Thermionic Vacuum Tubes and Their Applications

By ROBERT W. KING

NOTE: The present material was originally prepared for the National Research Council for use in a proposed *Manual* on "Physical Research Methods and Technique." As the appearance of the *Manual* has been postponed, the Committee in charge of its preparation has kindly consented to the separate publication of some of the sections in various technical magazines. In order to meet the requirements of the *Manual*, the form of expression has been made as compact as possible with practically no discussion of theory and no derivation of formulas. Since this style of presentation leaves much to be desired from some points of view, references have been given to the original literature wherever possible. However, many of the vacuum tube circuits presented have not as yet been treated in the literature. In the preparation of the new material the author has been greatly helped by persons whose contact with these subjects is at first hand.

Contents:

I. INTRODUCTION

1. *Thermionic Emission.* By thermionic vacuum tubes we shall understand those whose operation depends in an essential manner upon thermionic emission.

The design of the various types of thermionic tubes at present in use requires no knowledge of the exact mechanism of thermionic emission. It may be said, however, that the work of O. W. Richardson and others leaves little question but that this emission is a physical as distinguished from a chemical process, and occurs from certain substances as the result of the large velocities of thermal agitation acquired by electrons when these substances are raised to a high temperature.

On the basis of certain plausible assumptions, O. W. Richardson derived [2] the expression,

$$I_s = Ne = AT^{\lambda}\epsilon^{-\frac{w_0}{kT}}, \tag{1}$$

for the thermionic emission per cm.² in which I_s is the saturation current formed by drawing all the emitted electrons to a positively charged electrode placed near the emitting surface, e is the electronic charge and ϵ the Naperian base, A is a constant dependent on the emitting substance but independent of the absolute temperature T,

[2] Richardson, The Electron Theory of Matter, 1916 Edition, page 441.

w_o represents the energy lost by each electron as a result of becoming free, λ is a number which does not differ much from unity, and k is the gas constant per molecule. Experiments show that the value of λ for a wide range of substances is about unity, but its exact value is of little practical importance, since the variation of I_s with T is almost entirely controlled by the term in which T enters as an exponent.

The quantity w_o which expresses the *electron affinity* of the emitting substance is usually called the internal work of evaporation. In Equation 1, it is in terms of ergs per electron. Calling v_o the value of w_o when expressed in equivalent volts, $w_o = 1.59 \times 10^{-12}\ v_o$.

The term v_o is of great importance when considering the economy with which a substance acts as a thermionic emitter. Assuming that the emission of an electron occurs when its velocity acquires a value sufficiently high to overcome the potential drop v_o, it is apparent that the smaller v_o, the more copious will be the thermionic emission at any given temperature. For the substances thus far examined, v_o ranges between about two volts and five volts.[3] The two substances whose thermionic properties we shall consider particularly are platinum, coated with a mixture of barium and strontium oxides, and tungsten. For tungsten the value of v_o is approximately 5 volts, and for coated platinum it varies between 1.67 and 2.05 volts. The value of $(v_o)_A - (v_o)_B$ for two substances A and B is equal (except for a small term expressing the Peltier coefficient) to their contact difference of potential.[4]

2. *Thermionic Properties of Filaments.* In designing electron tubes with predetermined characteristics knowledge of the thermionic emissivity of the proposed filament is necessary. This property may be conveniently represented by curves of the type shown in Figs. 1, 2 and 3. The coordinates have been so proportioned [5] that, provided the electronic emission varies with the temperature as indicated by Equation 1 and the thermal radiation from the filament varies as the fourth power of the temperature, then the relation between the thermionic emission and the heating power supplied to the filament is a straight line.

Fig. 1 gives data for tungsten and for coated platinum filaments, Fig. 2 compares thoriated tungsten filament with pure tungsten and Fig. 3 gives data relating to a special coated filament, the core of which consists mainly of platinum alloyed with about 5% of nickel. Since

[3] For a Table of Values of v_o for the materials commonly used see Van der Bijl—Thermionic Vacuum Tube, page 29; also Langmuir, Trans. Am. Electro-chem. Soc. 29,166, 1916.

[4] Richardson, Electron Theory of Matter, 1916, p. 455.

[5] See Van der Bijl, The Thermionic Vacuum Tube, p. 82.

the thermionic emission of tungsten, and thoriated tungsten when freshly activated, do not vary much between different samples, they are given with sufficient accuracy for tube design purposes by single

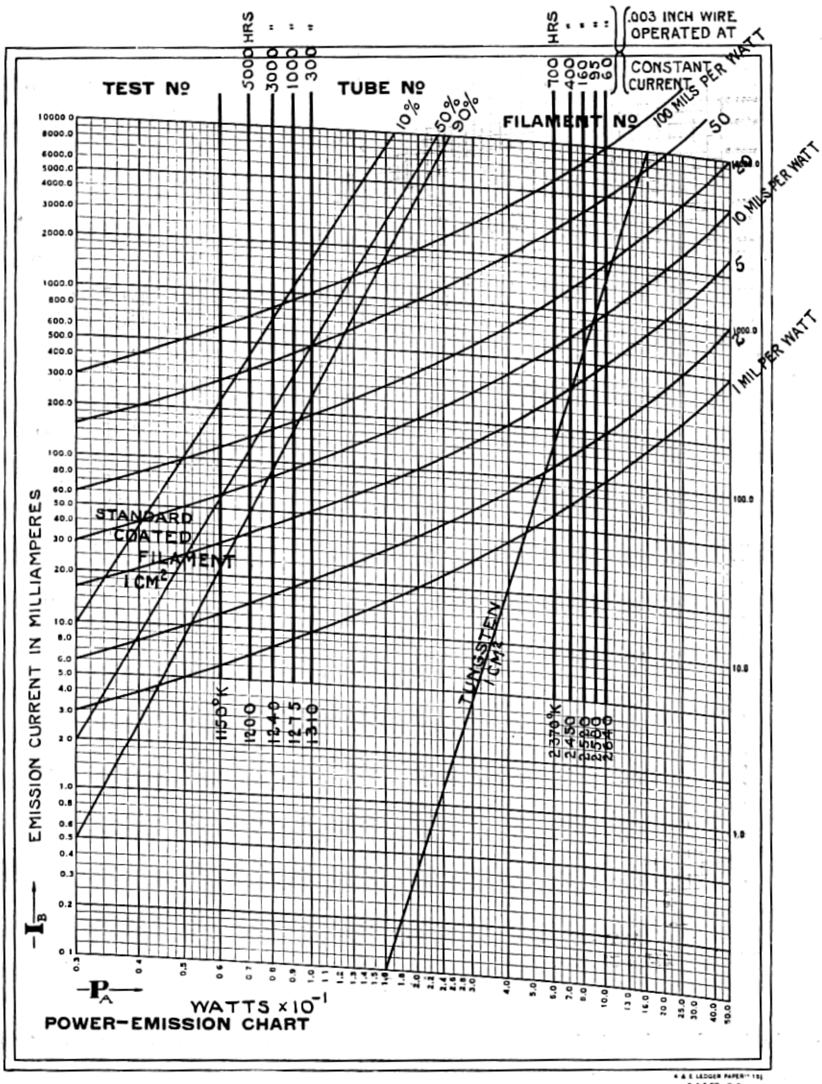

Fig. 1

lines. Coated filaments, however, show a rather wide variation as is indicated. The range of variation shown in Fig. 1 was obtained in the study of several thousand tubes; 10 per cent. showed activity greater than that represented by the 10% line, 50 per cent. showed activity greater than the 50% line and 90 per cent. showed activity greater than the 90% line. The three lines illustrating the range of

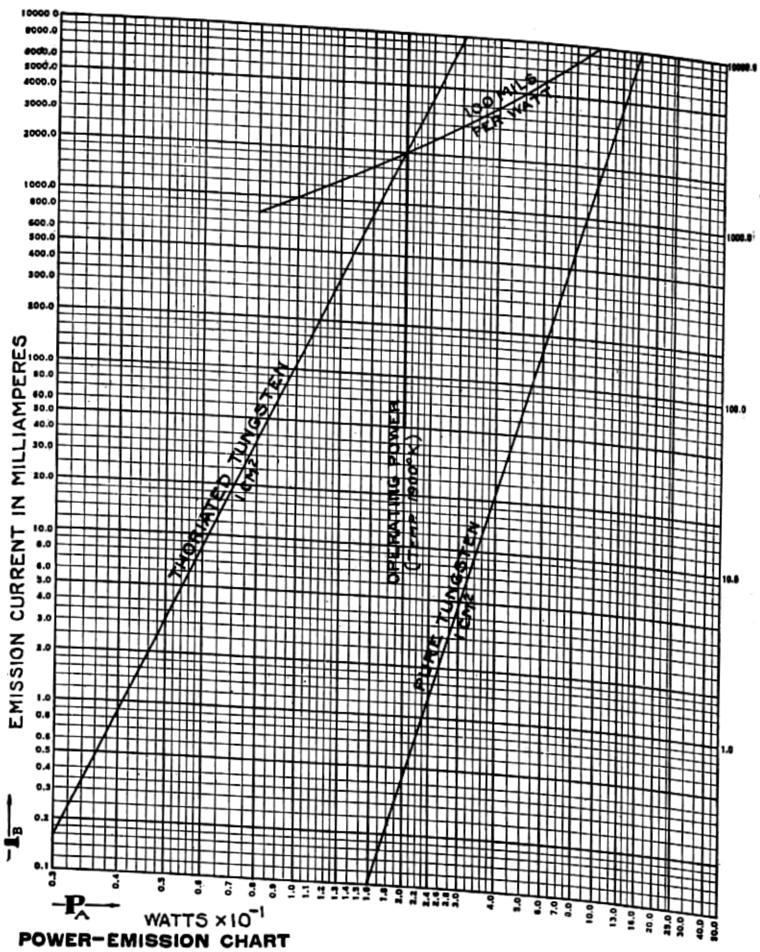

Fig. 2

variation in Fig. 3 do not correspond to these same percentages but have been labeled so as to be readily interpretable.

The efficiencies in milliamperes of emission current per watt used to heat the filament are shown by the curved lines that cross each chart. Operating temperatures and corresponding filament life are given for certain of the ordinates. The tungsten life data in Fig. 1 are for 3-mil wire and a constant heating current. If operating at a constant temperature, the life would be somewhat longer; furthermore, the larger the wire the longer the life for a given temperature. The activity of thoriated filaments tends to diminish with use but may

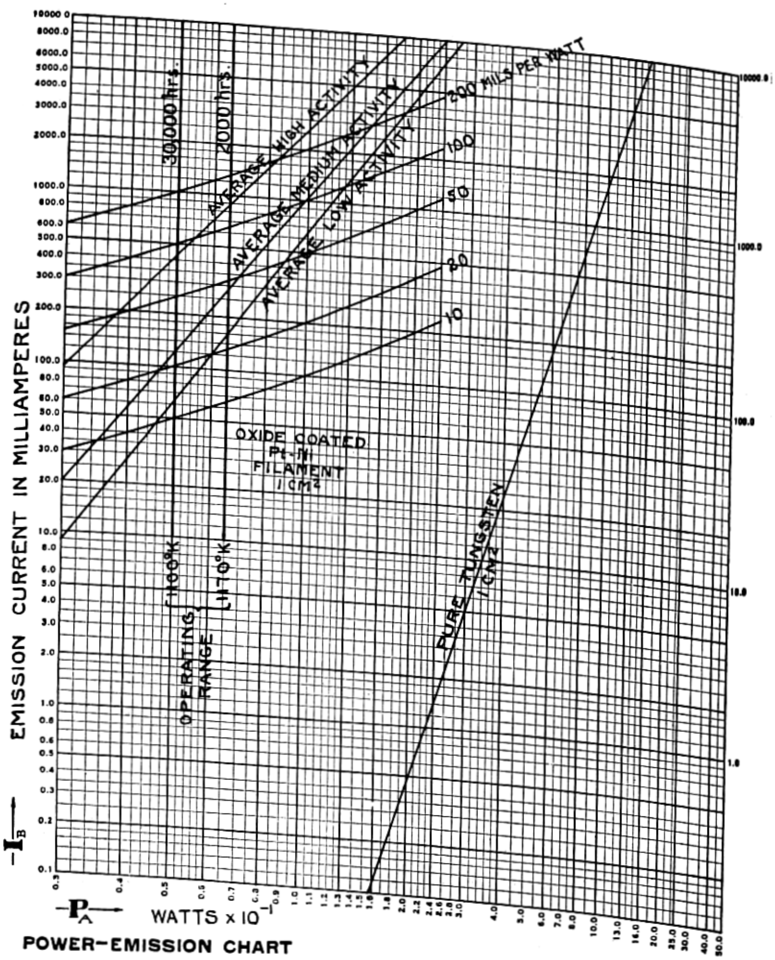

Fig. 3

be re-activated by heating to a temperature higher than the normal operating temperature. The useful life of these filaments is, therefore, somewhat indefinite but taking the possibility of re-activation into account, it is probably well in excess of 2,000 hours.

In using Figs. 1, 2, 3, it should be borne in mind that the emission values given represent saturation currents and that in general the normal operating space current in a tube must, for reasons which will appear later, be appreciably less than the saturation current. The difference between the saturation current and the maximum operating space current varies with the duty to which the tube is assigned. In the case of high voltage rectifiers, the space current may at certain points in the cycle reach the saturation value, while in a tube which is used as an amplifier it is often desirable, in order to avoid distortion, to have the total emission two to three times as great as the maximum working space current.

3. *Space Current-Voltage Characteristic.* Experiment shows that in a vacuum tube containing an emitting electrode and a conveniently placed anode, the space current I_p, varies with the temperature of the emitter and the anode potential E_p, as in Fig. 4. The three curves shown are for three temperatures such that $T_1 < T_2 < T_3$. It will be observed that between points O and A the three curves coincide;

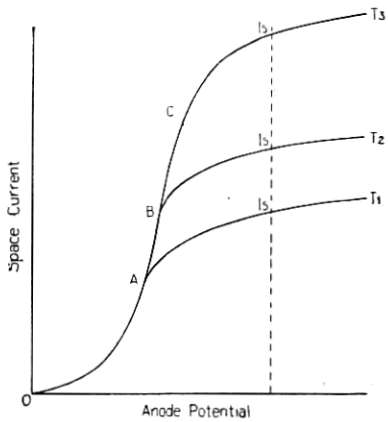

Fig. 4

between O and B the curves for the two higher temperatures coincide. The saturation values of the filament emission at the various temperatures are shown by I_s.

For values of I_p ranging from zero to somewhat less than I_s, the relation between I_p and E_p may be expressed with a fair degree of accuracy by $I_p = \kappa E_p^\eta$ in which the exponent η does not differ greatly from 3/2. This relation, therefore, is frequently known as the 3/2 power law. It has been deduced theoretically by Child [7] and Langmuir [8] and has been studied lately in greater detail by Fry.[9] Fry's analysis takes account of the initial velocities of emission of electrons,

[7] *Phys. Rev.*, Vol. 32, p. 498, 1911.

[8] *Phys. Rev.* (2), Vol. 2, p. 450, 1913.

[9] T. C. Fry, *Phys. Rev.*, Vol. 17, p. 441, 1921.

and, as he shows, the effect of the space charge is to create a region of negative potential immediately around the emitter. Let Fig. 5 represent the value of the potential as one proceeds from the cathode in the direction x, and V' represent the minimum value of the potential. Assuming indefinitely large emission from the cathode, V' (which is a function of E_p), determines the space current corresponding

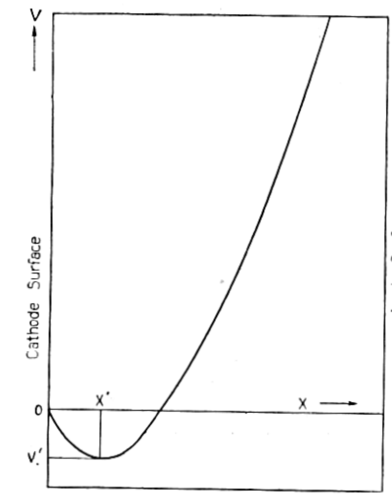

Fig. 5

to any particular value of E_p. The lower the value of V' the fewer the electrons with initial velocities sufficient to carry them past the equipotential surface V' into the region where they are attracted by the anode. Assuming the average initial velocity to be 0.3 volts (roughly a temperature of 2400° K), Fry finds an appreciable deviation from the 3/2 power law for $E_p < 30$ volts, but initial velocities need be considered only in tubes which operate at low E_p.

