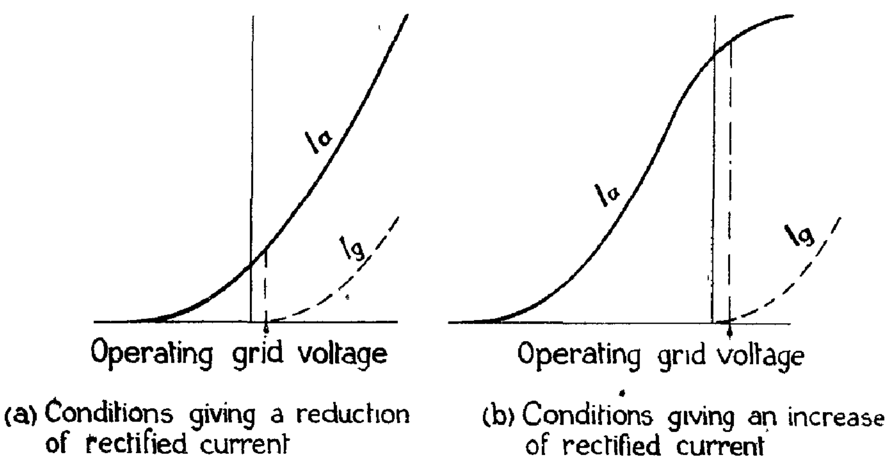


FIG. 26, CHAP. X.—Simultaneous cumulative grid and anode bend rectification.

rectification is a fall of anode current for each group of waves, whereas the effect of bottom anode bend rectification is to give an increase of anode current for each group, and the resultant change of anode current will be equal to the difference between the changes due to the two separate causes. It will therefore be less than in a properly adjusted cumulative grid rectifier. This phenomenon is likely to occur if a run down H.T. battery is used. If however a cumulative grid rectifier is so adjusted that the mean operating point on the $I_a - V_g$ characteristic is near the region of saturation current, fig. 26b, the change of anode current due to rectification in the grid circuit will be a decrease, and a further decrease will occur as a result of upper anode bend rectification. The two effects will thus combine to give a greater rectified current than would be given under normal operating conditions. This condition rarely arises in practice.

SIMPLE W/T RECEIVERS

40. The circuit diagram of an early aircraft receiver which is capable of either C.W. reception by the autodyne method or regenerative amplification of I.C.W. signals, is shown in fig. 27. Cumulative grid rectification is employed, while aerial tuning is accomplished by means of the variometer L_a, the windings of which may be placed either in series or parallel by means of a switch. When the windings are in series, the frequency range is from 300 to 120 kc/s, while with the windings in parallel the frequency range is from 600 to 200 kc/s. The whole of the aerial tuning inductance is wound with stranded cable in order to keep the radio-frequency resistance as low as possible. The capacitance of the average aerial used with this receiver is about $\cdot 0002 \mu F$, and the inductance alone is insufficient to provide the required frequency range, hence a bank of condensers is provided any one of which may be placed in parallel with the inductance. The arrangements for regenerative amplification, etc., are as follows. In series with the aerial tuning variometer is a coil consisting of a few turns of stranded cable which also forms a portion of the aerial circuit. This coil is wound on the stator of a pair of concentric formers, one of which is capable of rotation inside the other. This device is similar in appearance to a variometer, except that the two windings are not directly connected in any way, that carried by the rotor being the reaction coil and being connected in series between the anode of the detector valve and the telephone jack J_1. Variation of reaction coupling is performed by rotation of the inner coil with respect of the outer, an external knob and scale graduated from 0° to 180° being fitted. Since the rotor is capable of 180° rotation, the true zero inductive reaction is at 90°, when the coils are perpendicular to each other, and for any angular setting less than this, the inductive reaction is negative, tending to increase the damping of the aerial rather than the reverse. Owing to considerable capacitive coupling between the two coils, however, zero reaction, including that due to both capacitance and inductance, is generally found at about 45° on the scale. The range switch is arranged to cut out a portion of the anode reaction winding when reception of the higher frequency band is desired.

41. By means of the telephone jacks J_1 and J_2 the telephones may be inserted in the anode circuit of either the first or the third valve of the receiver. The valves T_2 and T_3 are used as audio-frequency amplifiers. When the telephones are plugged into the jack J_2, the primary winding of the transformer Tr 1 is connected in series with the anode circuit of the first valve, just as the telephones are connected in the circuits hitherto considered. The audio-frequency variation of anode current will now set up a varying flux in the iron core of the transformer Tr 2, and an E.M.F. will be induced in the secondary winding. This winding is connected to the grid and filament of the second valve, and consequently the secondary E.M.F. of the transformer will cause variations of its anode current at the audio-frequency. A similar action occurs in the transformer Tr 2 and triode T_3, so that the variations of anode current in the latter are a copy of those in the anode circuit of the detector valve T_1, but are magnified some 50 to 100 times, thus giving a much louder signal in the telephone receivers. The valves T_2 and T_3 are called audio-frequency amplifying valves, and a more complete account of their action is found in chapter XI.