Another factor which, for low E_p causes an appreciable deviation from the 3/2 power law, is the potential gradient in a filament cathode due to the heating current. Whereas velocity of emission tends to make $\eta < 3/2$, the potential gradient in the filament has the reverse effect. In general, the latter more than overbalances the former and for small anode voltages $\eta > 3/2$. The value of η when the cathode potential gradient is considered, but initial velocities are neglected, has been given by W. Wilson,[10] who finds that when E_p is less than the potential drop across the filament $\eta = 5/2$, while for higher E_p it gradually approaches the limiting value 3/2.

[10] For discussion of the 5/2 power relation, see Van der Bijl, The Thermionic Vacuum Tube, p. 64.

4. *Temperature Saturation and Voltage Saturation.* When a vacuum tube operates at such filament temperature and E_p that an increase in temperature produces no increase in I_p the tube is said to show *temperature saturation.* On the other hand when temperature and E_p are such that an increase in E_p does not increase I_p, the tube shows *voltage saturation.* Referring to Fig. 2 the curve T_1 shows temperature saturation between O and A and approaches voltage saturation beyond the point A. Similarly the curve T_2 shows temperature saturation up to the point B and approaches voltage saturation beyond.

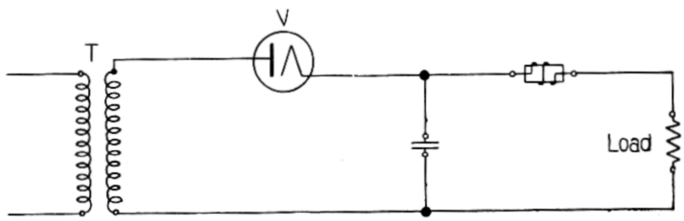

Fig. 6

5. *Effect of Gas.* In thermionic tubes as usually pumped the gas pressure is between 10^{-5} and 10^{-6} mm. At this pressure the gas generally does not manifest its presence in the operation of the tube. However, at higher pressures, and particularly above 10^{-4}mm, it produces certain objectionable disturbances. Thus many gases seriously reduce the filament activity; also for E_p greater than about 20 volts, ionization occurs and the resulting discharge differs in important respects [11] from the pure electron discharge of Fig. 4.

II. Two-Electrode Tubes

The two-electrode tube, which was first due to Edison, found an early practical application when Fleming used it to detect wireless telegraph signals.

However, since the advent of the three-electrode tube of De Forest, the earlier device has been almost entirely superseded as a detector and finds its principal application as a rectifier of a.c. voltages. Its range of applicability in this field is extremely large. With properly designed tubes, Hull [12] has succeeded in rectifying 5 k.w. at a potential of 100,000 volts, and in its transatlantic radio telephone experiments,

[11] See Van der Bijl: The Thermionic Vacuum Tube, p. 86.

[12] A. W. Hull, *General Electric Review*, Vol. 19, p. 177, 1916. Another good source of information is Van der Bijl's "The Thermionic Vacuum Tube."

the American Telephone and Telegraph Company is using a six phase rectifier giving about 200 kw. at about 10,000 volts.[13]

6. *Two-Electrode Tube as Rectifier.* Three typical forms of circuit are shown in Figs. 6, 7, 8, each of which has certain characteristics not possessed by the others. The circuit shown in Fig. 6 rectifies the full transformer voltage, but utilizes only one-half of the current wave; the circuit of Fig. 7 gives a d.c. voltage of only about half the transformer peak voltage but utilizes both halves of the wave, and Fig. 8 illustrates a circuit making use of the full transformer voltage and both halves of the a.c. wave.

A rectifier circuit employing a tuning condenser for the secondary of the high voltage transformer and giving a rectified d.c. voltage as large again as the a.c. voltage of the transformer and providing automatic control of the maximum d.c. voltage supplied by the rectifier, has been described by Webster.[14]

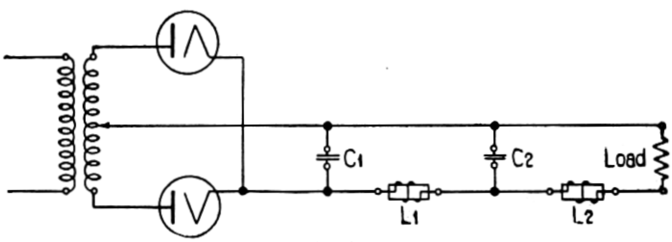

Fig. 7

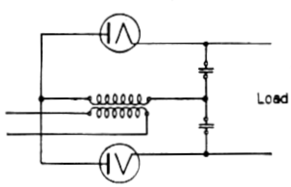

Fig. 8

The circuits shown in Figs. 6 and 7 provide means in the form of condensers C_1, C_2 and inductances L_1, L_2 for smoothing out the rectified voltage. Such an arrangement of conductors is essentially a network whose attenuation for electric currents of a certain range of frequencies is very low and for all other frequencies is high. This type of network is a special form of the *electric wave-filter* which is finding many ap-

[13] Arnold and Espenschied, *Journal of A. I. E. E.*, August, 1923; also *Bell System Technical Journal*, October, 1923.

[14] D. L. Webster, Procd. Nat. Acad., Vol. 6, p. 28, p. 269, 1920. These articles also suggest certain modifications of Hull's method.

plications at the present time and a complete account of its properties is to be found in recent literature.[15]

No definite statement can be made as to the exact range of frequencies over which the rectification of alternating currents can be satisfactorily accomplished by means of thermionic tubes, but it is apparent that this range is large. The degree of smoothness required in the d.c. output is of primary importance in setting the lower limit of the frequency range; on the other hand, the smaller the load resistance, the higher the frequency which may be satisfactorily rectified before the internal capacity of the tubes permits the flow of an objectionable amount of alternating current. Whenever an output with a minimum of ripple is required it is in general desirable to use as high a frequency as is readily available.

III. Three-Electrode Tubes

In 1906 De Forest brought out the three-electrode tube [16] in which a grid is interposed between filament and plate. Since the introduction of this tube, much study has been devoted to its properties and many investigations have been made concerning the best substances to use as thermionic emitters, the best metals for plates and grids, the best varieties of glass for the containing bulbs,[17] and the best methods of exhaustion,[18] so that today problems of design are well understood. At present the three electrode tube finds use as a rectifier, amplifier of small currents and voltages, detector of small a.c. voltages, modulator of alternating currents, and generator of electric oscillations. Tubes have been built which range in size from those about one inch long with a space current of about a milliampere to others which are water-cooled and have an individual output capacity of 100 k.w.[19] Amplifiers with a capacity of 150 k.w. are in operation (see footnote 13).

7. *Action of the Grid.* The general theory of the grid action is simple. As pointed out by Fry [19] the space charge creates a region of

[15] G. A. Campbell, *Bell System Technical Journal*, Nov., 1922; U. S. Patents 1,237,113 and 1,237,114, May 22, 1917; O. J. Zobel, *Bell System Technical Journal*, Jan., 1923; Carson and Zobel, *Bell System Technical Journal*, July, 1923; G. W. Pierce, Electric Oscillations and Electric Waves, p. 186, 1920; Karl W. Wagner, *Arch. f. Electr.*, Vol. 3, p. 315, 1915; Vol. 8, p. 61, 1919.

[16] Variously called the audion, vacuum tube, triode, pliotron, etc.

[17] Measurements of Gases Evolved from Glasses of Known Chemical Composition—Harris & Schumacher, *Jour. Ind. & Eng. Chem.*, Feb., 1923; also *Bell System Technical Journal*, Jan., 1923.

[18] For methods of exhaustion, see Dushman, *Gen. Elect. Review*, Vol. 23, p. 493, 1920, et seq.

[19] See W. Wilson, *Bell System Technical Journal*, July, 1922.

[19] T. C. Fry, l. c.

negative potential immediately around the cathode which persists for all values of E_p less than that required to produce voltage saturation. It is the minimum potential V' (see Fig. 5) that limits I_p, and any increase in V' will result in an increase in I_p. Because the grid is close to the filament, small changes in the grid potential, E_g, are as effective in changing V' and therefore I_p, as large changes in E_p. This leads to the so-called amplification constant μ of the tube which may be taken as

$$\mu = \frac{\pm e_p}{\mp e_g},$$

in which $\pm e_p$ and $\mp e_g$ are changes in E_p and E_g, the changes being opposite in sign as indicated, and such that they leave I_p unchanged.

It has also been shown[20] that if ΔE_p and ΔE_g are increments of E_p and E_g which cause equal increments in the electric field at the surface of the cathode (considered simply as an equipotential surface and not as a source of electrons) the amplification constant, μ, of the tube will be the ratio $\Delta E_p/\Delta E_g$.

8. *Characteristic Equation.* The electrical characteristics of the three-electrode vacuum tube may be represented [21] by the equation

$$I_p = \kappa\left(\frac{E_p}{\mu} + E_g + \epsilon\right)^\eta. \tag{2}$$

The constant κ is related in a simple way to the internal resistance of the tube. A consideration of ϵ which expresses the contact difference of potential between grid and filament is usually essential only in tubes which operate at a low E_p and particularly in detectors and amplifiers. In tubes with coated filament, ϵ may not only vary within a range of two or three volts between different tubes, but may also change during the life of any one tube. The exponent η varies in a given tube with applied voltage, being usually equal to about 2 when the effective voltage $\left(\frac{E_p}{\mu} + E_g + \epsilon\right)$ is comparable with the potential drop in the filament (see Fig. 9), and tending to approach the theoretical value 3/2 with increasing effective voltage. It has been found possible to deduce relations between the constants μ and κ of Equation 2 and the structure and dimensions of any tube which are in very fair agreement with experimental values.[22]

Typical curves corresponding to the characteristic Equation 2 are shown in Figs. 10 and 11. These curves are referred to as *static* char-

[20] R. W. King, *Phys. Rev.*, Vol. 15, p. 256, 1920.

[21] Van der Bijl, *Phys. Rev.*, 12, 180, 1918.

[22] King, l. c.

acteristics one parameter being fixed in each case. For the *dynamic* characteristic see section 12. Equation 2, of course, fits only the portions of the curves characterized by temperature saturation.

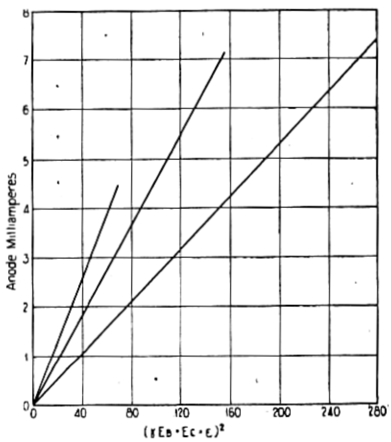

Fig. 9

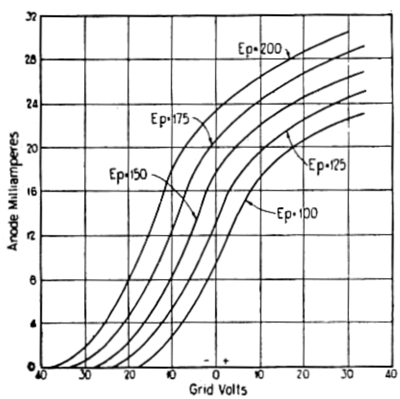

Fig. 10

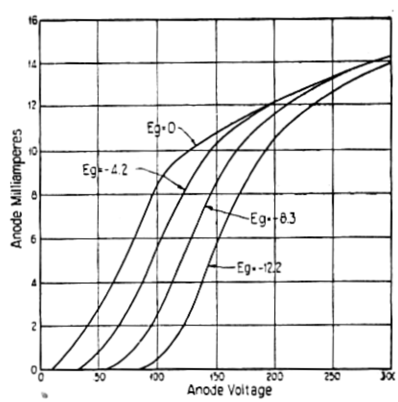

Fig. 11

The abruptness with which the curves of Fig. 10 meet the potential axis is important in certain uses to which tubes are put. The value of E_g which reduces I_p to zero is called the *cutoff voltage*. To have a sharp cutoff a tube should have a fairly large μ and its grid should be sufficiently large with respect to the filament to effectively screen all parts of the filament from the plate.

9. *Grid Current.* For certain purposes, a consideration of the grid current I_g, is necessary. Fig. 12 represents a characteristic relation between I_g and E_g for various E_p. Note that E_g in excess of about 10 volts results in *secondary emission* of electrons from the grid. These secondary electrons flow to the plate and, as shown, their number may actually exceed the total number of primary electrons striking the grid. The character of the grid surface plays an important part

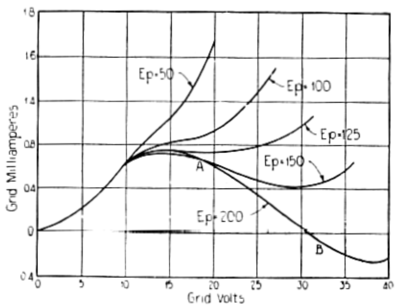

Fig. 12

in determining the amount of secondary emission. The secondary emission from the grid of a tube containing a pure tungsten filament is, in general, less than that from the grid of a tube with an oxide-coated filament. At high temperature a coated filament appears to evaporate a minute amount of its coating, some of which is deposited upon the grid presumably augmenting the secondary activity.[23]

10. *Vacuum Tube Constants.* The two most important constants of the three electrode tube are μ and its internal resistance r_p. The determination of μ and r_p from the characteristic curves (Figs. 10, 11) is obvious. For general design purposes these curves give the best insight into the behavior of a tube and furnish the most instructive means of determining μ and r_p.

11. *Dynamic Methods of Measuring Vacuum Tube Constants.* However, in cases where many tubes, all practically alike, have to be tested, certain "dynamic" methods are timesavers. Several such methods have been devised, but all are modifications of a scheme first published by Miller.[24]

[23] A. W. Hull has designed two types of tube known as the dynatron and pliodynatron which utilize the negative resistance characteristic (AB of Fig. 11) resulting from secondary emission. Procd. Inst. Radio Engrs., Vol. 6, p. 5, 1918.

[24] J. M. Miller, Proc. I. R. E., Vol. 6, p. 141, 1918. For variations of Miller's dynamic method the reader is referred to Van dèr Bijl, l. c., p. 198, Method of G. H. Stevenson.

Miller's method is illustrated in Fig. 13. To determine μ the key K_1 is open and K_2 is closed. The resistance r_1 is adjusted until the sound heard in the telephones T is a minimum, under which circumstances it is clear that $\mu = \frac{r_1}{r_2}$. To determine r_p, some definite relation between r_1 and r_2 is established. Then, with key K_1 closed, the resistance r_o is adjusted until the telephone response is a minimum. With this adjustment it may be shown that

$$r_p = r_o\left(\mu\frac{r_2}{r_1} - 1\right). \tag{3}$$

This measurement of r_p may be simplified as follows: suppose we adjust r_1 for a minimum tone in T when K_1 is open. Then $\mu = \frac{r_1}{r_2}$, and it is seen from Equation 3 that with this relation between r_1 and r_2 it would not be possible to obtain a balance with K_1 closed; but if

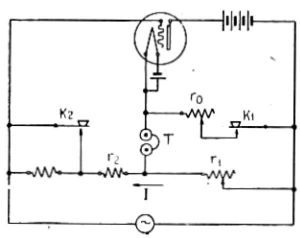

Fig. 13

r_2 be doubled, which can be done by opening K_2 thus adding a resistance equal to r_2, and r_o be now adjusted with K_1 closed to give a minimum tone in T, then $r_p = r_o$.

12. *Dynamic Characteristics of Vacuum Tubes.* In a circuit such as that shown in Fig. 13, the space current causes a fall of potential along any resistance r, and the difference in potential between filament and plate is therefore less than the potential difference across the battery by the amount $I_p r$. If I_p is increased in any way, as for instance, by an increase in E_g, the drop $I_p r$ increases and with a fixed battery e.m.f. the potential difference between the filament and plate diminishes somewhat. It follows, therefore, that a given change in E_g will cause a smaller change in space current when the plate circuit includes an external resistance r than when it does not.

This important fact supplies a simple means of straightening the characteristic of a vacuum tube to such an extent that it may become practically a distortionless amplifier.

To a first approximation,[26] the alternating component J of the space current, when a voltage $e=e_o \cos pt$ is applied to the grid is given by

$$J=\frac{\mu}{r+r_p} e_o \cos pt-\frac{r_p r_p' e_o^2}{2!(r+r_p)^3}(1+\cos 2pt). \tag{4}$$

In this equation r_p is the internal resistance of the tube and r_p' is its derivative with respect to the effective voltage $\left(\frac{E_p}{\mu}+E_g\right)$. It will be noted that the second term on the right side of Equation 4, which gives the first harmonic, diminishes rapidly with r as was to be expected from the preceding paragraph. The more or less straightened

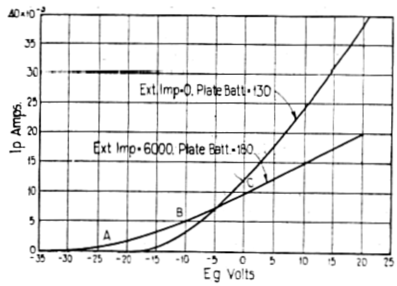

Fig. 14—Average I_p, E_g Characteristics for Five Tubes. Average $\mu=5.92$; average internal impedance $=6{,}000$ ohms for $E_b=130$ volts and $E_g=-9$ volts. Plate battery connected to +end of filament and grid battery to −end. Western Electric type 101-B tubes.

characteristic resulting from the effect of r is known as the *dynamic* characteristic; see Fig. 14, which curves fit a tube whose $r=6{,}000$ ohms. As will be pointed out in the section on amplifier circuits, the dynamic characteristic is a useful guide in selecting tubes as amplifiers.

Equation 4 also expresses the important fact that the application of the voltage e_o to the grid is equivalent, so far as current in the plate circuit is concerned, to the application of the voltage μe_o in the plate circuit.

13. *Internal Capacities and Effect on Input Impedances.* In certain uses to which the vacuum tube may be put, a knowledge of the influence which the internal electrostatic capacities have on the input impedance is important. The equivalent circuit of the tube[27] is

[26] J. R. Carson, Proc. Inst. Radio Engrs., Vol. 7, page, 187, 1919. In case the output circuit of a tube contains reactance as well as resistance, Eq. 4 becomes much more complicated as Carson shows.

[27] H. W. Nichols, *Phys. Rev.*, Vol. 13, p. 405, 1919; J. M. Miller, Bureau of Standards, Bulletin No. 351.

shown in Fig. 15 in which C_1 is the capacity between filament and grid, C_2 capacity between filament and plate, C_3 capacity between grid and plate, and r_1, r_3, are leakage resistances. As the action of the tube is such as to produce an equivalent voltage μe_o between filament and

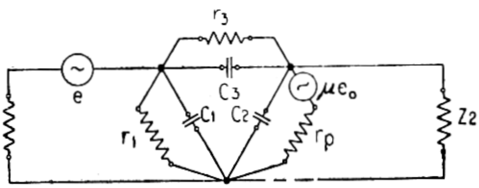

Fig. 15

plate, a generator of voltage μe_o is shown in series with the internal resistance r_p of the tube. Calling Y_g the input admittance of the tube, that is,

$$\frac{1}{Y_g}=Z_g=\frac{e_g}{i_1+i_3},$$

in which e_g is the alternating voltage between filament and grid, the solution of the above circuit gives for Y_g the value,

$$Y_g=\frac{1}{r_1}+jC_1p+\frac{\left(\frac{1}{r_3}+jC_3p\right)[jC_2pr_pZ_2+r_p+Z_2(\mu+1)]}{(jC_2pr_pZ_2+r_p+Z_2)+\left(\frac{1}{r_3}+jC_3p\right)r_pZ_2}. \tag{5}$$

Case 1, *Low Frequencies.* For low frequencies the admittance of the condenser C_2 is negligible compared with that of r_p. Dropping the terms containing C_2 gives the equation,

$$Y_g=\frac{1}{r_1}+jC_1p+\left(\frac{1}{r_3}+jC_3p\right)\frac{r_p+Z_2(\mu+1)}{(r_p+Z_2)+r_pZ_2\left(\frac{1}{r_3}+jC_3p\right)},$$

which yields important interpretations. In case the load impedance Z_2 is a pure resistance r_2, the admittance of the filament-grid branch of the tube may be much greater than the admittance which would result from R_1 and C_1 alone. This is due to the influence which the alternating component of the plate voltage exerts upon the input circuit through the condenser C_2. Figs. 16 and 17 show respectively the effective capacity and effective conductance between filament and grid as a function of the external resistance. For the particular tube studied (W. E. Co. 102-A) Fig. 17 shows that, if $r_2=40{,}000$ ohms, the effective capacity between filament and grid is not the capacity C_1

(about 10×10^{-12} farads) but is approximately 120×10^{-12} farads. Fig. 16 shows that the effective conductance is also greatly increased above that due to r_1. This increase in conductance means an increased absorption of input energy by the tube which, of course, is

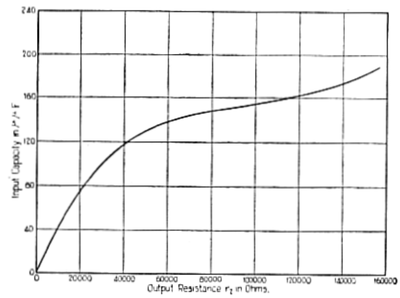

Fig. 16

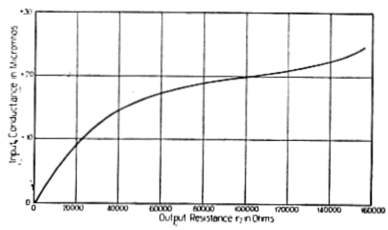

Fig. 17

not dissipated in the grid circuit but passes through the path supplied by the condenser C_3 to be wasted in the plate circuit.

In case Z_2 is a pure inductance L_2, the effective input conductance of the tube is negative and not positive as in the preceding case.

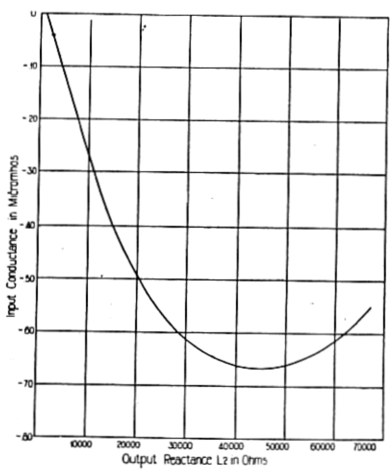

Fig. 18

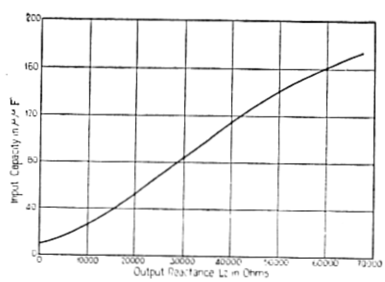

Fig. 19

Fig. 18 shows the variation of this negative conductance with L_2, and Fig. 19 the variation of effective input capacity with L_2. A negative input conductance means that the grid circuit draws power from the plate circuit; if the negative conductance is large enough, a tube in such a circuit will oscillate steadily or "sing" with no coupling but that provided by its internal capacities. This phenomenon is frequently encountered in vacuum tube amplifiers and at times proves quite troublesome.

Tubes can readily be constructed in which r_1 and r_3 are so large as to exert no influence on the behavior of the tube and may be ignored in the above equations. However, even in such tubes there is an effective input conductance, either positive or negative, depending upon the character [28] of Z_2.

Case 2, High Frequencies. For very high frequencies terms of the first order in p are negligible compared to terms of the second order, and Eq. 5, becomes,

$$Y_g = \frac{p(C_1C_2 + C_1C_3 + C_2C_3)}{C_2 + C_3},$$

indicating that as the frequency is raised the effective input impedance approaches that due to the condensers alone. Under these circumstances the grid absorbs very little power, but the amplification is lowered because the input is to an extent short-circuited by the electrode capacities. Fig. 20 shows the variation in voltage am-

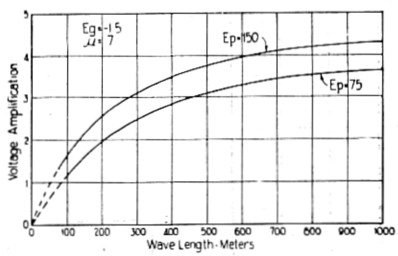

Fig. 20

plification against wave lengths in meters for high frequencies. The two curves are for different E_p, the higher E_p giving a larger amplification because r_p of the tube is lower. It is seen that the amplification at 1,000 meters is about three times as large as the amplification at 100 meters and the amplification at both values of E_p tends to approach zero as the frequency becomes infinite.

Nichols suggests [29] that the reduction in amplification for a given frequency can be avoided by shunting the grid-plate capacity C_3 with

[28] For cases in which Z_2 is neither pure resistance nor reactance, see Van der Bijl, l. c., p. 210.

[29] H. W. Nichols, *Phys. Rev.*, Vol. 13, p. 411, 1919.

an inductance of such a value as to make the impedance between grid and plate infinite at this frequency.

IV. Thermionic Amplifiers

Equation 4, given in Sec. 12 is of fundamental importance in the design of vacuum tube amplifier circuits. Neglecting the second term on the right hand side which, as previously pointed out, expresses distortional effects and should therefore be very small in amplifier circuits, the equation can be written

$$J=\frac{\mu e_o}{Z+r_p}, \qquad (6)$$

in which the impedance $Z=r+j\,x$ is substituted for r. From Equation 6 both the voltage and power amplification of a tube for any particular circuit can readily be calculated.

14. *Voltage Amplification.* Assuming as above that the tube works into an output impedance Z, it follows that the voltage amplification (i.e., the ratio of the output to the input voltage) is

$$\frac{\mu Z}{Z+r_p}.$$

This expression shows that the voltage amplification increases as Z increases. Considering separately the two cases in which Z is a pure resistance and pure reactance, typical values of the voltage amplification are plotted in Fig. 21. Curve a corresponds to reactance

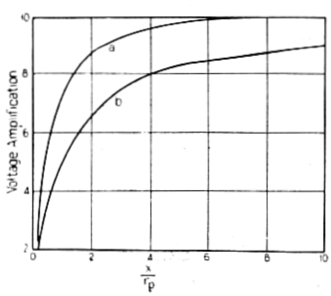

Fig. 21

in the output and b to resistance. These curves show that the voltage amplification rises much more rapidly when reactance is used, reaching 90% of its maximum value when $\frac{x}{r_p}=2$.

If the resistance component of Z is made as small as possible, E_p becomes practically equal to the potential across the plate battery, making possible a given voltage amplification with smaller plate battery than could be obtained if the output circuit contained an appreciable resistance.

15. *Power Amplification.* From Equation 6, which neglects harmonic terms, it is readily seen that the power output is

$$\frac{\mu^2 e_o^2 r}{(r+r_p)^2+x^2},$$

where $r+jx$ has been substituted for Z. This output is a maximum when $r^2=r_p^2+x^2$. The case in which $x=0$ is particularly important; evidently for maximum power output, a tube should work into a resistance equal to its internal resistance.

As pointed out in Sec. 13 the input impedance of a tube is not always readily determinable; however, calling the input resistance [30] r_g, the power amplification produced by a tube is given by the expression,

$$\frac{\mu^2 r r_g}{(r+r_p)^2+x^2}. \tag{7}$$

This expression has been obtained on the assumption that the grid draws no electron current from the space charge, which in turn requires that the grid remain at a negative potential at all times. Since the power amplification falls rapidly as the grid becomes positive, it is customary in most amplifier circuits to supply means of maintaining the grid at a negative potential.

Expressions 6 and 7 are of fundamental importance in the design of amplifier circuits.

16. *Selection of Tubes.* When selecting tubes for an amplifier, curves such as those shown in Fig. 14 are very useful. By their means it is readily possible to select the tube, the plate potential and the average grid potential which will give satisfactory results for any pre-assigned value of the input voltage. In order to obtain amplification as free from distortion as possible, it is necessary that the grid potential in its excursions neither become positive nor strike the lower end of the characteristic. To a sufficient approximation it is evident that when the variable grid or input voltage e_o is given, we should choose E_g and E_p such that

$$e_o \not> -E_g \not> \frac{E_p}{2\mu}.$$

[30] Where many tubes of the same design are to be interchanged in a given circuit, and where the conditions of manufacture are such that the insulation resistance between filament and grid is not always of the best, it may be found desirable to shunt the input with a fixed resistance, e.g., ½ megohm.

Referring to Fig. 14, for an input potential of 10 volts (peak value) and $r_p = 6{,}000$ ohms, the point B (but neither A nor C) is evidently a satisfactory mean position about which to operate.

Since both voltage and power amplification increase as E_p is increased (because r_p is decreased) it is frequently desirable to have the value of E_p considerably larger than the lower limit just indicated.

17. *Amplifier Circuits.* The fundamentals of thermionic amplifier circuits may be gathered from Fig. 22. The variable input voltage

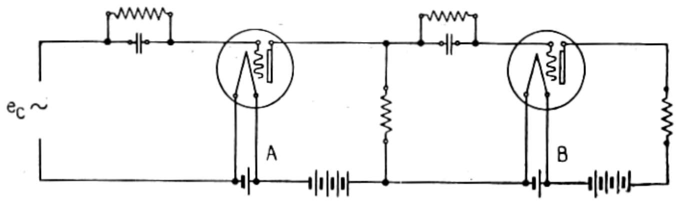

Fig. 22

e_o between grid and filament of the first tube A modulates the plate current of this tube. The circuit is evidently such that the variable I_p of tube A varies the grid potential of B and, due to the properties of the three electrode tube, not only is the power applied to the grid of B greater than that applied to A, but the potential variation may be many times as large as e_o. Hence the variations in I_p of B will be larger than those of I_p in A, thus yielding an amplifying action. Tubes A and B and their associated circuits are known as the first and second stage respectively.

Amplifier circuits may for convenience be divided into six general classes:

1. Resistance coupled circuits (Fig. 23).
2. Resistance-condenser coupled circuits (Fig. 24).
3. Retard-condenser coupled circuits (Fig. 25).
4. Transformer coupled circuits (Fig. 26).
5. Feed-back circuits (Fig. 31).
6. Push-pull circuits (Fig. 32).

The Sections immediately following will point out the advantages of each type of circuit and general design considerations. Equations 6 and 7 show that the amplification of which a single tube (or "stage") is capable is definitely limited. For greater amplification than a single stage can produce, it is necessary to arrange two or more stages in cascade. Multistage amplifiers frequently consist of combinations of certain of the above types of circuits as will be pointed out in the following paragraphs.

18. *Resistance Coupled Amplifier.* This simplest of all amplifier circuits (Fig. 23) is particularly useful where a wide range of frequencies is to be amplified without selective amplification of any particular frequencies. For this reason, it is often used as an amplifier in con-

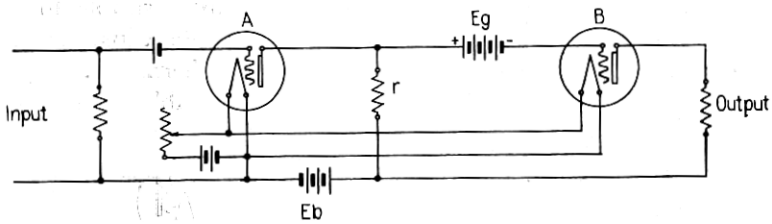

Fig. 23

nection with an oscillograph. It is also one of the few types of circuit which can be used for direct current amplification. However, as will be pointed out later, a special type of push-pull circuit makes a more satisfactory d.c. amplifier for many purposes.

One or more stages of the resistance coupled circuit may be substituted for transformers in voltage amplification. Voltage amplifier tubes having an amplification constant $\mu=30$ are common and it follows from Equation 6 that such a tube can readily produce a voltage amplification of from 20 to 25. It can, therefore, take the place of an input transformer in one of the other types of amplifier circuit. Unless special considerations require another adjustment, it is customary to arrange all but the last stage of an amplifier for voltage amplification, the last stage being designed for power amplification. (See Secs. 14 and 15.)

Since in resistance coupled amplifiers there is a d.c. path between the plate of one tube and the grid of the following tube, a negative grid battery large enough to counterbalance the plate battery must be used in every stage in order to supply the necessary negative grid potential. As shown in Fig. 23, a common plate battery can be used for two or more stages. A more complete discussion of battery requirements is given under Power Supply.