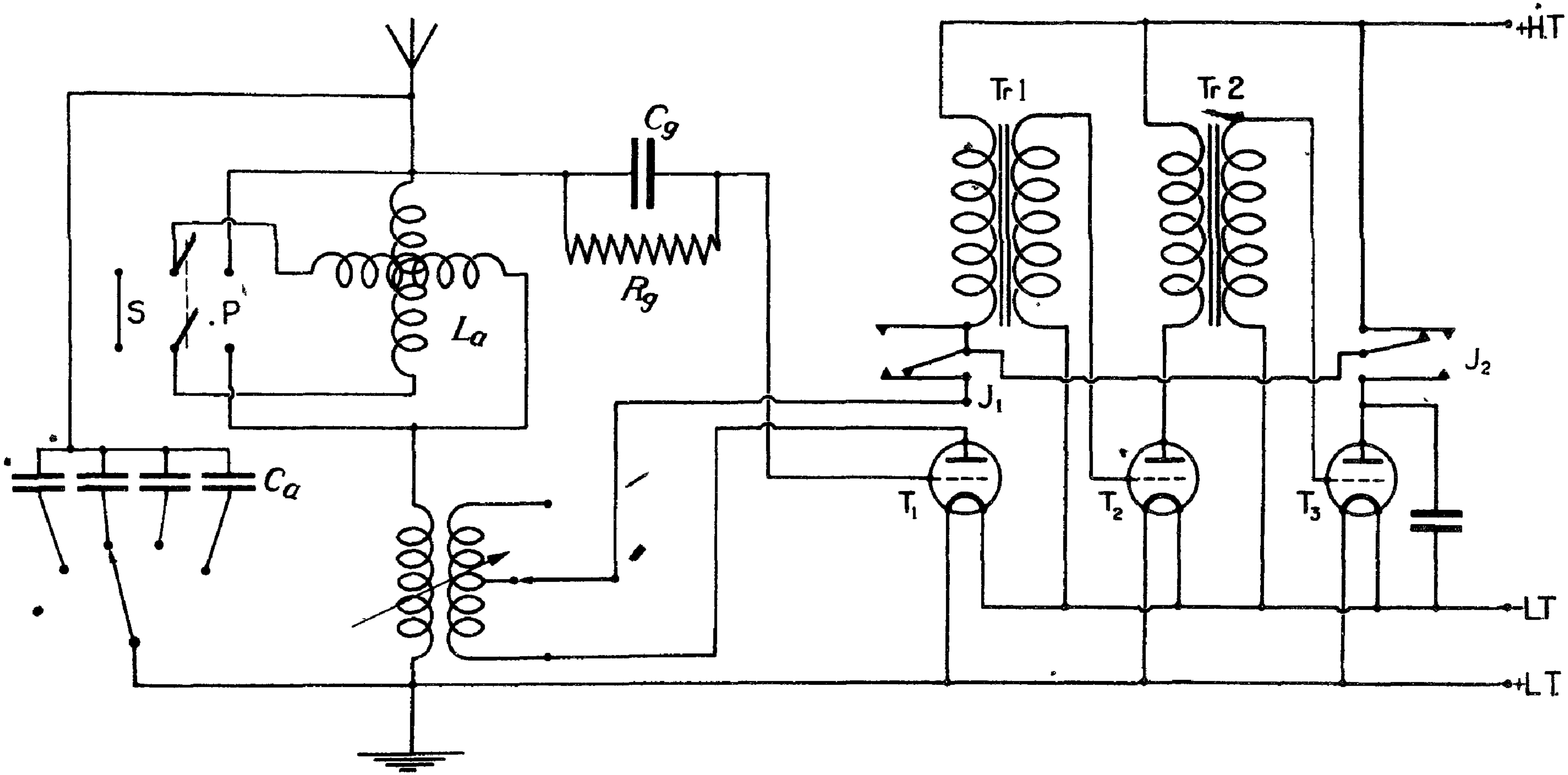
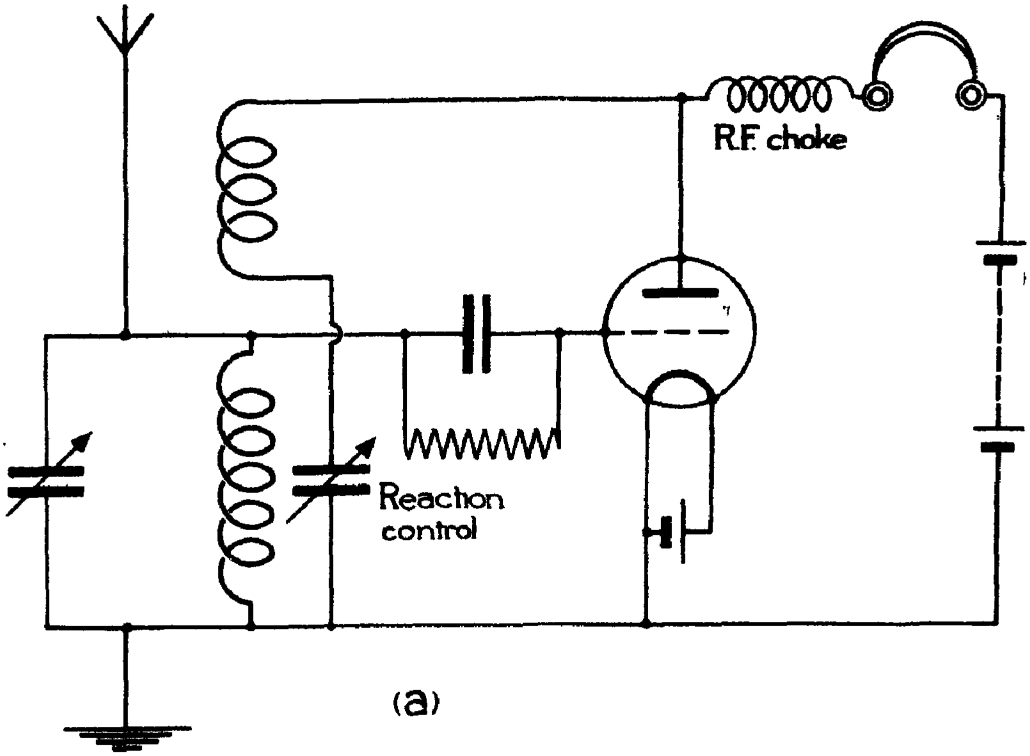
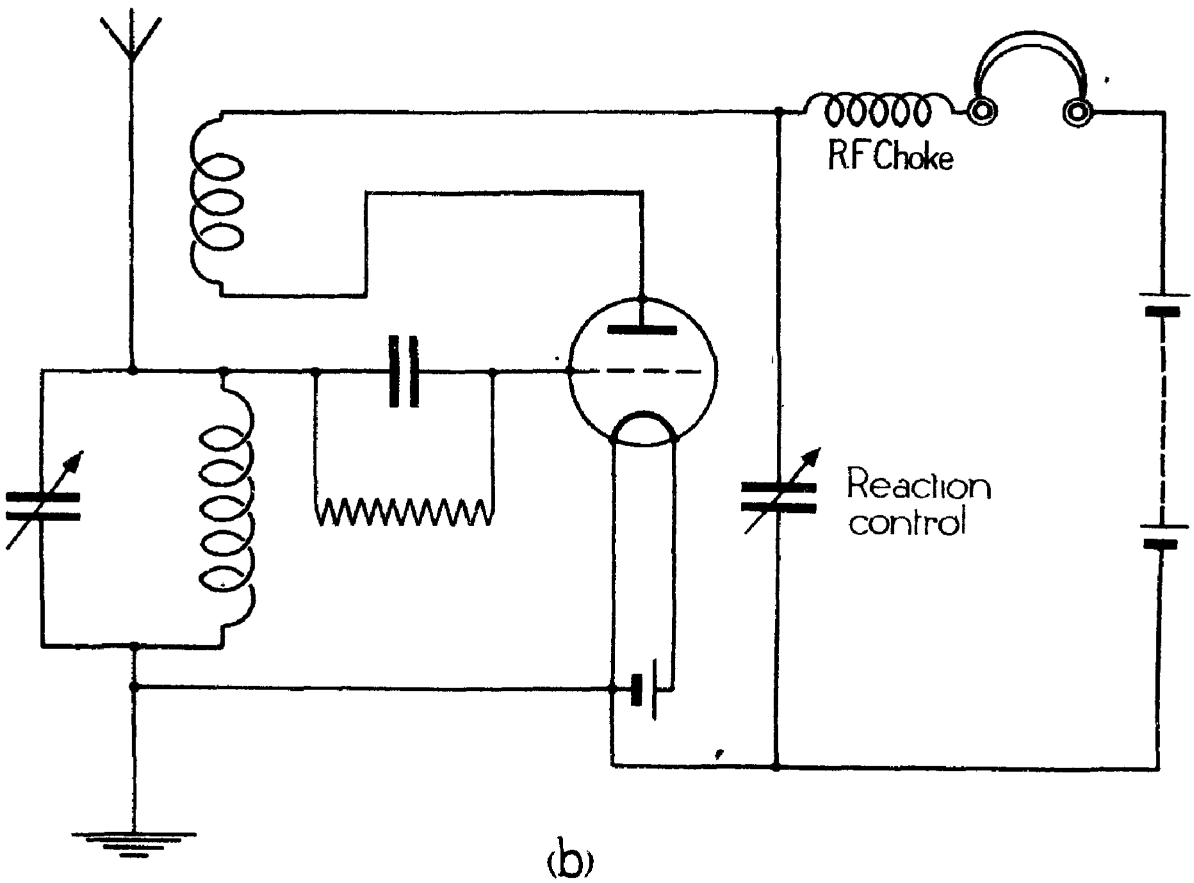


FIG. 27
CHAP X

SIMPLE RECEIVER FOR I.C.W. OR C.W. WAVES



(a)



(b)

METHODS OF CONTROLLING REACTION

FIG. 28
CHAP. X

Manipulation of C.W. receiver

42. When a receiver of this kind is used on the ground, a syntoniser is usually also available. This instrument is only calibrated approximately and its scale is marked in wavelength. Its primary use is as a separate heterodyne, and the method of employment is as follows. Tune the receiver to the exact frequency of the desired transmission, using the wavemeter W.39 if possible for this purpose. This instrument is a calibrated oscillator capable of emitting either tonic train (i.e. modulated) or pure C.W., a switch being provided in order to change the type of emission. The wavemeter should be set up to emit tonic train waves in accordance with the instructions on the lid, and the receiver tuned to this emission, reaction being so adjusted that the receiver is near to the point of oscillation but not actually oscillating. The wavemeter should then be set to emit C.W. of the same frequency. This will produce no sound in the receiver telephones, because no beat effect has yet been produced. On setting up and rotating the tuning condenser of the syntoniser, until its frequency is near that of the wavemeter, heterodyne beats will be set up and detected by the receiver; the frequency of the syntoniser can be then brought within 200 cycles or so of the wavemeter frequency by adjusting it to the middle of the dead space. Note the adjustments of both syntoniser and receiver, then switch off the wavemeter and return it to its stowage place. Subsequent reception is performed on the receiver, using the syntoniser to provide the local oscillation. It will be found that the signal strength obtained in this manner is much greater than when the same receiver is used for autodyne reception, while the selectivity is also superior. For preliminary adjustment the syntoniser should be placed as close as possible to the tuning coils of the receiver, although a reduction of coupling may afterwards be found advantageous, and of course slight " trimming " adjustments must be made when the desired station is first heard.

Control of reaction

43. In the simple receiving circuits hitherto discussed, autodyne reception of C.W. or regenerative amplification of I.C.W. is achieved by the use of a reaction coil, and variation of the degree of coupling between anode and grid circuits is performed by varying the mutual inductance of the grid and reaction coils. This is not the best method of reaction control, because a very small change in the relative position of the coils may in certain conditions result in a large change of mutual inductance. In particular it is desirable that the circuit should possess the following property. Starting with no appreciable transfer of energy from anode to grid circuit, that is, negligible reaction, let the coupling be gradually increased until the grid circuit just commences to oscillate. If then, the slightest movement of the reaction control device in the contrary direction causes the oscillation to cease, the circuit is said to have no overlap, while if oscillations, once started, persist in spite of an appreciable reduction of reaction coupling the circuit is said to possess overlap. The condition of no overlap is preferable to the condition of overlap, because for I.C.W. reception the receiver can be brought very near to the point of oscillation with instability, the latter term being in general use to denote a tendency to break into oscillation when some slight irregularity occurs in the operating conditions. e.g., a movement of the operator which may alter the capacitance of some portion of the receiver with respect to earth. Again when receiving C.W. signals by the autodyne method, it is usally found that maximum sensitivity is achieved when the amplitude of the local oscillatory current is a maximum; this condition is generally obtained with the weakest reaction coupling which is capable of maintaining the oscillation. A receiver having overlap can therefore never be operated at the point of maximum sensitivity either as a C.W. or I.C.W. receiver.

44. The usual method of reducing this tendency is to use a fixed amount of mutual inductance between grid and anode circuits, and to control the reaction by controlling the amplitude of the radio-frequency component of anode current. A typical arrangement is shewn in fig. 28a. Here the aerial and input circuits are connected to the valve in the usual manner, cumulative grid rectification being employed. A radio-frequency choke is inserted in series with the telephones so that no appreciable oscillatory current may flow in this direction. This choke is necessary owing to the self-capacitance of the telephone windings which would otherwise provide a path

for radio-frequency current. The reaction coil consists of a winding which is carried on the same former as the grid tuning inductance, the mutual inductance between grid and reaction coils depending only on the relative number of turns and on their separation. The reaction coil, in series with a variable condenser, is connected between the anode and filament of the valve, and the condenser is used as a reaction control, the action being as follows. If the reaction control capacitance is set to zero, no radio-frequency variation of anode current will flow in the reaction coil and therefore no transfer of energy from anode to grid circuits will occur, i.e. no regenerative amplification will take place. As the capacitance is increased, however, the impedance of the circuit is reduced and an increasing radio-frequency current will flow through the reaction coil, so that an appreciable E.M.F. will be induced in the grid circuit giving regenerative amplification of I.C.W. signals ; still further increase of capacitance will result in additional energy transference and self-oscillation will occur. Overlap is avoided by careful design of the reaction coil and by choice of a suitable maximum capacitance for the reaction control condenser. An alternative scheme of connection is shewn in fig. 28b in which the action is precisely the same.

Use of negative reaction

45. When a receiver is intended for employment under specially ardous conditions, for instance, as a portable receiver such as is used in battery ground stations for army co-operation, certain difficulties arise. In the first place, it is preferable to avoid the use of variable condensers of ordinary design, which are of somewhat delicate construction and may easily be damaged by the vibration to which they must be subject during transit on a gun limber over rough ground.

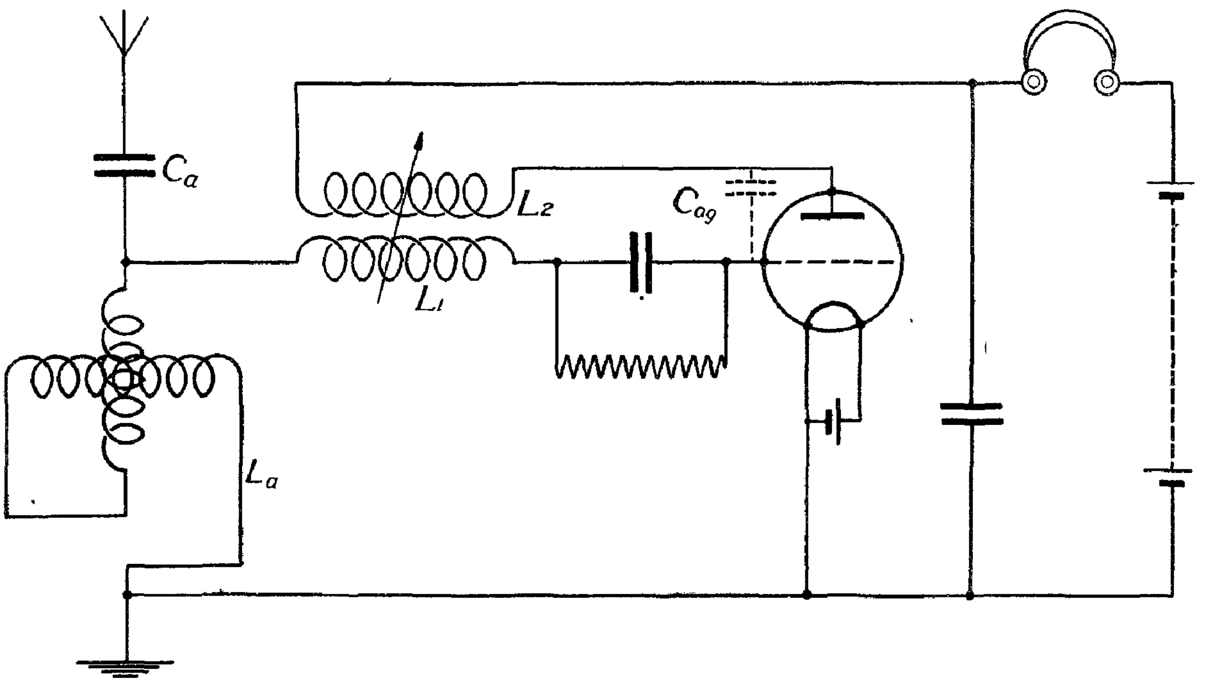


FIG. 29, CHAP. X.—Receiver with combined capacitive and negative inductive reaction.

In the second place, if the variable mutual inductance type of reaction control is employed, the inherent compactness leads to difficulties, for owing to the large and unavoidable capacitance which exists between anode and grid components due to their close proximity, it is found that oscillations may occur even if the reaction and grid coils are separated by the greatest distance possible. On the other hand, if the reaction coil is entirely omitted the sensitivity is poor because the grid circuit is excessively damped owing to the Miller effect. In these circumstances control of the degree of regenerative amplification may be obtained by so connecting the reaction coil that the effect of increasing the mutual inductance is to impose additional damping upon the input circuit. This type of reaction control was used in an early type of portable receiver for the reception of I.C.W. signals only; the essential portions of the circuit, from the present aspect, are shown in fig. 29. The aerial circuit consists of a fixed condenser C_a and a variometer L_a, the windings of which may be placed either in series or parallel in order to cover a wide frequency range. In series with the grid condenser and leak is a fixed inductance L_1 of very compact design and therefore with little external magnetic field, the inductance being about 1500 μH. The anode circuit is similar to that previously discussed, the reaction coil L_2 being connected in series with the telephones; its electrical and mechanical dimensions are identical with those of the inductance L_1 and it is pivoted upon an arm in such a manner that the coupling between L_1 and L_2 can be varied between wide limits. When the two coils are widely separated oscillations are maintained in the aerial circuit by the stray capacitive coupling existing between grid and anode circuits. As the reaction coil is connected in such a manner that an increase of magnetic coupling increases the damping of the input circuit, an increase of reaction coupling tends to suppress the oscillation and this suppression occurs when the coupling exceeds a certain critical value. The reaction coil can then be locked in this position.

46. The variation of reaction may be shown graphically. In fig. 30 positive reaction is considered to be that which causes a reduction of damping and negative reaction that which increases the damping of the input circuit. A certain amount of positive reaction is present owing to the stray capacitance, this amount being above that necessary to maintain oscillation.