19. *Resistance-Condenser Coupled Amplifier.* This type of circuit (Fig. 24) is similar to the preceding in all respects except that condensers are inserted between the plates and grids of adjacent stages. This makes the employment of large negative grid batteries unnecessary although it is still important that steady negative potentials be applied to the grid of each tube sufficiently large to prevent their being carried positive by the variations. For example, in Fig. 24, r_g' may be two meghoms and the grid battery emf 2 to 3 volts. This

type of circuit is in general the easiest to handle. Due to the insertion of condensers it will, of course, not serve as a direct current amplifier,

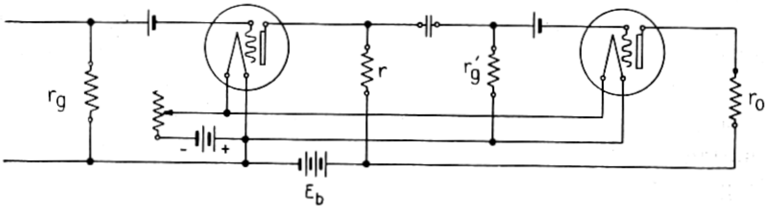

Fig. 24

but with sufficiently large condensers it can handle low frequencies with little or no distortion.

20. *Retard-Condenser Coupled Circuit.* The substitution of retard coils for resistances (see Fig. 25) in the circuit last described affects

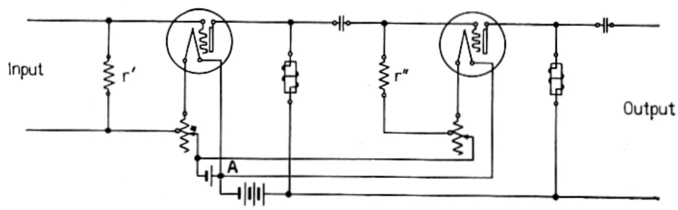

Fig. 25

the behavior of the circuit in several ways. An advantage in the change lies in the fact that a given plate potential can be secured by a smaller plate battery (Sec. 14). Since the tubes in all but the last stage of an amplifier generally act as voltage amplifiers, it is desirable that the inductance of the retard coils be made large. By employing retard coils of the proper inductance and resistance and shunting them with condensers, such an amplifier may be tuned for any particular frequency.

It follows that the width of the frequency band which can be amplified without distortion is likely to be less than for the resistance coupled amplifier. Since the impedance of the retard coils increases with increase of frequency the higher frequencies will, in general, be amplified more than the low. However, it is impossible to make retard coils without a certain amount of distributed capacity, the shunting effect of which tends to limit the amplification of the higher frequencies. By the proper design of coils it is possible to construct a retard-coupled amplifier which will give practically uniform amplification, e.g. throughout the speech range of 200 to 3,000 cycles. It is customary to make the retard and choke coils of the toroid or closed core type.

21. *Transformer Coupled Amplifiers.* From a theoretical point of view the transformer coupled amplifier (Fig. 26) should be the ideal type. By the proper choice of transformers it should be possible to match stages with respect to one another in such a way as to obtain the greatest efficiency from tubes and batteries. The chief advantage of transformer coupling lies in the fact that the input voltage to the second stage may be made greater than the voltage

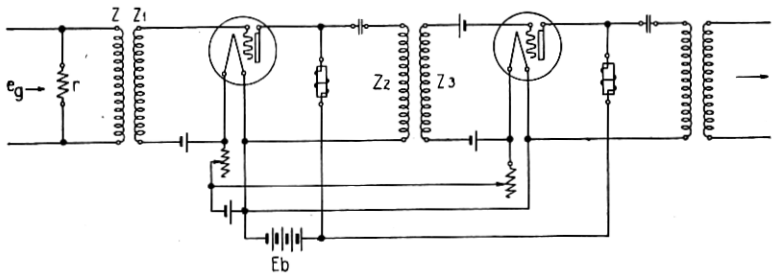

Fig. 26

output of the first, and so on, at the same time that each tube operates into a properly matched impedance to give maximum power output. When uniform amplification over a relatively wide band of frequencies is not required, the interstage transformer may be designed to step up the voltage as many as 30 to 40 times. Other advantages are the economical use of plate batteries (Sec. 14) and the elimination of grid condenser and grid leak or high voltage grid battery.

However, the difficulties attendant upon the design and making of transformers are such that to realize the apparent advantages of this type of circuit will require very careful planning. This will be illus-

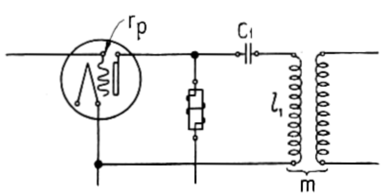

Fig. 26a

trated by the following example of a transformer to handle the frequencies of speech. Given an interstage transformer as in Fig. 26a, we will assume that the transformer works out of a tube impedance r_p and into a grid circuit impedance which has infinite resistance.

Then, imaging for the moment that the condenser C_1 has been removed, the output voltage e_2 of the transformer is

$$e_2 = \frac{emp}{r_p + jl_1 p}, \tag{8}$$

in which e is the input voltage, l_1 is the inductance of the primary winding, m is the mutual between the windings, and p is 2π times the frequency. This neglects resistance of the winding and also capacity effects. Inspection of Equation 8 shows that e_2 varies with the fre-

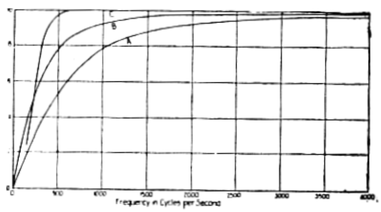

Fig. 26b—Curve A corresponds to $l=1$ henry. Curve C to $l=2$ henries, $C_1=.141$ f.

quency or with p in the manner shown in curve A, Fig. 26b, from which it is seen that the transformer tends to suppress the lower frequencies.

Curve A shows the performance of a transformer as calculated from Equation 8 assuming $r_p=5{,}000$ ohms and $l_1=1$ henry. Such a transformer would be quite unsuited for a speech frequency amplifier as it introduces very serious distortion below 1,000 cycles. Curve B is calculated on the assumption that $l_2=2$ henries and shows marked improvement over A for the lower frequencies.

In input transformer design it is ordinarily necessary to limit the inductance of the two windings not only because of the limited winding space but also because of the need of keeping down the capacity between windings and the capacity within each winding. Curve C shows the performance of the same transformer as Curve B when the capacity C_1 (Fig. 26a) is put in the primary circuit, C_1 having a value of .141 m.f. and being so chosen as to tune l_1 to 300 cycles. With the capacity present Equation 8 becomes

$$e_2 = \frac{e\,m\,p}{r_p + j\left(l_1 p - \frac{1}{C_1 p}\right)}. \tag{8A}$$

Use of the capacity improves the transformer characteristic for all frequencies above about 200 cycles and the combination therefore gives better results in a speech amplifier than the transformer alone.

The effect of distributed capacity in the windings (present especially in the secondary because of its greater number of turns) is, more or less, to shunt the high frequencies. This may be counteracted either by the inductance in the primary winding or, if this is not sufficient, by insertion of the proper inductance in series with the primary. It may be said, in a general way, that the lower the ratio of a transformer the better suited its frequency characteristic will be to a wide band of frequencies such as occurs in speech, and transformers with a ratio of 1 to 4 are made which require no correcting provided they are properly chosen with respect to the impedance characteristics of associated tubes.

The selective amplification of an amplifier for particular frequencies may be increased by tuning one or more of the secondaries of the interstage transformers with condensers. (See Equation 8A.)

Due to the fact that there is an appreciable distributed capacity between the primary and the secondary windings, an interstage transformer supplies capacity coupling as well as inductive coupling between adjacent stages, the phase of the capacity coupling being independent of the direction of winding while the inductive coupling is not. Therefore, the transformer may be so placed in the circuit that these two effects either aid or oppose one another. In order to secure the greatest amplification they should aid.

The transformer used in speech frequency work is, in general, made with an iron core; therefore, care should be taken to prevent the d.c. component of I_p magnetizing the core and reducing its efficiency. One method of accomplishing this is shown in Fig. 26 in which the d.c. component of I_p is bypassed by a choke coil. In circuits in which two or more interstage transformers are used, attention should be paid to the danger of magnetic feed-back. This can be largely eliminated by using transformers with closed magnetic circuits. Both the toroid type core and the shell type core (commonly employed in power transformers) have been found satisfactory, and especially the latter.

22. *Amplification of Higher Frequencies.* The transformer coupled amplifier is the type perhaps best suited to use at frequencies higher than those of speech. As a special case the amplifier circuit of Fig. 27 will be considered first. This circuit contains a tuned output and should be used only in case a single frequency or very narrow band of frequencies is to be amplified but in this case will be found very satisfactory. The inductance L may consist of two parallel windings, insulated from each other to avoid any conductive connection between the plate battery and the output. Such an arrangement would be desirable if the output went to a detecting tube or another

amplifying tube. By using a variable condenser *C*, the frequency of maximum amplification can be readily shifted but for any one setting the amplification will be as shown by curve *A* of Fig. 28. For maxi-

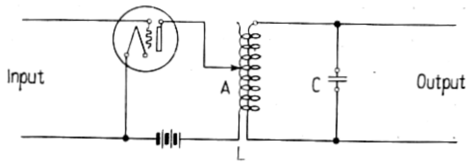

Fig. 27

mum output, the position of the tap *A* should be set so that the impedance of the tuned circuit *LC* as seen from the tube is equal to the output impedance of the tube. Tuned circuit amplifiers are especially adapted for amplification at very high frequencies (above 2,000,000 cycles), where the effect of the capacities between the elements of the tubes makes other types of amplifiers very inefficient.

The amplification curve *A* will be broadened when more and more turns are added to the inductance *L* and the capacity of the tuning condenser *C* is diminished due to the effect of the distributed capacity

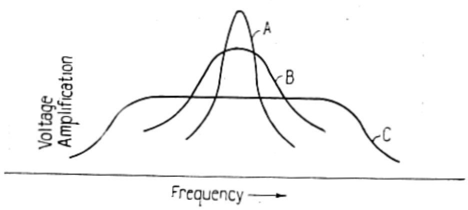

Fig. 28

of the coil. Curve *B* gives the amplification for a circuit where the condenser *C* is omitted in which case it becomes a retard coupled amplifier. Maximum amplification occurs at the natural frequency of the coil including the capacity effects of the leads and elements of the tubes.

In case a relatively wide band of frequencies is to be amplified, transformer coupling is usually resorted to, and given suitably designed transformers one to two octaves can be amplified with very fair uniformity at frequencies between 100,000 to 2,000,000 and four to five octaves at frequencies below 100,000 cycles. Use of transformer coupling will broaden the characteristic of the amplifier as shown in curve *C*, Fig. 28, the exact shape of this curve being largely dependent upon the design of the transformers employed.

For frequencies up to about 100,000 cycles, transformers with iron cores of the ring type are suitable and are preferably enclosed in metal covers which are grounded. A transformer suitable for frequencies higher than 100,000 cycles may consist of two choke coils (one to two inches in diameter) of very fine wire, these coils being mounted close together on a suitable form. The natural frequency of the coils will approximately determine the middle of the band of frequencies which are amplified and the coupling between the two coils will determine the width of the band, closer coupling resulting in a wider band. The coupling is generally a combination of electrostatic and electromagnetic coupling and therefore, in connecting all transformers for high frequency uses, it is essential to establish the proper phase relations between them (see paragraph 21). Each stage of the amplifier should be shielded as shown in Fig. 29 although in certain cases it may be dispensed with. The shielding should

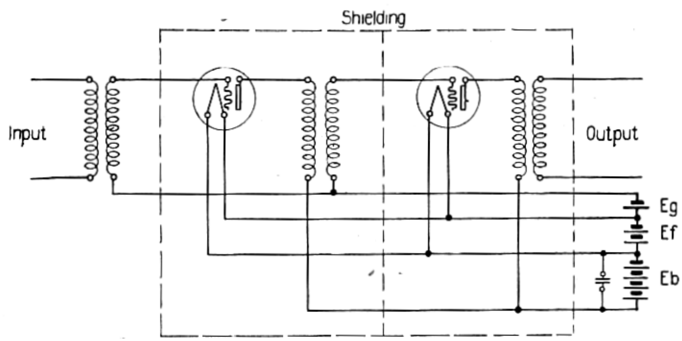

Fig. 29

consist of brass or copper sheeting made into boxes with well-soldered joints and tightly fitting covers. Holes through the shielding should be just large enough to pass the insulation of the wires.

A common plate battery may safely be used for four or more stages provided a condenser is placed across the terminals of the battery as shown in Fig. 29. This condenser should have a capacity large enough to offer practically no impedance to the high frequency currents, and its use may be desirable although the plate battery is common to but two stages. Use of a common grid battery, as shown, introduces a small feed-back from the second stage to the first. This feed-back may be either positive or negative, depending upon the phase relations in the intermediate transformer and may be eliminated by placing a condenser across the grid battery terminals.

It has been the practice in high frequency amplification to use tubes with μ's between 6 and 10, interstage transformers being selected to step up the voltage as much as is possible consistent with the desired flatness of the amplifier characteristic. In general, the larger the ratio of the transformer, the more pronounced is the peak of the characteristic. Other things being equal, the most suitable tubes are those with the smallest internal electrostatic capacities. The largest of these capacities, in general, is that between grid and plate and tubes have been produced in which this does not exceed 5 $\mu\mu$ f. and in which the internal plate resistance is about 20,000 ohms.

In amplifying the higher frequencies the feed-back which occurs through the tube may require attention. In section 13, it was pointed out that an inductive output for a tube gives rise to a negative resistance characteristic in the input which means that feed-back is occuring. To eliminate the possibility of singing and also to eliminate unequal amplification of different frequencies which feed-back introduces, various means of neutralizing it have been proposed.[29] One

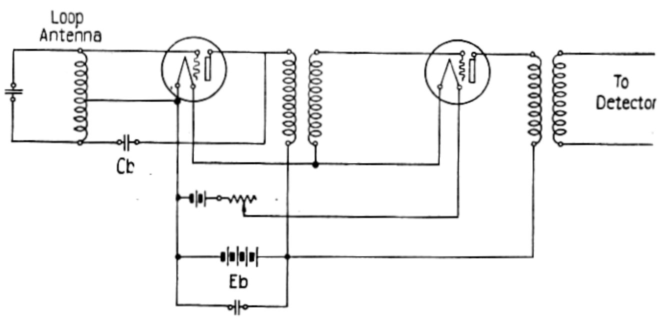

Fig. 30

such means is illustrated in Fig. 30 which is drawn to show radio reception with a loop antenna. Note that the grid of the first tube is joined to one end of the loop and the plate is joined to the other end through the balancing condenser C_b, the filament being joined to the midpoint of the loop. When C_b is chosen equal to C_3 the capacity between grid and plate, it is evident that the feed-back occurring through the tube is just balanced by that occurring through C_b. By adjusting the condenser C_b so as to permit of feed-back, very large amplification may be obtained at a single frequency but at the expense of flatness of characteristic.

[29] See Patent No. 1,183,875 issued to R. V. L. Hartley, and Patent No. 1,334,118 issued to C. W. Rice.

23. *Feed-Back Amplifiers.* This amplifier may be either resistance or inductive coupled, a typical resistance coupled circuit being shown in Fig. 31. In a feed-back circuit, attention must be paid to phase relations. In Fig. 31, let the arrow along the resistance R_1 represent an increase in electron current to the grid of tube A. This corresponds to an increase in the potential of this grid. In phase with this increase in potential is an increase in electron current in R_2 as shown by the arrow. This, in turn, corresponds to a fall in potential of the grid of tube B and therefore to a reduction of the I_p in B, as indicated by the arrow at R_3, which produces an increase in I_p in C. Therefore, in this particular circuit the correct phase relations require the output of one tube to be returned to the input of the second preceding

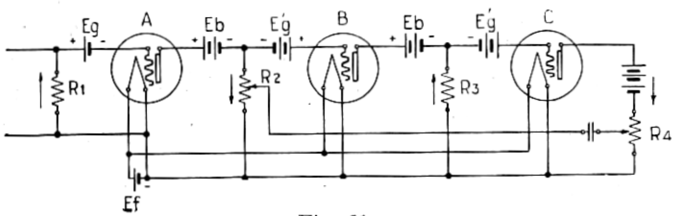

Fig. 31

tube or one of its alternate preceding tubes. The amount of energy fed back can readily be controlled by varying the portion of R_2 through which the feed-back current flows.