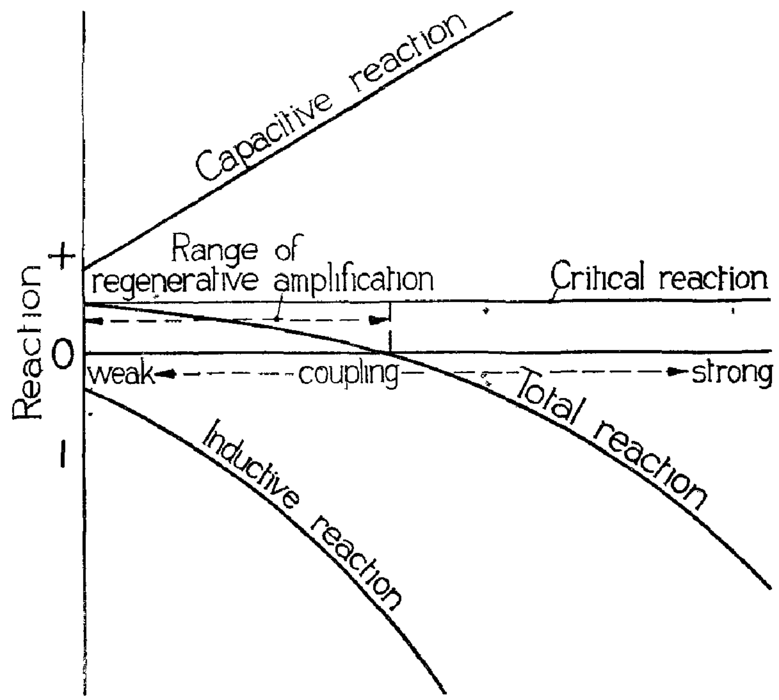


FIG. 30, CHAP. X.—Control of reaction in receiver of fig. 29.

The capacitive coupling between grid and anode circuits increases slightly as the two coils approach each other, so that the total positive (i.e. capacitive) reaction increases as the controlling lever is moved from one end of its travel to the other, as shown in the diagram. The magnetic coupling between the coils, however, is inversely proportional to some power of the distance between the coils; the variation of inductive reaction is therefore somewhat as shown, the total reaction being the algebraic sum of the capacitive and inductive reactions. It will be seen that by suitable adjustment of the circuit constants and operating potentials the reaction may be made to approach in a very gradual manner the critical value at which oscillation commences. Intelligent operation of this device is essential if optimum results are to be obtained. In particular, it should be realised that although the valves fitted in the portable receiver referred to are designed for a filament voltage of 2 volts, the inert battery used for the filament supply has an initial E.M.F. of nearly 3 volts, gradually falling during prolonged use, and returning nearly to its original value after a period of rest, unless the battery is near the end of its useful life. It is, therefore, not only unnecessary but a positive disadvantage to move the filament rheostat to the full " out " position when coming into action. The rheostats, and in particular the detector valve rheostat, should be set at a position giving both ample signal strength and a smooth control of reaction, the latter being only obtained when the anode current of the detector valve is not excessive. Only by attention to this detail will satisfactory operation of the reaction control be ensured. The fact that this receiver tends to break into the squegger type of oscillation (Chapter XI) when the reaction control is mishandled, is also an advantage, for it prevents the operator from using the receiver in an oscillating condition in an endeavour to obtain increased signal strength. In this connection it must be noted that operation in this way not only causes the characteristic note of the I.C.W. transmitter to be unrecognisable, so that " zone calls " are indistinguishable from ordinary signals, but renders the battery station liable to location by enemy direction-finding apparatus.

Send-receive switches

47. Where a transmitter and receiver are installed conjointly as is usual in aircraft, it is obviously desirable to utilise the same aerial both for transmission and reception. To a certain extent this usage also applies to ground stations, except where the transmitter is erected at some distance from its receiver and is controlled via land line by the receiving operator. When the same aerial is to be used for both reception and transmission, a send-receive switch is used to change the aerial connection from transmitter to receiver, and it is usual to combine this function with others. In an aircraft transmitter the send-receive switch will usually perform the following duties :—

(i) In the " transmit " position :—

(*a*) Connect aerial to transmitter aerial coil.

(*b*) Complete positive and negative H.T. supply from generator to transmitter.

(*c*) Complete positive L.T. supply to transmitter.

(*d*) Disconnect receiver from aerial.

(*e*) Transfer telephones from receiving circuit to side tone unit (*see* Chapter XII) in the case of I.C.W. or R/T transmitters.

(ii) In the " receive " position :—

(*a*) Break the connections (*a*), (*b*), (*c*) above.

(*b*) Connect aerial to receiver.

(*c*) Transfer telephones from side tone unit to anode circuit of receiver.

Listening through

48. In signalling by wireless telegraphy it is often desirable that the receiving operator shall be able to interrupt the transmitting operator at any point during the transmission, either because a portion of the message has been missed, or to give urgent operating instructions. This entails that the receiver in use by the transmitting operator shall be operative at all times except when the transmitting key is actually pressed, a requirement which obviously is not met by the use of a send-receive switch as described above. The original solution of this problem was to provide an electrically operated switch which on pressing the transmitting key automatically performed the functions enumerated under (i) (*a*), (*b*) and (*d*) above, while on releasing the key the operations (ii) (*a*) and (*b*) were performed. This device is known as a listening-through key and is still in use to a limited extent. It has the disadvantage that it is difficult to attain a

high operating speed owing to the inertia of the moving parts. A device which entails no mechanical motion whatever has supplanted this in modern service sets. The aerial is permanently connected to the transmitting aerial circuit, and the receiver is capacitance-coupled to the latter circuit by means of a very small condenser, the arrangement being as in fig. 31. It will be noted that during actual transmission the whole of the voltage across the aerial coil is applied to the coupling condenser and receiver aerial circuit in series. Even in the most favourable instances, i.e. on high radio-frequencies, with a comparatively small inductance in the transmitting aerial circuit and with low aerial current, the P.D. set up across the input circuit of the receiver will be much higher than that caused by a normal signal. Unless suitable precautions are taken this excessive voltage will probably damage the receiver coils, condensers and valves, and in order to prevent this a limiting valve is fitted.

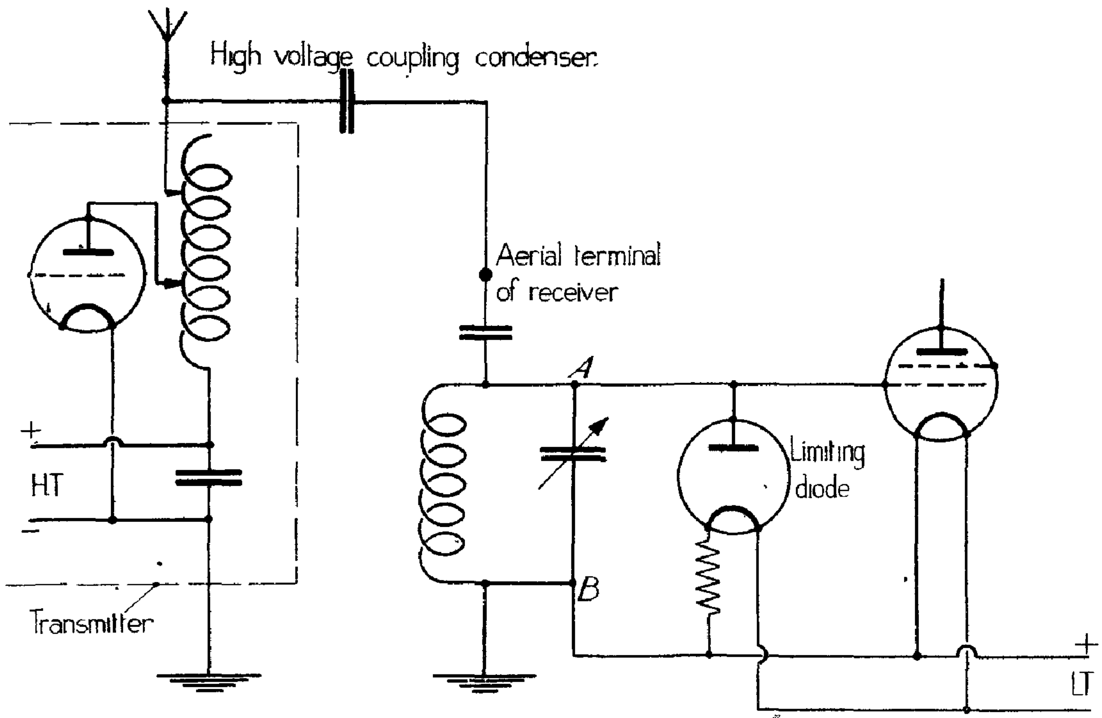


FIG. 31, CHAP. X.—Listening-through device.