24. *Push-Pull Amplifier.* See Fig. 32. This type of circuit is particularly useful as a terminating stage since it makes possible the use of a low impedance in the output circuit without serious distortion. If the tubes A and B have identical characteristics, it is readily seen that the coils of the output transformer may be so connected that the fundamental and odd harmonics will aid one another, while all even harmonics will oppose. Since the third and higher harmonics (counting the fundamental as first) are very small compared to the second, this circuit gives very nearly distortionless amplification. In speech amplifiers it permits of considerable overloading without this being very apparent in the quality of the output.

By reversing the transformer connections it is possible to cause the circuit to add the even harmonics and give the differences of the odd.

An additional use for this circuit will be pointed out in the section dealing with modulation.

Fig. 33 shows a special type of push-pull circuit which is particularly adapted to the amplification of steady and low frequency voltages. It consists of a Wheatstone bridge in which two similar tubes form one pair of arms. The output circuit is the branch in which the galvanometer is ordinarily placed. When a voltage is applied to the two tubes in such manner that the potential of one grid is raised by the same amount as the grid of the other is lowered, the bridge becomes unbalanced and current flows through the output

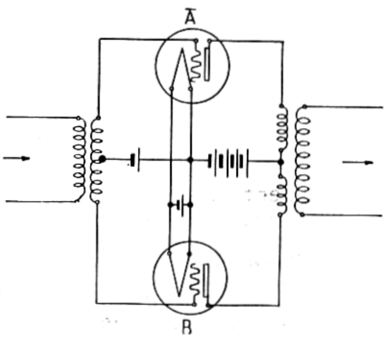

Fig. 32

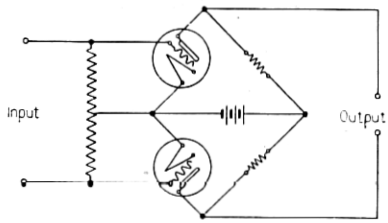

Fig. 33

branch. For small applied voltages the amplification of the circuit is very nearly distortionless. The circuit has the obvious disadvantage of requiring a close balance between the tubes and is therefore liable to require careful adjustment during use.

The push-pull circuit possesses one marked advantage over the resistance-coupled d.c. amplifier described in Sec. 18 for in it current flows through the output branch only when voltage is applied to the input. For the same reason it is also useful for amplifying low frequency alternating voltages.

V. Amplifier Power Supply

The proper power supply for amplifiers is an item of prime importance.

25. *Plate Voltage Supply.* The principal requirement placed on plate voltage is that it be steady. For this reason storage batteries are usually best, but good dry cells are more often used and when fresh, prove very satisfactory. The principal trouble encountered in the use of dry cells arises from an attempt to use partially rundown cells. A dry battery should be tested periodically for voltage, the reading being taken while the battery is delivering a current at least as large as that drawn by the amplifier. Whether dry cells or storage cells are used for plate voltage, in general not more than four stages

should be operated from a single battery. In the case of a retard coupled amplifier whose stages are tuned with condensers, each stage should preferably have a separate plate battery to reduce the tendency to "sing."

A generator as a source of plate voltage is frequently used for power amplifiers. In case a direct current generator is used, a filter is generally necessary in the plate circuit to remove commutator ripples.

26. *Filament Voltage Supply.* A source of constant filament voltage is not necessary in order to insure constant space current within the tubes at temperature saturation, but in general any variation in filament current will affect the relative potential difference between filament and grid, and is, therefore, equivalent to a variation in the input voltage. This possible source of trouble must be particularly guarded against in such a circuit as that shown in Fig. 25, in which a portion of the adjustable resistance of the filament circuit is included between the filament and the "common point" A. If storage batteries are available, they form the best source of filament current; generators have been used satisfactorily however.

27. *Sources of Grid Potential.* A flow of electrons to the grid of a tube is liable to result either in distortion or a loss of amplification or both (see Secs. 15 and 16). The steady negative grid potential required to prevent the input voltage carrying the grid to a positive potential may be obtained from either one of two sources: by a grid battery or by an *IR* drop in some resistance in the circuit. The requirements for a grid battery are very light since it is called upon to give no appreciable current. As was pointed out in Sec. 26, use of an *IR* drop for grid voltage pre-supposes steady filament or plate battery according to circumstances, and since the proper grid battery is readily obtainable the use of an *IR* drop is likely to prove desirable only in very unusual circumstances.

VI. Troubles in Amplifier Circuits

28. *Noise.* The noise in amplifier circuits is due to several causes which may, in general, be grouped into two classes. Certain noises originate within the tubes and other noises find their origin in the circuit. The amount of noise in any amplifier limits the minimum input voltages which it will handle satisfactorily, for obviously input voltages which produce output currents of the same order of magnitude as the currents giving rise to noise will not be satisfactorily amplified.

29. *Tube Noises.* Tubes may be responsible for three distinct kinds of noises. (a) Ringing or rattling is due to the vibration of the tube elements and may be eliminated by proper tube construction or by some form of vibration proof suspension for the early stages of the amplifier. (b) Crackling may be produced by high resistance films on the inner surface of the bulb, forming conducting paths between the leads. Faulty electrical contact between the plate, grid and filament and their respective leads is also a frequent source of crackling. Furthermore, in tubes which are well constructed in regard to the points just mentioned, but which contain tungsten filament, crackling may be observed. This trouble is not found in all tungsten filament tubes but, when present, is sufficiently marked to become apparent in a two stage amplifier. (c) In carefully constructed amplifiers of more than three or four stages a noise which can best be described as a hissing or sighing is certain to be present. It appears to be related to an unavoidable statistical variation in the escape of electrons through the grid to the plate. Its magnitude has been found to correspond approximately to an output voltage from the first stage of between 5×10^{-7} volts and 5×10^{-6} volts. Between these limits the noise is found to increase as the output impedance of the first stage is increased, and also to increase as the resistance across the terminals of the input increases. Its components, above 300 cycles, appear to be of about equal magnitude and uniformly distributed. It is, therefore, impossible at the present time to build amplifiers to handle voltages of less than this order of magnitude, at any rate when the frequencies involved are in the audible range.

30. *Circuit Noises.* In general, circuit noises in amplifiers are due to one or more of the following causes: variations in grid and plate batteries, loose contacts and variations in resistances, leakage of condensers and leakage across the insulating mounting upon which the amplifier parts are fastened, and external electric or magnetic fields acting inductively on the circuit. The remedy in each case is obvious once the exact cause has been found. To eliminate inductive effects in the wiring it is usually sufficient to run wires in pairs and to shield them electrically, the shielding being grounded. In laying out the various parts of an amplifier it is well to place the bulky pieces at points in the circuit at which they will have as near zero potential as possible.

31. *Singing.* Singing, which is one of the most serious troubles in amplifiers, is always due to some form of feed-back. This may be magnetic, electrostatic, or in the form of mechanical vibrations as in an amplifier having a microphone attached to the input and a receiver

to the output. Mechanical feed-back can also occur in the case of tubes whose parts can easily be set into vibration and a cure is usually found in some form of vibration-proof mounting. The coupling which is responsible for feed-back may be difficult to locate, but when found can usually be removed. Both retard coils and transformers may afford an easy method of coupling due to stray fields. If the coupling induces voltages which are in phase with the input voltages, it may cause singing, and if out of phase, the amplification may be seriously reduced. Closed core coils and magnetic shields are the usual remedies for this condition, although a rearrangement of the circuit parts may be necessary.

Certain kinds of electrostatic feed-back may be removed by enclosing each stage in a separate grounded metal cage or box. The electrostatic coupling due to tube capacities (Sec. 13) cannot be eliminated but it is possible to so design circuits that trouble from this source will not present itself. Thus an inductive impedance in the output circuit may prove troublesome because it induces a *negative* resistance back in the input circuit; a non-inductive output can never do this. Feed-back through tubes increases with frequency, and in the case of high frequencies, it may sometimes be necessary to use resistance coupled rather than reactance coupled circuits.

32. *Blocking*. Two entirely different types of blocking may occur in an amplifier. They both result from the grid of one or more tubes having been carried to a positive potential by the input voltage. While positive, the grid picks up a negative charge of electrons which is removed more or less rapidly by the grid leak. In case the leak resistance is high, a residual charge may remain upon the grid for an appreciable length of time, depressing its mean potential to so low a value that the output of the tube is cut to zero or very nearly zero. The remedy is obviously to reduce the input voltage or to increase the voltage of the negative grid battery. In certain cases, a readjustment of the resistance of the grid leak may be desirable.

The second type of blocking involves secondary emission from the grid as discussed in Sec. 9. It can occur only when the input is sufficient to force the grid potential of some tube positive by as much as 10 or 15 volts, and then if the grid leak resistance is large enough, secondary emission will hold the grid at about this positive potential and entirely prevent proper functioning of the amplifier. In eliminating this type of blocking, the first step should be to note the effect of increasing the filament currents as secondary emission is less likely to occur when the filament yields a copious supply of electrons. If this does not remove the trouble, the negative grid batteries in the stages at fault may be increased and lower grid leaks may be desirable. The volume of input to each stage should also be considered.

33. *Distortion.* Distortion in an amplifier circuit may result either from a failure to amplify all frequencies by the same amount or from the generation of overtones of the fundamental frequencies in the input.

The unequal amplification of various frequencies arises from the presence of resonant characteristics in the circuit. This may take the form of a feed-back which discriminates in favor of certain frequencies, the feed-back not being pronounced enough to cause singing. A negative feed-back may also occur, causing a loss of efficiency over some particular frequency range.

The distortion which arises from the generation of overtones is due to non-linear voltage-current characteristics in one or more branches of the circuit. The usual sources of this trouble are curvature of the plate and grid characteristics (See Equation 4) and the variable permeability of the iron used as cores. With properly chosen coils, practically distortionless amplification can be secured by the method indicated in Sec. 12. In general, to accomplish this, the output impedance need not be more than two or three times r_p. In case it is necessary to use a low output impedance in the final stage, distortion may be reduced by using the push-pull circuit of Sec. 23.

In using an amplifier under circumstances such that distortionless output is desired, care should be taken that no tube by itself is overloaded or caused to work in such fashion that its dynamic characteristic is curved. Distortion which arises from curvature of this characteristic can be detected by inserting an ammeter in the plate circuit of each tube. When each characteristic is straight, or nearly so, there should be no change in ammeter reading as the source of input voltage is thrown on and off, and in the case of a variable input such as that arising from speech, the ammeter readings should remain constant while the amplifier is in operation. This test will not detect distortion which arises from selective amplification with respect to frequency.

34. *Calculation and Measurement of Amplification.* Provided all parts of an amplifier circuit are functioning properly and its constants are known, its amplification can be calculated quite accurately. The following example will illustrate the procedure to be followed in any case. Referring to the transformer coupled amplifier of Fig. 26, assume that the ratio of the first input transformer is z:z_1 and that the ratio of the second input transformer is z_2:z_3; assume also that z_2 is numerically equal to r_p, the plate circuit resistance of the first tube.

Then, calling e_g the input voltage, the voltage across the first tube is

$$e_g \sqrt{\frac{z_1}{z}};$$

the voltage across the primary of the second input transformer is

$$e_g \frac{\mu}{2} \sqrt{\frac{z_1}{z}}$$

since z_2 is numerically equal to r_p; and across the secondary is

$$e_g \frac{\mu}{2} \sqrt{\frac{z_1}{z}} \sqrt{\frac{z_3}{z_2}}.$$

Hence the voltage amplification of this portion of the amplifier is

$$\frac{\mu}{2} \sqrt{\frac{z_1}{z}} \sqrt{\frac{z_3}{z_2}},$$

and a similar argument applies to the following stages.

The measurement of amplification can be accomplished by the obvious procedure of determining the magnitudes or the relative magnitudes of the input and output current. This can be done for either a single stage or for several stages at once.

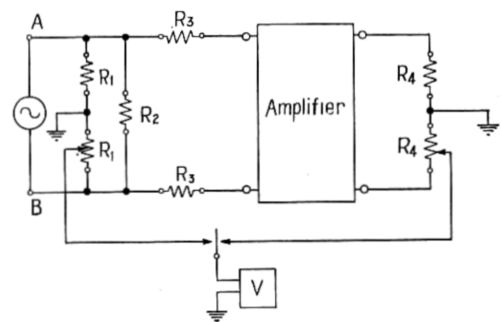

Fig. 34

A very satisfactory circuit for measuring amplification is illustrated in Fig. 34 and through use of a vacuum tube voltmeter (see Sec. 56) as a comparison means, it is capable of an accuracy of about 2%. The conditions which the resistances R_1 and R_2, etc., should satisfy are very simple. The network connected between the oscillator and amplifier input should present an impedance, looking into it from the right, equal to the input impedance of the amplifier; likewise the output impedance of the amplifier should equal $2R_4$. The input impedance of the vacuum tube voltmeter is so high as not to shunt the resistances across which it is connected appreciably. The grounds at the mid points eliminate the disturbing effects of capacities to ground. Under these conditions the voltage amplification a is given by the equation:

$$a=\frac{\alpha}{\beta}\left[\frac{4R_3(2R_1+R_2)+2R_1R_2}{2R_3(2R_1+R_2)+2R_1R_2}\right],$$

in which α, β are the fractions of R_1 and R_4 respectively, across which the voltmeter is connected to obtain equal readings when the switch W is thrown from one position to the other. In case R_2 is made quite small with respect to R_1, R_3, the expression for a reduces approximately to $a=\frac{2\alpha}{\beta}$. An expression for current amplification can readily be derived.

Another simple measuring circuit is shown in Fig. 34*a* in which O is an oscillator of the desired frequency, F is a filter to remove harmonics from the oscillator current, R_1R_2 and R_3R_4 are attenuating networks consisting of resistances, WWW are switches by which the telephone receiver T can be joined either to the output of the amplifier

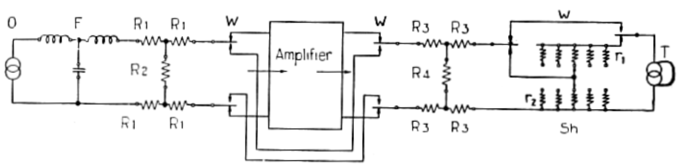

Fig. 34a

or directly to the oscillator, and also provide means for removing the known attenuation in the shunt *Sh* (receiver shunt) at the same time the amplifier is removed. By the proper design of the receiver shunt, which will be discussed presently, the attenuation required to give the same volume of sound in the receiver whether the amplifier is in or out may be read directly.

In setting up the circuit of Fig. 34*a*, special attention must be given to the networks R_1R_2 and R_3R_4. In addition to reducing the input to the amplifier to a value safely below the overload point, R_1R_2 should be designed to present an impedance (when seen from the amplifier) equal to that out of which the amplifier is to operate in service. Otherwise the measurements of amplification may be without significance.

The network R_3R_4 serves two important purposes. It is designed to present toward the amplifier the same impedance as the amplifier is to work into in service, and this in turn requires that the input and output impedances of the amplifier be practically equal (or if not, then small with respect to R_1) for otherwise the network R_3R_4 when joined to R_1R_2 will not draw the same fraction of current as the amplifier, thereby upsetting the comparison upon which the measurements are based. Furthermore, the attenuation in R_3R_4 is to be sufficiently large that variations in the impedance of the receiver and its shunt as seen from R_3R_4 will not appreciably affect the impedance into which the amplifier works as the receiver shunt setting is changed. A simple calculation will show how great the attenuation must be in any given case to satisfy these conditions.

Proper values for the steps of the receiver shunt may be calculated as follows, reference being made to Fig. 35 in which the currents and potentials indicated are in accordance with the assumptions made

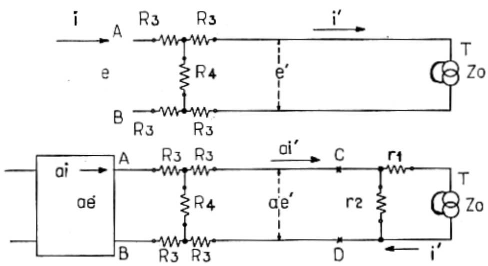

Fig. 35

regarding the attenuation in the various portions of the circuit. Calling a the amplification to be measured it may readily be shown that

$$\frac{(a-1)^2}{a}=\frac{r_1}{r_2}. \qquad (9)$$

Or if R is the impedance of the network R_3R_4 as seen from the receiver, and the shunt Sh is proportioned so that it also presents the impedance R to the receiver, whence

$$R=r_1+\frac{r_2 R}{r_2+R},$$

then Equation (9) gives

$$a=\frac{R+r_2}{r_2}.$$

Taking account of the necessary approximations it is readily possible to measure current amplification to within 5%, for a range of frequencies extending from 200 to 3,000 cycles. Receiver shunts are made which, in 10 to 15 steps, will reach a maximum reduction ratio in current of 25:1 which corresponds to an energy reduction of 625:1, and this does not represent the greatest range possible.