49. The limiting valve consists of a diode (or a triode with grid and anode linked together), which is connected in parallel with the tuning condenser in the receiver aerial circuit. The anode is maintained at a small negative potential with regard to the filament, say − 1 volt. During ordinary reception, the peak oscillatory voltage across the points A and B, to which the diode is connected, never reaches one volt, and the anode never becomes positive with respect to the filament; hence anode current will not be established at any point in the cycle, and the receiver operates in exactly the same manner as it would with the diode removed. During transmission, however, the peak value of the induced E.M.F. in the tuned circuit of the receiver may be greatly in excess of one volt, and during the positive half-cycles the anode of the diode becomes highly positive with respect to the filament. An anode current is therefore established, and the anode-cathode space is equivalent to a resistance connected between the points A and B, the value being comparatively low, e.g. about 400 ohms. The damping imposed on the tuned circuit by this resistance in parallel with the tuning condenser is equivalent to that imposed by a series resistance of thousands of ohms, so that the oscillatory voltage across the points A and B is never built up to an excessive value. Alternatively, if the diode is considered practically to "short-circuit" the points A and B when anode current is passing, it is obvious that no P.D.

can exist between these points and the whole of the voltage developed in the transmitter aerial coil is thrown across the high voltage coupling condenser. It will be observed that the phenomenon is precisely the same as in the case of damping caused by excessive grid current in a receiver, but to a much greater degree.

50. This arrangement has certain advantages and disadvantages over the mechanical listening-through key; the higher speed of signalling has already been mentioned. The further advantages are :—

(i) Although when the transmitter is operated the voltage applied to the receiver is quite small, it is not zero, and the receiver can be accurately tuned to the transmitter frequency.

(ii) If the receiver is independently tuned to a distant transmitter, the local transmitter can afterwards be tuned to the same frequency.

(iii) The signal strength and selectivity in the "listening through" position are higher than if the receiver is connected directly to the aerial, provided that the transmitter aerial circuit has very low losses. Circuit arrangements usually provide for this method of reception to be used independently of the position of the send-receive switch; the principal function of the latter is then to break the power supplies to the transmitter.

The disadvantages are :—

(i) Since the receiver and transmitting aerial circuits are coupled together, signals are only received when the transmitter and receiver are tuned to approximately the same frequency. This is of only minor importance because this is the standard practice in the present W/T organisation.

(ii) Steps must be taken to ensure that the noise level due to commutation, etc., is not excessive, otherwise signals cannot be heard during the "space" intervals.

(iii) If the limiting valve becomes soft in use it may become appreciably conductive under the influence of quite small applied voltages, of the order of those set up in the receiver by signals of moderate strength. The valve will then damp the input circuit during reception and cause a reduction in selectivity and in signal strength. This can easily be tested by removing the limiting valve during reception, and the only remedy is replacement by an efficient diode.

INTERFERENCE

51. It is a matter of everyday observation that when a wireless receiver is in operation, a considerable background of noise may be in evidence. Collectively these undesired sounds are referred to as interference, and in turn may be divided into the following classes. (i) Signal interference. (ii) Atmospheric interference. (iii) Electrical interference (also sometimes called "man-made atmospherics" or "man-made static"). (iv) Amplifier noise. The latter will be considered briefly in chapter XI.

Signal interference

52. This term is applied to interference with reception by signals emanating from radio transmitters other than that with which communication is desired. It is only rarely that an interfering signal possesses a frequency identical with that to be received; when this is the case directional reception is the only remedy. Provided both frequencies are controlled by the use of master oscillators, a judicious use of the heterodyne principle may be very effective in reducing interference on frequencies which differ from the desired signal by only a few hundred cycles per second. Interference from stations giving a high field strength owing to their proximity

to the receiver and their high power, is reduced to a minimum by the use of selective receivers. The following methods are all in common use, separately or in combination :—

(i) Regenerative amplification in combination with a separate heterodyne for C.W. reception. This gives a high degree of selectivity but requires skilful manipulation.

(ii) The use of an aerial circuit having a very high ratio of effective inductance to resistance.

(iii) Reduction of aerial damping by the use of a series aerial condenser of small capacitance. This is a special application of method (ii).

(iv) The employment of loose coupling between the aerial and the input circuit to the detector valve.

(v) Employment of tuned radio-frequency amplifiers. These are dealt with in the following chapter. Method (i) has already been described, and methods (ii), (iii) and (iv) will now be discussed.

53. The resistance of an aerial circuit may be divided into three portions. First, the ohmic resistance of the conductor ; this is reduced to a minimum by using wire of suitable gauge, stranded cable being employed if necessary. Second, the resistance of the earth or counterpoise ; the importance of this has been emphasised in connection with transmitting aerials (Chapter VII), but it is often forgotten that a perfect earth may be rendered useless by a high resistance connection to the receiver, and all metallic contacts at terminals, etc., should always be kept clean and bright. Third, the radiation resistance ; in reception, the electro-magnetic field is the cause of an oscillatory current in the aerial, and re-radiation must take place to some extent. This phenomenon must be distinguished from the radiation which takes place due to the use of an oscillating receiver for C.W. reception. Re-radiation must occur whenever an electro-magnetic wave sets up an oscillatory current in a conductor ; steel-framed buildings, large cranes and even trees act in this way. The phenomenon of re-radiation implies the existence of a radiation

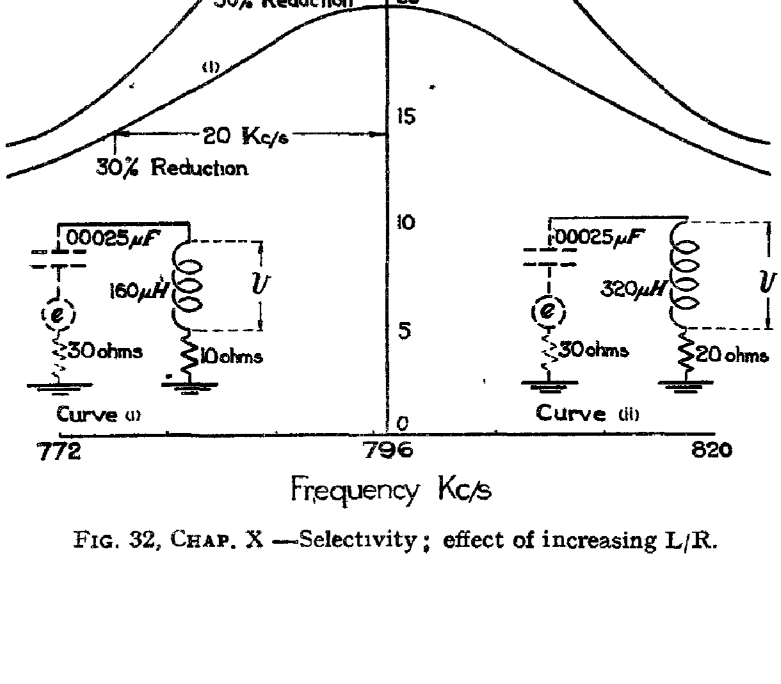


FIG. 32, CHAP. X —Selectivity ; effect of increasing L/R.

resistance; it is usual to assume that the radiation resistance of a given aerial when used for reception is equal to that which it possesses when used for transmission, although this cannot be strictly true because the current distribution is not the same in each case. As an example of the influence of the various components of aerial resistance, the following results of actual measurement may be quoted. An inductance of 160 μH and a condenser of ·00025 μF were combined to form a closed oscillatory circuit and its resistance at the resonant frequency was found to be 8 ohms. On removing the condenser and connecting the coil to an aerial and earth of the same effective capacitance, the resistance was found to be 36 ohms. The earth connection in these experiments was not very good, being made on the ordinary water supply system by a metal clamp, but the results are typical of what may be expected when a properly constructed earth system is not used. The calculated radiation resistance of the aerial was only 2 ohms, and it is possible that a large proportion of the 26 ohms resistance which is apparently inherent in the aerial-earth system itself is really due to eddy current and dielectric absorption losses; these would be reduced by the use of an earth screen as in the case of transmitting aerials. (Chapter VII). The resonance curve of an aerial circuit having the above values of L and C,

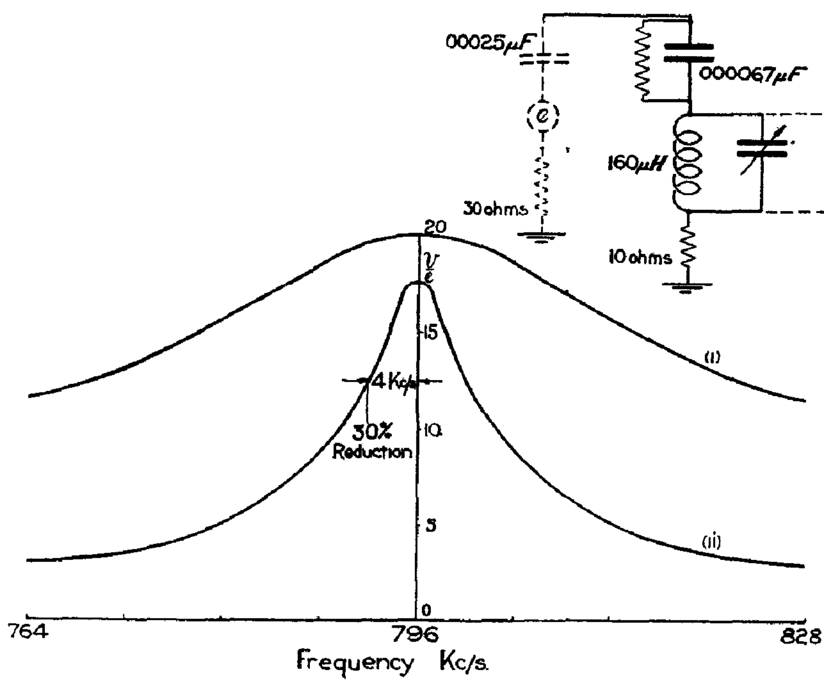


FIG. 33, CHAP. X.—Selectivity; effect of small series condenser in aerial circuit.

but having a total resistance of 40 ohms, is shewn in fig. 32, curve (i). It will be observed that the tuning is very flat, signals 20 k.c/s. off resonance giving an input to the detector equal to 70 per cent. of the desired signal (equal field strengths being assumed).

54. An improvement may be expected by increasing the inductance of the tuning coil to say 320μH, inserting a variable condenser in series in order to reduce the total effective capacitance to ·000125μH. This will increase the resistance also, but the ratio $\frac{L}{R}$ will increase in greater proportion. Assuming that the additional inductance increases the resistance to 50 ohms, the resulting resonance curve is shown in curve (ii) of fig. 32. The selectivity is somewhat improved, a 30 per cent. reduction in input voltage being obtained from signals only 12 k.c/s. off resonance. It is not practicable further to improve the selectivity by increasing the value of L without limit, for this entails a corresponding reduction in the series capacitance which eventually approximates to a complete disconnection of the aerial, and the signal strength fails off. Even a

moderate increase of inductance is accompanied by a corresponding increase of distributed capacitance, again limiting the amount of inductance required for resonance. Finally, the larger the coil dimensions become, the more difficult it is to secure controllable reaction and to avoid stray coupling with other inductances in the receiver.

55. The expedient usually adopted in order to attain the equivalent of a high ratio of inductance to resistance is shewn in the circuit diagram of fig. 33. A fixed condenser of small capacitance compared with that of the aerial is connected in series, and a variable condenser in parallel with the tuning coil. The effect of the series condenser is to reduce the damping thrown upon the circuit by the aerial resistance. The resonance curves in the diagram are, (i), which is repeated from the previous figures for comparison, (ii), the resonance curve of a circuit having the constants shown in the circuit diagram. A 30 per cent. reduction in input voltage is now obtained from signals only 4 k.c/s. off resonance. This method of attaining a high degree of selectivity possesses considerable advantages, being simple in operation and requiring only the addition of a very small and light component. A possible disadvantage is that the aerial may collect static charges which will gradually raise its potential until it is sufficient to puncture the insulation of the series condenser. This is avoided by connecting in parallel with the latter a high resistance, e.g. 250,000 ohms, which allows the static charge to drain harmlessly to earth.

56. The aerial may be inductively coupled to the input circuit of the receiver, two types of coupling being in common use. In the first type, both the aerial and input circuits are tuned to the desired frequency. A very high degree of selectivity is obtainable by this method, but

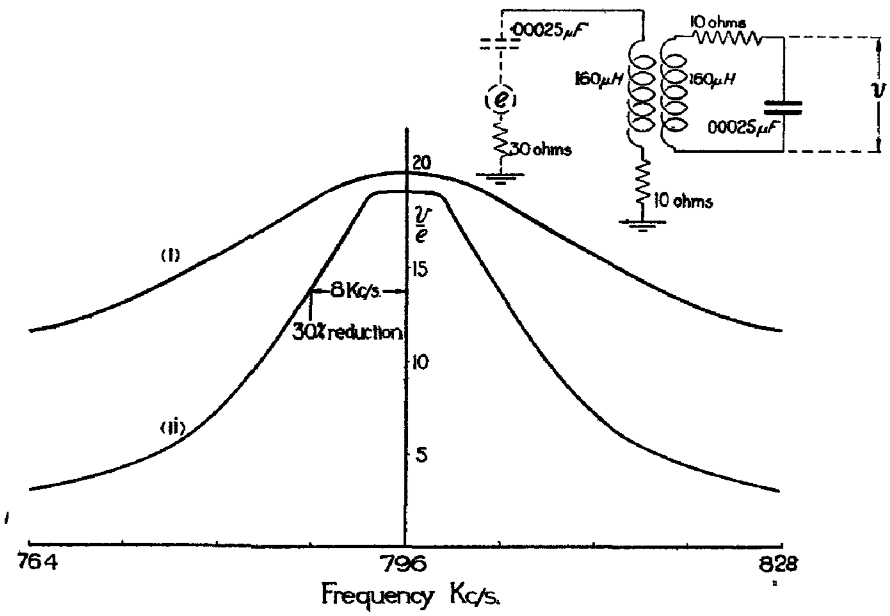


FIG. 34, CHAP. X.—Selectivity ; tuned coupled circuits.

it has the serious disadvantage that if the tuning control of each circuit is entirely independent, some little practice is required in order to achieve exact tuning with the desired degree of selectivity. It is possible to link the two circuits together in such a manner that both circuits are tuned simultaneously by rotation of one control and the circuits are then said to be ganged. Fig. 34, curve (ii) shows the resonance curve of a receiver having an aerial and input circuit of the separately adjustable type, curve (i) being repeated from fig. 32 for comparison. It is not absolutely necessary to tune the aerial circuit, provided that a rather higher percentage of coupling is used ; fig. 35 has been drawn to illustrate this. The aerial circuit has an inductive coupling to the input circuit, but no provision is made for varying either the tuning of the aerial circuit or the degree of coupling. This arrangement is generally referred to as " aperiodic aerial coupling." It will be seen from the diagram that the selectivity of the circuit shown is approximately the same as that of the circuit of fig. 34. Actually the centre of the resonance curve is at about 800 k.c/s. instead of 796 k.c/s., i.e., the resonant frequency of the combined circuits is slightly higher than that of the tuned circuit alone. All the resonance curves of fig. 32 to 35 inclusive have been calculated by a graphical method but the degree of accuracy is sufficient for the present purpose, namely, to illustrate the comparative selectivity of certain specific arrangements. The curves show that for C.W. or I.C.W. reception there is very little to choose between the selectivity obtainable by the various means. The requirements of R/T reception are somewhat different and will be dealt with in Chapter XII. Regenerative amplification may be used in conjunction with any of these devices, giving a further increase of selectivity as shown in earlier paragraphs. It appears that from a practical point of view the aperiodic mutual inductive coupling and the use of a small series condenser are equally good; both these methods are in use in different types of service receiver.