In case a rougher approximation of the amplifying power is sufficient, the circuit of Fig. 34*a* may be simplified by omission of the network R_3R_4 and reversal of the receiver shunt to present a constant impedance (except for variation of impedance with frequency and phase angle) toward the amplifier. The network R_1R_2 should preferably be retained and should be so proportioned that the current through the right hand R_1 branches is practically the same whether connected with the amplifier or directly to the receiver.

In measuring the over-all amplification of a multistage circuit, it will probably be desirable to add fixed but known attenuation units similar to R_3R_4 to the receiver shunt which may be cut in or out as required. These units may be given an attenuation equal to and twice the total attenuation of the shunt, etc., after the fashion of the ordinary resistance box. In constructing attenuation networks the arrangement indicated in Fig. 34*a* will be found desirable in that the symmetrical placing of the branches tends materially to eliminate errors which might otherwise arise due to capacities to ground in the oscillator and amplifier. Pairing of lead wires and shielding of leads and resistance coils will be found desirable for accurate work.

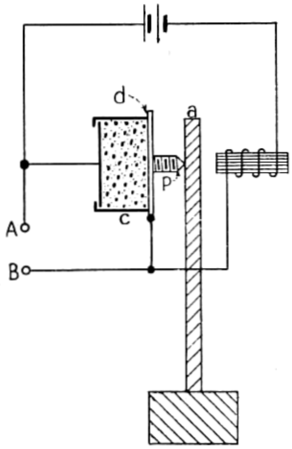

Fig. 36

The filter *F* should be used in case the amplifier tends, because of the limited range of frequencies which it passes or because of some other kind of distortion, to modify the quality of the note given by the oscillator, it being very difficult to match sounds for intensity which differ in quality.

A very satisfactory type of audio-frequency generator is shown in Fig. 36; it is a buzzer which operates, not by making and breaking current, but by varying it periodically with a microphonic button. The vibrating parts of this generator may be tuned to any audio-frequency, e.g. 800 cycles, and it gives quite accurately a sinusoidal variation of current, although it is customary to insert a filter (Sec. 6) to insure the input energy being accurately of one frequency.

VII. Thermionic Modulators

In discussing modulation the terminology which has been developed in connection with radio and carrier-current signaling will be used.

By the term "modulation" is meant the varying of the amplitude of a relatively high frequency wave, so that its envelope represents a particular low frequency wave or combination of such waves. (See Curves A, B and C, Fig. 37). The combination of low frequency

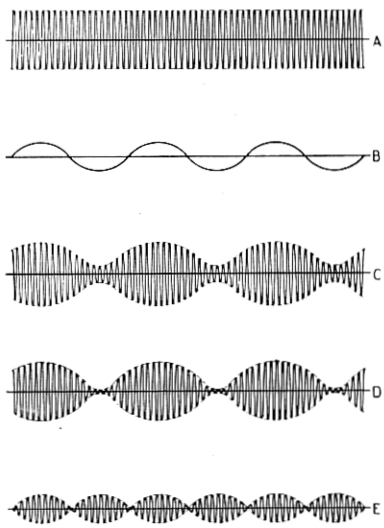

Fig. 37

modulating waves may be very complicated, as in the case of speech, but the principle involved is common to all cases of modulation and can be clearly brought out by the consideration of a single low frequency.

Let Fig. 37, C, represent a high frequency wave modulated by a sinusoidal low frequency. The wave C can be represented by

$$y = a(b + \cos qt)\cos pt, \tag{10}$$

in which $\frac{p}{2\pi}$ is the high (carrier) frequency and $\frac{q}{2\pi}$ the low (signal) frequency. Equation 8 can be rewritten in the form

$$y = ab\cos pt + \frac{a}{2}[\cos(p-q)t + \cos(p+q)t], \tag{11}$$

which brings out the fact that the modulated wave C contains, in general, three distinct frequencies—the carrier frequency $\frac{p}{2\pi}$, a difference frequency $\frac{p-q}{2\pi}$, and a summation frequency $\frac{p+q}{2\pi}$. These latter frequencies represent the so-called "side bands" of the modulated wave.

Two special cases of the wave represented by Equations 10 and 11 are represented graphically at D and E of Fig. 37 and correspond to $b=1$ and $b=o$ respectively. When $b=1$ it is evident that the amplitude of each side band is half the amplitude of the carrier frequency; such a wave is said to be "completely modulated"; when $b=0$ the carrier frequency $\frac{p}{2\pi}$ is absent altogether.[31]

35. *Means for Producing Modulation.* Perhaps the simplest case of modulation is that illustrated by continuous-wave radio telegraphy, in which the intermittent radiation of a uniform wave is accomplished by means of a telegraph key. In most cases, however, modulation requires a gradual change in the amplitude of the high frequency wave. For effecting this the vacuum tube possesses two properties which make it particularly useful—(a) the E_g, I_p characteristic is very nearly parabolic (Sec. 8); (b) the current in the plate circuit is a function of the grid potential (Fig. 10).

Circuits, by means of which modulation may be effected by each of these properties, are described in the following paragraphs.

36. *Modulation by Curved Characteristic.* Considering the circuit of the type illustrated in Fig. 38, let it be assumed that a voltage

$$e = A\cos pt + B\cos qt$$

is applied to the input of the tube. The result is shown graphically in Fig. 39. When this value of e is substituted in Equation 4 we

[31] For a more complete discussion of modulation and the nature of the side bands, see R. V. L. Hartley, Procd. Inst. of Radio Engrs., Feb., 1923, or *Bell System Technical Journal*, Apr., 1923.

obtain for the modulated output (i.e., terms whose frequencies are of the order $\frac{p}{2\pi}$).

$$J_m = A\left[\frac{\mu}{r+r_p} + \frac{\mu^2 r_p r_p'}{(r+r_p)^3} B \cos qt\right]\cos pt. \tag{12}$$

As pointed out above, the first term gives the carrier wave and the second term, the two side bands. It will be remembered that this

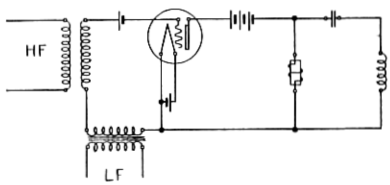

Fig. 38

equation neglects terms of higher order than the second, which is permissible, so long as the tube characteristic is approximately parabolic.

Certain points regarding Equation 12 should be noted. In the first place, the amplitude of the side bands is proportional to the

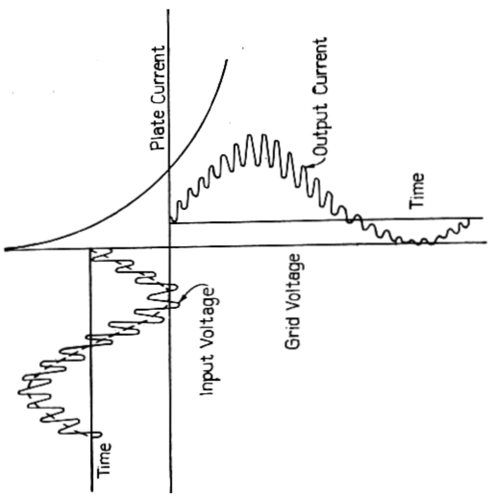

Fig. 39

product AB and is therefore, independent of the relative amplitudes of the original carrier and modulating frequencies. Also the modulated current is proportional to the first power of B, the amplitude of the low frequency wave; i.e., although the modulation is effected by the curvature of the tube characteristic, the modulated output is free from distortion. Furthermore, the modulated output voltage is proportional to $\frac{r}{(r+r_p)^3}$ which is a maximum when $r=\frac{1}{2}r_p$; and the modulated output energy is proportional to $\frac{r}{(r+r_p)^6}$ which is a maximum when $r=\frac{1}{5}r_p$.

Another type of circuit in which the modulation is dependent upon the curvature of the E_g,I_p characteristic is shown in Fig. 40. The two tubes are supposed to be alike; so long as no low frequency is impressed on the grids the high frequency space currents are equal,

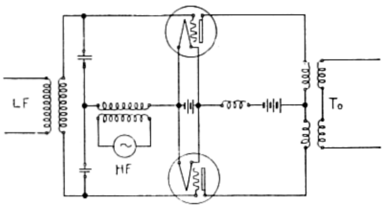

Fig. 40

each passing through one of the primary coils of the transformer T_0, the order of winding these coils being such that this condition gives zero current in the secondary. However, the presence of a low frequency voltage (*L.F.*, Fig. 40) raises one grid potential at the same time that it lowers the other, with the result that the high frequency currents in the two primary coils are no longer equal, and a high frequency current therefore flows in the secondary of T_0, the amplitude of which is determined by the degree to which the two tubes are unbalanced by the low frequency input. It is apparent that the output of this modulator circuit contains only the two side bands and none (or very little, if the tubes are not exactly identical) of the carrier frequency and therefore corresponds to curve E in Fig. 37. It is particularly useful in communication circuits where several telephone or telegraph channels are desired on the same pair of wires. Since only the side bands are transmitted the total current which must be handled by repeaters and other line apparatus is materially reduced. By the use of the proper wave-filter it is also possible to suppress one side band, thereby approximately cutting to one half, the width of the frequency band to be transmitted. As will be pointed out under homodyne detection, the suppressed carrier frequency must be supplied locally before detection can occur.

37. *Modulation Effected by Controlling Plate Current with Grid Potential.* Numerous circuits have been developed for modulation, making use of the fact that the grid potential affects the resistance of the plate circuit. Two circuits of this type are shown in Figs.

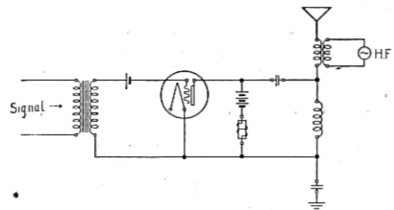

Fig. 41

41 and 42. In the first, the plate circuit of the tube forms a shunt across a portion of the antenna inductance. As the grid potential is varied, the antenna is, therefore, thrown more or less out of tune, with the consequent radiation of a variable amount of high frequency energy.

Fig. 42 shows one of the most efficient modulating schemes thus far developed. As the grid potential of the modulator tube *A* varies, causing a change in plate current through this tube, the plate voltage

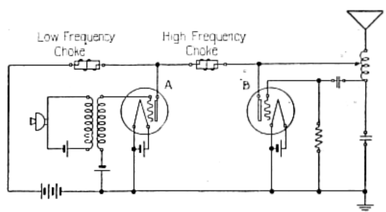

Fig. 42

applied to the oscillator tube, *B*, fluctuates, because of the presence of the low frequency choke coil. Under this condition of variable plate-voltage the oscillator gives a variable amount of high frequency energy to the antenna. When used for speech modulation this circuit is very efficient and gives good quality. The tubes *A* and *B* are ordinarily of the same type.

Many other modulating circuits have been designed, and those given above are to be considered merely as illustrative of the general manner in which the properties of the vacuum tube may be applied to the problem of modulation.[32]

[32] For other types of modulator circuits see a paper by R. A. Heising, Procd. Inst. Radio Engrs., Aug., 1921.

VIII. Thermionic Detectors

Like the modulator the detector is a device for the production and separation of difference frequencies. The object of modulation is, in general, to transform a high frequency $\frac{p}{2\pi}$ and a low frequency $\frac{q}{2\pi}$ into two high frequency side bands, $\frac{p \pm q}{2\pi}$. Detection accomplishes the inverse operation of forming from a carrier frequency $\frac{p}{2\pi}$ and either or both side bands the original low frequency $\frac{q}{2\pi}$, detection often being referred to as demodulation. Detection, like modulation, can be most readily described by the consideration of a single pair of frequencies.

When carried out by means of a vacuum tube it results from rectification in either the grid circuit or the plate circuit. This rectification

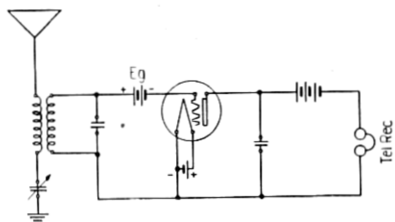

Fig. 43

may arise either from unilateral conductivity or a curved current-voltage characteristic as pointed out in the following paragraphs.

38. *Detection by Curved Plate Characteristic.* Considering the circuit shown in Fig. 43 and assuming an input voltage $e = A(B + \cos qt) \cos pt$, it follows from Equation 4 that the output current, considering only those terms whose frequencies are of the order $\frac{q}{2\pi}$, is

$$J_d = \frac{1}{2!} \frac{\mu^2 r_p r_p'}{(r + r_p)^3} A^2 (B \cos qt + \frac{1}{4} \cos 2\, qt). \tag{13}$$

The current J_d, known as the "detected current," therefore, consists of a term whose frequency is $\frac{q}{2\pi}$ and another term whose frequency is twice this. The presence of these two frequencies is readily understood. The detected current of frequency $\frac{q}{2\pi}$ corresponds to the difference frequency (See Equations 10 and 11) of the carrier of amplitude AB and each side band of amplitude $\frac{A}{2}$ and is therefore proportional to $2 \cdot \frac{A}{2} \cdot AB$. The second term of the detected current represents the difference frequency $\frac{q}{\pi}$ between the two side bands themselves and, as is to be expected, its amplitude is proportional to $\frac{A^2}{4}$. In case one of the side bands is suppressed before detection, this term of double frequency is entirely absent in the detected current. Furthermore, the amplitude of the detected current of frequency $\frac{q}{2\pi}$ is independent of the *relative* amplitudes of the carrier wave and the side bands. In general, AB is large compared to $\frac{A}{2}$ with the result that the term of double frequency in the detecting current is negligible. It follows, therefore, as in the case of modulation that the detecting current is practically free from distortion.

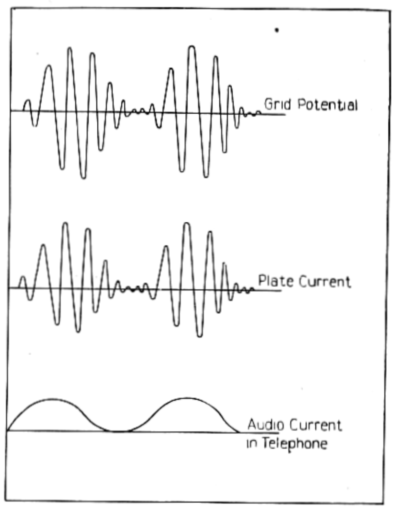

Fig. 44

The detecting action resulting from the curved plate characteristic is shown in Fig. 44.

Equation 13 leads to the result that the output voltage of a detector tube, when working as above, is a maximum when $r = \frac{1}{5} r_p$. In using these relations note that r represents the value of the output resistance for the high frequency and not the low frequency. When using an amplifier on the output of a detector (see Fig. 45), it is important to choose r to give the maximum detecting *voltage.* As in amplifier cir-

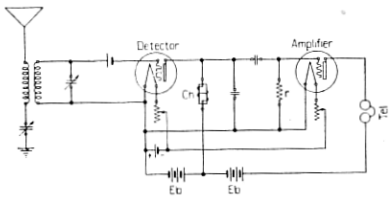

Fig. 45

cuits it is essential in this type of detector that the grid remain always negative. See also the sections on amplifiers.

39. *Detection by Rectification in Grid Circuit.* This type of circuit (see Fig. 46) is now in very general use for radio purposes, and is characterized by the grid blocking condenser C_s. Contrary to the preceding type of detector, the present requires the flow of electrons to the grid and works best when the grid is held permanently at a

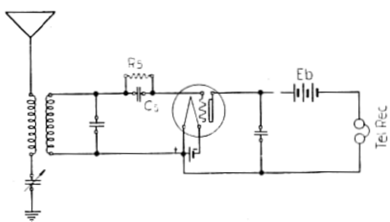

Fig. 46

small positive potential. The action of the high frequency input causes the periodic accumulation of a negative charge upon the grid and the blocking condenser, thus lowering E_g and diminishing I_p. This action is clearly illustrated in Fig. 47. This circuit is most effective when the carrier frequency is much greater than the signal frequency, and not as efficient as the circuit described in Sec. 38 when the carrier is say only four or five times as great as the signal frequency.