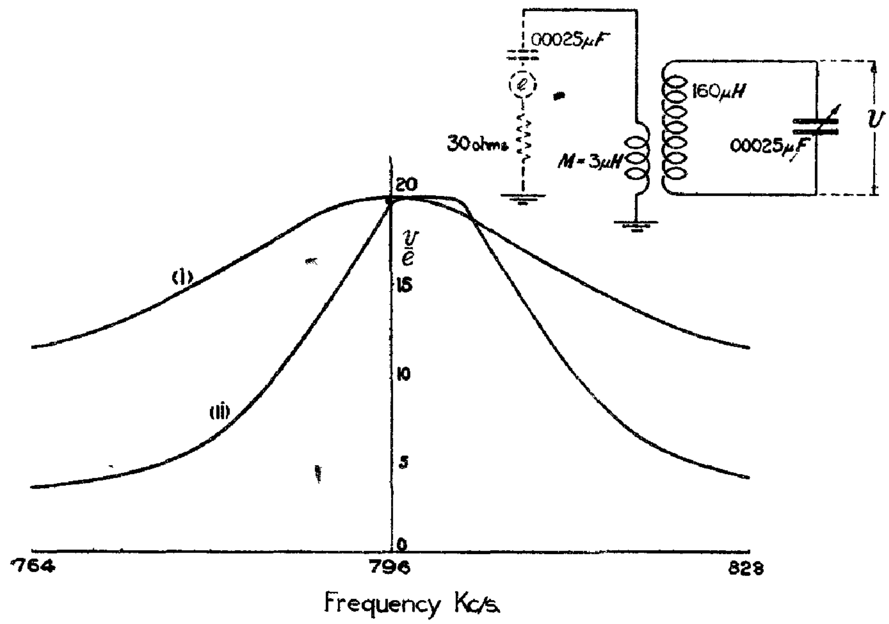


FIG. 35, CHAP. X.—Selectivity; coupled circuits with aperiodic aerial.

The decibel

57. (i) The relation between the strength of a signal at one point in a transmission chain and the strength at any other point depends upon the ratio of the power available at each of the two points. The magnitude of two powers P_1 and P_2 are said to differ by N bels when

$$\frac{P_1}{P_2} = 10^N$$

or

$$N = \log_{10} \frac{P_1}{P_2}$$

For general use a submultiple of this unit—the decibel—is employed, and the gain or loss in the transmission system is n decibels (db) when

$$n = 10 \log_{10} \frac{P_1}{P_2}$$

The two powers to be related need not correspond to dissipation of the same kind of energy, for instance P_1 may be the electrical power delivered to a telephone receiver and P_2 the power radiated by the diaphragm in the form of sound. One decibel corresponds approximately to the smallest change in sound intensity which can be perceived by the human ear, and the corresponding power ratio is

$$\frac{P_1}{P_2} = \text{antilog } 0\cdot1$$
$$= 1\cdot259,$$

i.e. an increase in power of 26 per cent. is the smallest which will give an appreciable increase in audibility. The practical value of the decibel arises from its logarithmic nature, for it enables an enormous range of power ratios to be expressed in convenient figures; for example if $\frac{P_1}{P_2} = 10^6$, the gain or loss is 60 db. It also simplifies the calculation of a number of successive gains, for example, if the gain between two points A and B is n_1 db and between B and C, n_2 db, then the gain between A and C is $(n_1 + n_2)$ db. When the two powers under comparison are dissipated in equal resistances the power ratio is proportional to the square of the voltage ratio, or to the square of the current ratio. In these circumstances the gain or loss may be expressed in db by the relation

$$n = 10 \log\left(\frac{E_1}{E_2}\right)^2 = 10 \log\left(\frac{I_1}{I_2}\right)^2$$

or

$$n = 20 \log\frac{E_1}{E_2} = 20 \log\frac{I_1}{I_2}.$$

This relation must not be used unless the resistance associated with E_1, I_1, is the same as that associated with E_2, I_2.

(ii) The following examples show how the decibel system is applied :—

(*a*) In the arbitrary " audibility scale " used in W/T procedure to indicate the strength of signals, an increase of one unit corresponds, very roughly, to an increase of 6 db.

(*b*) The gain between two points A and B in a certain transmission system is 30 db. Between B and C there is a gain of 6 db, while between C and D there is a gain of ·7 db. The total gain between A and B is $30 + 6 + \cdot7 = 36\cdot7$ db, corresponding to a power ratio of 4,670 to 1. This example shows the advantage of the decibel system. If the above calculation were performed in power ratios, it would be necessary to find the continued product of 1,000, 3·98 and 1·175, instead of the sum of 30, 6 and ·7. Again, if between B and C there is a negative gain, i.e. a loss of 6 db, the overall gain will be $30 - 6 + \cdot7$ or 24·7 db, and the power ratio $1{,}000 \times \frac{1}{3\cdot98} \times \cdot175 = 295$ to 1.

58. In the receiving aerial the initial voltage is dependent only upon the configuration of the aerial and the field strength of the signal, but is independent of the aerial impedance. The output voltage of the complete receiver is that across the telephones, and the latter are not of the same impedance at all audio-frequencies. If we stipulate (i) that the desired and undesired signals are both I.C.W. of the same note-frequency, and (ii) that the response of the receiver (between the input terminals to the first valve and the output terminals) is linear, we may compare the selectivity of the various arrangements shown in fig. 32 to 35 by stating that, for equal field strengths, an interfering signal will be n db below the desired signal. Suppose the latter to be on 796 k.c/s. and the interference on 780 k.c/s. In fig. 32, curve (i) the magnification $\left(\frac{v}{e}\right)$ at 796 k.c/s. is 20 and at 780 k.c/s. is 15·5. The latter is $20 \log_{10} \frac{20}{15\cdot5}$ or about 2 db below the former. In curve (ii) the magnification at 796 k.c/s. is 32 and at 780 k.c/s. is 19; the interference is 4·5 db below the desired signal. In fig. 33 curve (ii) the interference is 11 db, in fig. 34, curve (ii), 8·6 db and in fig 35, curve (ii), 8·3 db, below the level of the desired signal. For the purpose of comparison we may assume that an expert operator may be able to " over-read "

the desired signal if it is one strength on the audibility scale, i.e. 6 db, above the interference, and it is seen that in the particular circumstances stipulated above, only the last three arrangements are sufficiently selective. In practice, of course, the receiver rarely has a linear response ; e.g. a square law rectifier will discriminate in favour of the stronger signal, further improving the selectivity. In C.W. reception, with the same frequency separation, conditions would be much better. In the above circumstances, for instance, to receive the signal of 796 k.c/s. the heterodyne may be adjusted to 795 k.c/s. giving a 1,000 cycle note. The interfering signal would then set up a beat note of 15,000 cycles per second, and to such a high frequency the combination of telephone, ear and brain is comparatively insensitive.

Atmospheric interference

59. (i) This is caused by electro-magnetic waves of natural origin, and its intensity varies greatly with the location of the station—being least in the temperate zones—and with the seasons of the year. Until a few years ago the origin of atmospherics was unknown, but with the aid of the cathode ray oscillograph, the wave-form, field strength and the direction of incidence have been measured in certain instances. As a result of this research it is now believed that most atmospherics originate within the region to which the atmosphere of the earth extends, and are chiefly caused by lightning discharges between clouds, or from clouds to earth, perhaps thousands of miles from the receiving station. The wave form of an atmospheric is almost invariably aperiodic, showing no reversal of polarity, a typical shape being a single pulse rising sharply from zero to a field strength which may be as large as ·1 volt per metre, falling to zero in about ·002 second. The E.M.F. induced in the aerial circuit then causes it to oscillate at its natural frequency with a decrement depending upon the ratio of inductance to resistance. From another point of view, such an aperiodic pulse may be considered to be built up of a spectrum of oscillations of all frequencies between zero and infinity, the lower frequency components possessing the greater amplitude. The receiver then responds to that portion of the spectrum which is embraced by its resonance curve, and the noise level caused by atmospherics will be directly proportional to the width of the frequency band which the receiver will accept. The position is exactly analogous to the emission from a white-hot solid body of light, which consists of a continuous spectrum in which every colour is present. A colour filter may be transparent to a narrow band of frequencies, e.g. red, and opaque to all others, thus resembling the tuned circuits of a receiver. Such a filter passes most of the light thrown upon it by a red-hot solid, but will pass some light from any incandescent body, and the light which it transmits is red only. In like manner, a wireless receiver always finds in the spectrum of an atmospheric a certain band to which it will easily respond.

(ii) In these circumstances, it appears to be impossible to combat atmospheric interference with W/T signalling by modifications to circuit design, although in the past many futile attempts have been made in this direction, such as the introduction of resistance to damp out disturbances, balancing schemes designed to neutralise the atmospheric without affecting the signal, detuning the receiver, etc. Experience and theory combine to show that such devices are valueless in increasing the ratio of signal strength to noise, and elimination of atmospheric interference must be sought mainly in the following directions :—

(*a*) The provision of high signal field-strength.

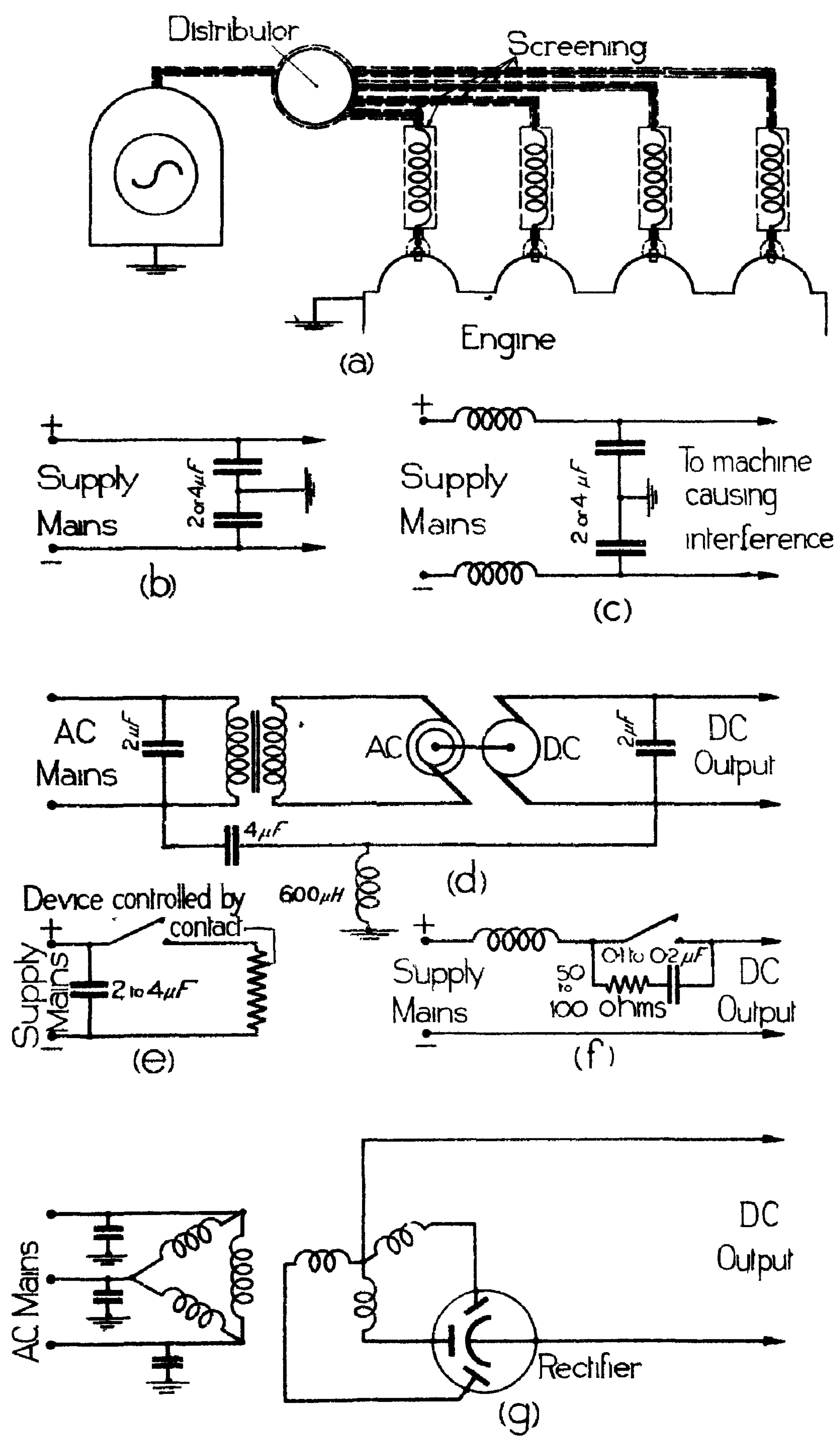
(*b*) Choice of frequency ; atmospheric interference being much less troublesome on the frequencies above 3 m.c/s. than below.

(*c*) Use of directional receivers and aerial arrays.

(*d*) Use of receivers of high selectivity.

Electrical interference

60. Electrical interference may be of three kinds, (i) radio-frequency, ether-borne, (ii) radio-frequency, mains-borne and (iii) audio-frequency. The first two are due to the fact that electric oscillations are established in every circuit of less than critical damping whenever the electrons



SUPPRESSOR DEVICES

FIG 36
CHAP X

therein receive acceleration; the frequency of the oscillation is determined by the circuit constants. In practice it is found that radio-frequency oscillations of a heavily damped nature are established by the current variations caused by switches, commutation in motors and generators, the operation of neon signs, etc. Owing to the heavy damping, the interference is not confined to a single frequency but is distributed to some extent over the entire spectrum as in the case of atmospherics. Some of the energy is carried to the vicinity of the receiving aerial by true radiation, and where any electric circuits, e.g., the lighting or power mains, connect the place of origin with the receiving station, the latter is also subject to mains-borne interference. This is picked up by the aerial circuit of the receiver in the ordinary way. The third type of interference is caused by direct induction from the mains into the audio-frequency circuits of the receiver and is much more easily combated. The following sources of interference may be found at R.A.F. ground stations, the first-named being also the predominating cause of interference in aircraft.

(i) *Spark ignition systems.* This is of the directly radiated type and causes serious interference only on the higher frequencies. (Fig. 36a).

(ii) *Motors and generators.* Chiefly directly radiated, although a considerable portion is mains-borne. It is usually inappreciable beyond a range of 200 yards. Induction motors cause little interference as a rule. (Fig. 36b or c).

(iii) *Rectifiers, commutator type.* This apparatus is sometimes used for battery charging and for arc lamps (cinema, searchlight, etc.). Chiefly directly radiated, mains-borne component usually small. Very severe up to 200 yards range. (Fig. 36d).

(iv) *Road and rail control signals, telephone switching plant, electric bells, ovens, thermostatically controlled heating apparatus.* Chiefly mains-borne, range up to 100 yards. (Fig. 36e).

(v) *Lift plant.* Including motor and controller, also trailing cables. Both direct and mains-borne radiation, range up to 25 yards. (Fig. 36c and f.).

(vi) *Mercury arc rectifiers.* Chiefly audio-frequency induction, but possibly direct radiation also. Range may be considerable. (Fig. 36g).

(vii) *High tension transmission lines.* These cause directly radiated interference when corona losses are occurring at insulators. Range indeterminate.

(viii) *High frequency medical apparatus.* Causes very intense radiation and may have considerable range. Mains-borne interference extends to 300 yards or more.

The devices shown in fig. 36 have been successfully applied in many cases, those applicable in particular cases being denoted in the preceding paragraph. It will be observed that there is no simple remedy for items (vii) and (viii). In the latter, complete electro-magnetic screening of the room housing the medical equipment appears to be the only solution. In addition to fitting such interference suppressors at the source, devices such as that shown in fig. 36a, and 36b, may be found useful at the point where the supply mains enter the receiving room.