Attempts to deduce a quantitative relation for the detecting current in this type of detector have as yet met with little success, one of the principal reasons being that very little is known about the "dynamic" grid current characteristic.[33] Experiments show, however, that the

[33] For a discussion of this topic see Hulbert & Breit, *Phys. Rev.*, Nov., 1920, pp. 408–419; Oct., 1920, pp. 274–281.

detecting current is practically proportional to the square of the input voltage, provided that this is small, thus establishing the relation,

$$J_d = ae^2,$$

which corresponds in form to Equation 13 above.

In designing this type of detector circuit, attention must be paid to the value of the blocking condenser C_s and its leak R_s. It is clear that the capacity of C_s should be sufficiently small to cause the grid to undergo the maximum potential change as a result of the relatively

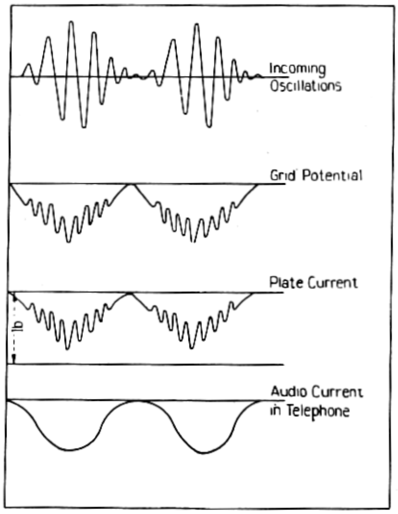

Fig. 47

small electron charge picked up, and yet it must be several times larger than the tube capacity between grid and filament. Furthermore, the time constant of C_s and R_s should approximately match the frequency of the detected current. With the more common detector tubes and radio frequencies, capacities of the order of 200 $\mu\mu$f. are satisfactory.

Detector circuits with grid blocking condensers may be coupled to amplifiers as readily as the other type of detector, and, in general, a higher output resistance for the detector can be used, thus making possible more efficient coupling between the detector and the first stage of amplification. In increasing the output resistance of the detector it should, however, be borne in mind (see Sec. 13) that a secondary result is to reduce the input impedance of the detector, which may entail a reduced input voltage.

40. *Heterodyne and Homodyne Detection.* In continuous-wave radio telegraphy, the dots and dashes of the code are transmitted by a continuous carrier wave of a single frequency. *Heterodyne* reception consists in supplying a slightly different frequency at the receiving station, the transmitted and locally generated frequencies when applied to the detector acting exactly as the carrier and side band frequency described above. The useful output of the detector is the difference frequency which, of course, is chosen in the audible range.

It follows from Sec. 38 that the heterodyne detecting current is proportional to the product of the amplitudes of the transmitted and locally generated waves. Because of this fact a feedback circuit may be used to advantage as a means of increasing the strength of both high frequency terms. In the usual type of feed-back detector, the detector tube is also used as the source of local high frequency. Such

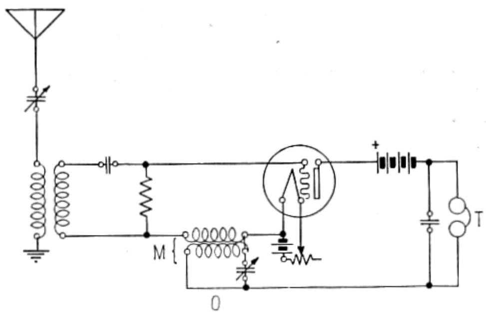

Fig. 48

a circuit is shown in Fig. 48. The oscillatory circuit *O* is tuned to differ in frequency from the incoming signal by an amount which will give a satisfactory difference frequency in the telephone receiver *T*. By varying the coupling at *M*, the intensity of the beat note can be readily changed. It must, however, be sufficient to cause the circuit as a whole to oscillate at the natural frequency of *O*. A feed-back arrangement is particularly applicable to those cases in which the carrier frequency is much higher than the signal frequency and is therefore generally used with a blocking condenser.

In telephone systems, whether radio or carrier current, it is frequently desirable to suppress the carrier frequency and transmit only one[34] or both of the side bands. Detection with only the side bands present would result in a double frequency detecting current which obviously would not be permissible in a telephone circuit. Whenever

[34] For a discussion of the advantages of *single* side band transmission, see reference given in footnote 13.

the side bands alone are transmitted, a locally generated high frequency exactly equal in frequency and phase to the original carrier frequency must be supplied.[35] This is known as *homodyne* reception.

41. *Measurement of Detection Coefficient.* The constant a in the relation $J_d = ae^2$ is called the "detection coefficient." Its measurement by direct means is not difficult but as seen from Equation 13 it involves so many factors that no satisfactory indirect methods of determination have been developed. The requirements of the direct method are quite obvious, and for circuit details reference is made to the *Thermionic Vacuum Tube* by van der Bijl.

42. *Detecting Efficiency.* A knowledge of the detecting coefficient a tells very little about the detecting efficiency of a tube, the efficiency being defined as the ratio between the low frequency energy in the output and the high frequency energy in the input. The efficiency involves the input impedance of the tube which is a function of the circuit constants as well as the tube. It is therefore impossible to specify the detecting efficiency of a tube without certain data concerning the circuit in which it is to be used; a is therefore without much significance.

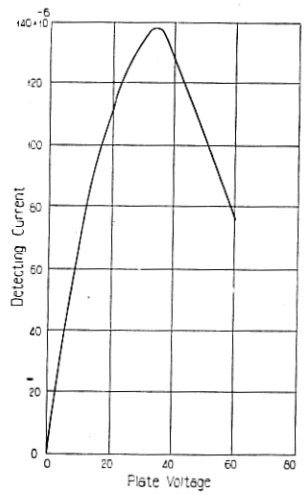

Fig. 49

43. *Detecting Coefficient and Plate Voltage.* The variation of the detecting coefficient with plate voltage depends upon the type of circuit. If detection is accomplished by a curved plate characteristic, experiment shows (see Fig. 49) that the operation is best when the effective voltage is about equal to the potential drop in the filament,

[35] See J. R. Carson, Procd. Institute of Radio Engineers, Vol. II, p. 271, 1923.

it being presupposed (see Sec. 38) that E_g is enough less than zero to keep the grid negative at all times. If detection is accomplished by means of a blocking condenser, the variation is as shown in Fig. 50, no sharply defined maximum being present in the curve.

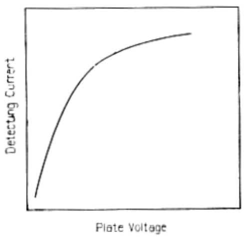

Fig. 50

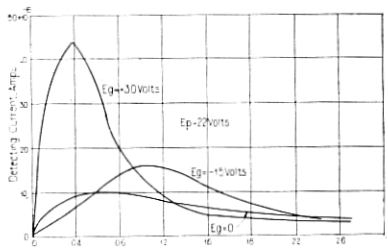

Fig. 51

The variations of detected current under heterodyne operation are shown in Figs. 51 and 52 which refer respectively to detection with and without a blocking condenser. The abscissa, e_1e_2, gives the product of the two high frequency amplitudes in the input. As is to be expected when no grid condenser is used (see Equation 13), the

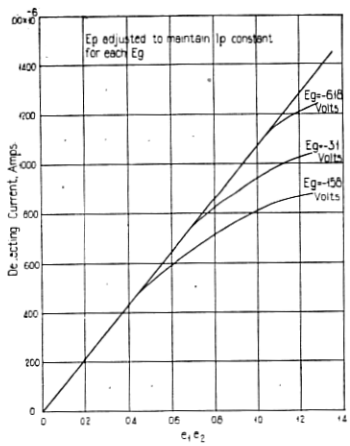

Fig. 52

variation of detected current with e_1e_2 is very nearly linear provided E_g is sufficiently negative. Fig. 51 referring to detection with grid condenser shows no linear relation however. The data for Figs. 51 and 52 are taken from Van der Bijl.

44. *Comparison of Tubes as Detectors.* If a tube is available whose detecting coefficient is known, other tubes may be calibrated in terms

of this standard. The comparison of detectors can be very readily carried out by means of such a circuit as shown in Fig. 53. This circuit makes use of a grid blocking condenser but could readily be rearranged not to employ it. In use, switches S and K are operated together in such manner that the receiver shunt is cut out when the

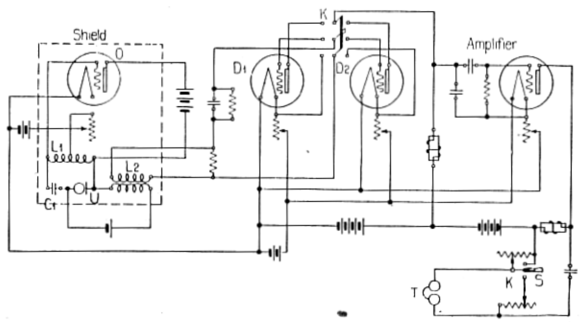

Fig. 53

receiver is connected to the tube of lower detecting power. By proper adjustment of the shunt the two tubes can then be brought to apparent equality, the difference being read from the calibration of the shunt.

IX. Vacuum Tube Oscillators

As pointed out in the section on amplifiers, it is easy to design feed-back circuits which will sing, i.e., will generate continuous oscillations. The necessary requirements which an oscillating circuit must meet are two in number and are readily understood. Any small alternating voltage when applied to the input generates a current in the output, and by virtue of the feed-back a portion of this energy is returned to the input. For continuous oscillations, the energy returned must be in phase with the original input supply. Furthermore, letting e represent the initial input voltage, the feed-back coupling must be sufficient to return to the input a voltage greater than e. If it is less than e the circuit will amplify but will not oscillate.

The circuit requirements necessary for any given tube to return a voltage greater than e may readily be stated in mathematical form, but so far as the practical design of oscillators is concerned, this statement has no particular value. The design of circuits is still very largely an empirical matter, and the problem is not so much to make the circuit oscillate as to make it oscillate with the proper frequency, efficiency and output power. These requirements can usually best be met by trial and adjustment taking into account such general theoretical considerations as follows.

Vacuum tube oscillators make a convenient way of obtaining large high frequency currents at small voltages and large a.c. voltages at small currents for testing purposes.[36] A special oscillator circuit for giving a very pure sine wave output of constant frequency is discussed in Sec. 53.

45. *Equivalent Resistance of the Oscillator Circuit.* Oscillator circuits are of many types, but the fundamental action of all of them can be reduced to common terms, and to simplify the discussion the type of circuit illustrated in Fig. 54 will be discussed.

It will be noted that a d.c. voltage is applied between filament and plate by means of a battery in series with a choke coil. This choke

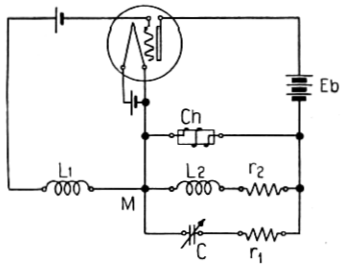

Fig. 54

may be considered as having zero d.c. resistance and virtually an infinite resistance to the a.c. generated by the oscillator. An oscillating circuit consisting of inductance, resistance and capacity is also connected between filament and plate, and by means of another inductance joining filament and grid a portion of the output energy is fed back to the input by virtue of the inductive coupling M.

In circuits as usually constructed the ohmic resistances r_1 and r_2 of the oscillating circuit are very small compared to the impedances of L_2 and C. It follows that the frequency of oscillation differs but slightly from the natural frequency $1/2\pi\sqrt{L_2C}$, and the oscillating circuit may therefore, be looked upon as introducing nothing more than a pure resistance (so far as the fundamental component of I_p is concerned) into the output circuit of the tube. Except for considerations of feed-back, we may therefore imagine the oscillating circuit L_2, C, replaced by an equivalent resistance whose value is given by the equation $R=\dfrac{r_1r_2+L_2/C}{r_1+r_2}$. This "equivalent resistance" is important in dealing with oscillating circuits.

[36] See W. C. White, Gen. Elect. Rev., Vol. 20, p. 635, 1917.

46. *Phase Relations.* Typical phase relations between the various currents and voltages in the oscillating circuit are illustrated by the oscillograms in Fig. 55. Note that the oscillation current I_o, and also E_p and E_g show practically sinusoidal variations. Such variations

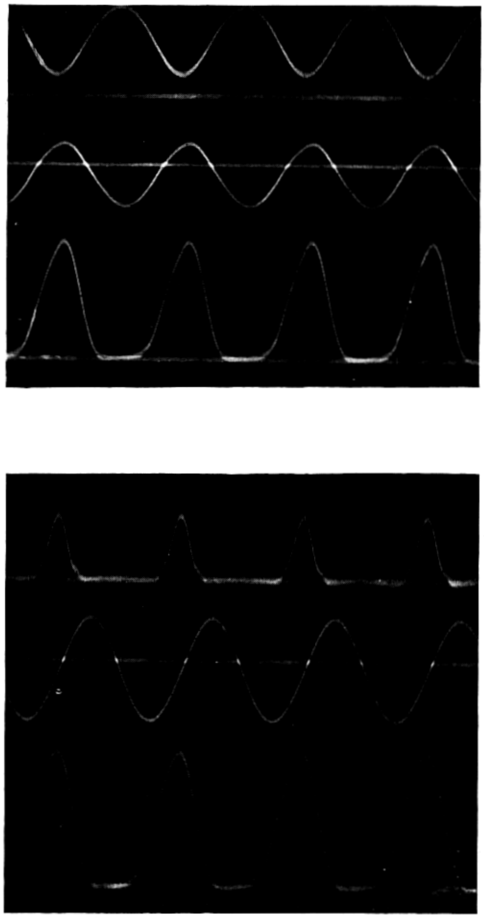

Fig. 55

will be found over very wide ranges of adjustment. Although I_p does not show a sinusoidal variation, the fundamental component (whose frequency is the same as that of I_o) is relatively much larger than the higher components.

Note that the variations of E_p and E_g are practically 180° out of phase, and also that E_p and the fundamental of I_p are 180° out of phase. This latter condition is obviously required for maximum power output by an a.c. generator. In order that I_p be a maximum when E_p is a minimum, E_g must be a maximum at this time.

47. *Dynamic Characteristic.* A tube when operating into an output resistance follows a dynamic characteristic (also called derived characteristic)[37] whose slope is somewhat less than that of the static (see Sec. 12). The dynamic characteristic is flatter than the static characteristic since the oscillating circuit L_2, C acts as an equivalent resistance. In fact, the dynamic characteristic of the oscillating tube may differ in one important respect from that of Sec. 12, for in an oscillator the grid potential has a relatively very high positive value for a portion of the cycle. Consequently the dynamic plate characteristic very frequently turns downward at its upper end (point B, Fig. 56). As will be pointed out later, this feature of the dynamic

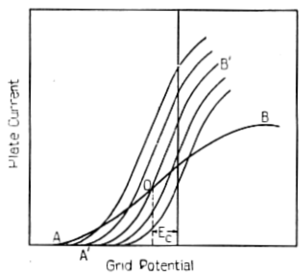

Fig. 56

characteristic is likely to be one of the factors tending to limit the amplitude of oscillation.

48. *Amplitude of Oscillation.* As yet no very comprehensive formula has been derived, either theoretically or empirically, to express the amplitude of oscillation in terms of the tube and circuit constants and the applied E_p. However, certain general statements can be made which will serve as useful guides.

We shall not consider further the circuit shown in Fig. 54; it shows a negative grid battery in the grid filament branch, which, if sufficiently large to control the oscillator when in operation, usually makes the starting difficult and uncertain, and is therefore undesirable. To eliminate the grid battery and yet supply sufficient negative potential, once oscillations have started, circuits are usually supplied with a grid blocking condenser and high resistance leak (see Figs. 64 and 65). Since for a portion of each oscillation the grid is positive, it

[37] See L. A. Hazeltine, Procd. Inst. of Radio Engrs., April, 1918.

picks up a charge of electrons which in flowing off through the leak creates an average negative grid potential. It is apparent that as the amplitude of oscillation increases, the charge picked up at each positive swing of the grid potential increases, with the result that this average negative potential tends to sink lower. The importance of this control feature will be brought out presently.

It is generally found that the oscillations build up to such a value that the greatest positive potential of the grid, which will be represented by $E_{g\max}$, becomes practically equal to the lowest plate potential, $E_{p\min}$. It is not difficult to understand why this condition should represent a sort of limit. It is usually found that the dynamic characteristic, as shown at *B*, Fig. 56, tends to bend rapidly downward as $E_{g\max}$ becomes greater than $E_{p\min}$. When $E_{g\max}$ tends to become greater than $E_{p\min}$ the electron current to the grid rises suddenly (see cathode ray oscillogram, Fig. 57) with the result that the average

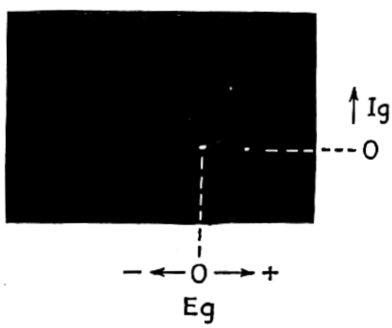

Fig. 57

current flowing through the grid leak increases very rapidly, which in turn results in a marked depression of the average grid potential.

The increased electron current to the grid as E_g tends to become greater than $E_{p\min}$ also represents a greater dissipation of energy upon the grid which is equivalent to an increase in the effective resistance *R*.

It is quite possible that any one of these three factors, in the absence of the others, would be sufficient to limit the oscillations; but as each springs into importance when the amplitude of the oscillation has reached about the same value, we shall not discuss the exact combination of the three which actually determines the amplitude.

Adopting the relation $E_{g\max} = E_{p\min}$ and making the additional assumption that the dynamic characteristic is straight (which is very nearly true) an expression for the amplitude of oscillation can readily be obtained. Introducing certain approximations this expression may be written,

$$i_{p1}(R+R_o)=\frac{1}{\sqrt{2}}\,\overline{E}_p, \tag{14}$$

in which terms of the order $\frac{1}{\mu}$ are neglected in comparison to unity. i_{p1} is the fundamental component of the space current, $\overline{E}_p$ is the mean plate voltage and the term R_o is largely determined by the tube, and while not generally equal to r_p, is apparently not much different from it. This equation indicates that the amplitude of oscillation is practically independent of the value of μ.

The remarkably simple relation given by Equation 14 has been tested for a wide variety of circuits and tubes and has been found to hold with a very fair degree of accuracy. It may safely be taken as indicating quite approximately what response may be expected from any tube and circuit when operated at a particular applied E_p. The equation is likely to be more closely followed the more carefully the adjustment of circuit for maximum efficiency has been made.

The condition $E_{g\max}=E_{p\min}$ should not be considered as invariable. Adjustments can readily be made for which $E_{g\max}$ will either be ap-

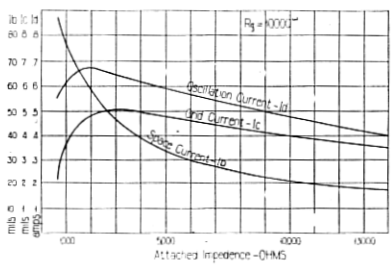

Fig. 58

preciably less or greater than $E_{p\min}$. It is generally found however that these adjustments do not give the most efficient operation.

Additional information as to the relation between the amplitude of oscillation and certain circuit constants are given in Figs. 58, 59, 60, 61. Fig. 59 shows that an oscillator tube may present a well-defined condition of temperature saturation. Figs. 60 and 61 show that the value of the feed-back voltage and grid leak resistance r_g may be varied within wide limits without affecting the output markedly.

49. *Efficiency.* The efficiency of an oscillator may be defined as the ratio between the energy of oscillatory current and the d.c. energy supplied to the plate circuit. This leaves out of account the energy

required to actuate the filament. The efficiency of oscillator circuits ranges all the way from a few per cent. to as high as 90% or better. The principal factors determining the efficiency are those which determine the amount of energy dissipated upon the plate of the tube. Inspection of the oscillogram, Fig. 55, shows that the sharper and

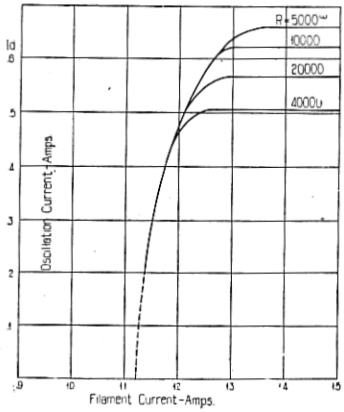

Fig. 59

narrower the plate current wave and the more nearly the plate voltage approaches zero, the higher will be the efficiency. In an extreme case such as the hypothetical one illustrated in Fig. 62 it is evident that the efficiency would be very large indeed. The μ of the tube

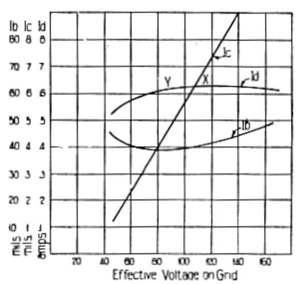

Fig. 60

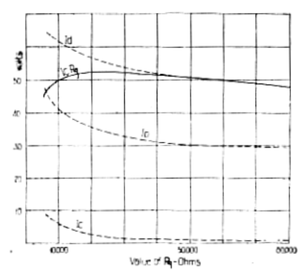

Fig. 61

largely determines the sharpness of the plate current wave and experience shows that for efficiencies of about 50% and better, μ should be at least ten; an increase above this value does not result in any very large improvement. It is also generally true that for the highest efficiencies the circuit constants should be so arranged that R is at least four or five times as great as r_p, and it may advantageously be made 10 to 15 times as great. In these latter cases R_0 is relatively

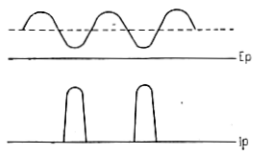

Fig. 62

negligible compared to R in Equation 14 with the result that i_{p1} can be quite accurately calculated although the exact value of R_0 may be unknown.

50. *Types of Oscillating Circuits.* There are many different types of oscillating circuits and as they do not lend themselves readily to classification, only a few of the more common types will be described.

One of the simplest oscillating circuits is that shown in Fig. 63 which is characterized by a tuned grid circuit inductively coupled

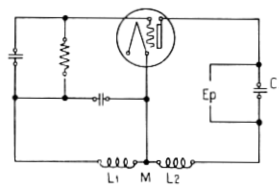

Fig. 63

to a coil in the output. This type is satisfactory for low plate voltages and small powers, but is not to be recommended where large amounts of power and high efficiencies are desired.

The condenser C_o is inserted to prevent short circuiting of the plate battery or generator and may be made so large as to have no effect on the frequency.

A circuit of similar properties is shown in Fig. 64, the output being tuned instead of the input.

51. *Colpitts and Hartley Circuits.* Two very similar types of circuits which have proved satisfactory for a wide range of frequencies, voltages and powers, and which yield very high efficiencies, are shown in Figs. 64 and 65, the former being known as the Colpitts and the latter as the Hartley circuit. In both circuits, as illustrated, the mean grid potential is secured by a grid leak. The blocking condenser C_g should be large enough to offer very little impedance to the flow of the alternating current which causes the variation of the grid potential,

and as seen in Fig. 61 the resistance of the leak can be varied within wide limits without an appreciable effect upon the performance of the circuit. The source of plate potential may be either battery or generator. The choke in the generator supply should be sufficiently large to prevent an appreciable amount of oscillating current flowing

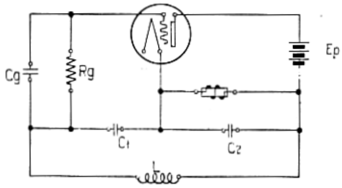

Fig. 64

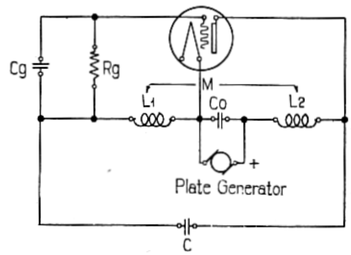

Fig. 65

through the generator. In order to avoid short circuiting the generator in the Hartley circuit, a large condenser C_o is interposed as shown in Fig. 65. For high frequencies it is customary to make this condenser so large that it has very little effect upon the frequency of oscillation.

The power of the oscillating current may be removed either by capacity or magnetic coupling, or it may be dissipated by resistance within the oscillating circuit. Magnetic coupling is very satisfactory for radio frequencies, but for the audio frequencies unless iron core transformers are used, capacity coupling usually proves more convenient. In regard to the use of iron core inductance and transformers, the reader should note the following Section.

52. *Frequency of Oscillation.* It is frequently found that the tube causes an appreciable deviation from the calculated frequency of oscillation. This is not so much because the tube influences the normal operation of the oscillating circuit as it is due to the fact that the impedances of inductance coils (particularly when iron cored) and of the condensers are liable to vary in value with the current amplitude. Hence any change in applied plate potential, filament current, or output resistance, because of its effect upon the amplitude of the oscillating current, will give rise to changes in frequency. In designing circuits to operate at a constant frequency regardless of slight changes in tube constants, plate potential, filament current, etc., the most important requirement is to provide inductances and condensers whose impedances are independent of the currents they carry, and whose resistance components are very small.

53. *Oscillator for A.C. Measurement Purposes.* For many a.c. measuring purposes an oscillator whose output is both free from harmonics and constant in frequency is desirable. Such a circuit is shown in Fig. 66. the design of which is radically different from the oscillator circuits already discussed. It possesses a tuned input LC and coupling is supplied by the resistance R. R is usually given a

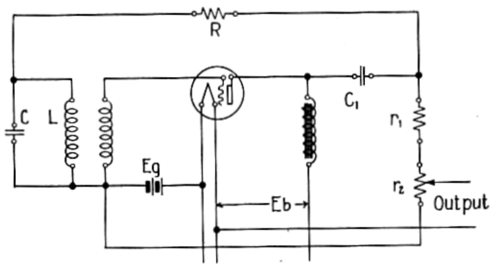

Fig. 66

value between 100,000 and 400,000 ohms. A negative grid battery fixes the average grid voltage, the emf, of this battery being about 8 to 10 volts. It is customary to make the resistances r_1 amd r_2 several thousands ohms apiece, r_1 being perhaps 5 times r_2. The condenser C_1 is merely a blocking condenser and should offer little impedance to the a.c.

It is not difficult to make the oscillator of Fig. 68 maintain a frequency that is constant within 3/10 of 1% and when the feed-back is not too large the harmonics in the output will comprise only 5% or even less of the total a.c. output.

54. *Range of Frequencies Obtainable with Vacuum Tube Oscillators.* Circuits have been constructed whose frequency is but a fraction

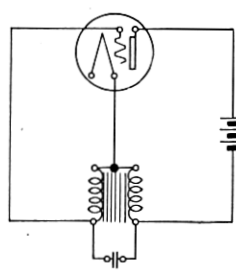

Fig. 67

of a cycle per second. The requirements of such a circuit are large inductance and capacity and very close coupling between input and output. A satisfactory circuit for low frequencies is that shown in Fig. 67; the two inductances taking the form of an iron core transformer.

At the other extreme, frequencies as high as 5×10^7 cycles per second can be obtained by means of tuned vacuum tube circuits of the Hartley or Colpitt type. At this point the coupling reactance of the tube becomes appreciable with that of the circuit.

Circuits capable of considerably higher frequencies have been described by Van der Pol,[37] Southworth,[38] Gutton and Touly,[39] and Holborn.[40] In all of these cases the oscillatory circuit is made up of distributed inductance and capacity connected to the tube in such a way as to utilize the capacity between the elements of the tube as a means of coupling.

The circuit shown in Fig. 68, when properly arranged, is as efficient as those used for lower frequencies and will give frequencies as high as 3×10^8 cycles per second. The oscillatory circuit is indicated by the heavy lines. It consists of a rectangle whose dimensions are appreciable with the wave length. Therefore, waves produced by variations in the electron emission through the grid are guided along the rectangle and are reflected at the ends. The reflected waves produce the proper voltage changes on the grid to sustain oscilla-

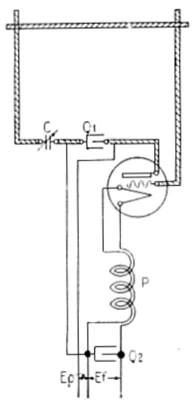

Fig. 68

tions. The ground imposed by the power leads places at least one point of the circuit at earth potential. If the condenser *C* is properly adjusted relative to the capacity between the grid and the plate the wave front can be made essentially perpendicular to the sides of the rectangle. It has been found that a large part of the power loss in the circuit is due to radiation. This circuit has been used as a basis

[37] B. van der Pol, *Phil. Mag.*, 38, July, 1919.
[38] G. C. Southworth, *Radio Rev.*, 1, Sept., 1920.
[39] Gutton and Touly, Comptes Rendus, 168, Feb. 3, 1919.
[40] F. Holborn, *Zs. fur Physik*, 6, p. 328.

of directive radio in which a metallic mirror was used to reflect the transmitted signals.

Very different means of producing high frequencies have been used by R. Whiddington,[41] Barkhausen and Kunz,[42] and by Gill and Morrell.[43] In some cases they employ tubes having considerable residual gas. The frequencies produced depend on the relative voltages applied to the grid and plate. Probably the best explanation of this phenomenon has been given by Gill and Morrell. Frequencies higher than 3×10^8 cycles per second have been reported.

The most accurate way of measuring these high frequencies is by observing the length of standing waves produced on a parallel wire system. The constancy of the vacuum tube generator, compared with spark ocsillators, combined with the fact that the sharpness of resonance in a parallel wire circuit is comparable with that in ordinary radio circuits, makes it especially adaptable to measurement purposes. It may be used, for example, to measure small inductances and capacities or to determine the dielectric constant of liquids. Many of the corrections necessary when a damped source is used are eliminated.

55. *The Mechanically Coupled Oscillator.* In addition to the types of oscillators described above where the frequency is determined by

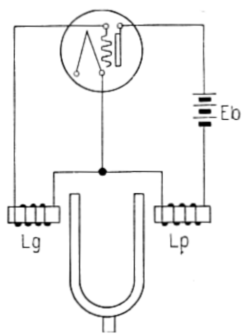

Fig. 68a

inductance and capacity, we may have oscillators in which the frequency is governed by a mechanical system such as a pendulum or a tuning fork.[44] An example is shown in Fig. 68a. The two coils

[41] R. Widdington, *Radio Rev.*, 1, Nov., 1919.

[42] Barkhausen and Kunz, *Phys. Zs.*, Jan, 1, 1920.

[43] Gill and Morrell, *Phil. Mag.*, 44, July, 1922.

[44] See Eckhardt, Karcher and Keiser, *J. O. S. A. & R. S. I.*, Vol. 6, p. 948, 1922; Eccles & Jordan, Phys. Soc. Proc. 31, Aug., 1919 and Phys. Soc. Proc. 32, Aug., 1920; Abraham & Bloch, J. d. Physique, Vol. 9, July, 1920.

L_p L_g are inserted in the plate and grid circuits of the tube. Variations in the plate current through the coil L_p impress forces on the tuning fork which result in its motion. This motion of the fork causes variations in the magnetic field through L_g and induces a varying voltage on the grid. With the proper coupling, sustained oscillations result having a period very nearly that of the tuning fork.

The electrically driven tuning fork described above constitutes a very satisfactory source of either sound or electromotive force. Horton, Ricker and Morrison [45] have made improvements which make it

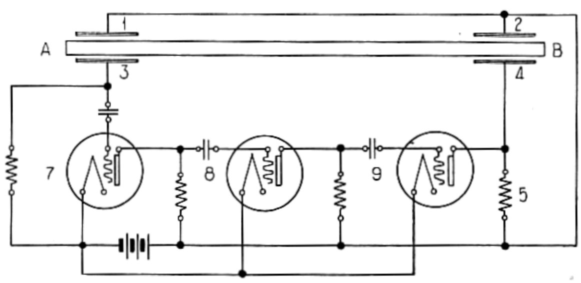

Fig. 68b

constant in amplitude and frequency to six parts in a million over very long periods of time.

An entirely different form of mechanical coupling has been used by Cady.[46] The circuit is shown in Fig. 68b. It makes use of the piezo-electric effect and mechanical vibrations of a crystal. Variations in the plate current in the tube 9 cause a voltage change across the resistance 5. This is communicated to a crystal AB such as quartz by means of the plates 2 and 4. A transverse electric field applied to such a crystal causes a change in its length. If this electric field be periodic, compression waves will travel along the crystal with a velocity depending on its density and elastic properties. These waves will, in turn, cause a varying electric field between plates 1 and 3 which may be communicated to the grid of the tube 7, amplified by 8, and finally transmitted to tube 9. This provides conditions for sustained oscillations having a frequency which is roughly inversely proportional to the length of the crystal.

Cady describes oscillators ranging in frequency from 3×10^4 to 10^6, and states that the frequency is constant to about one part in 10,000. The effect of temperature change is not great.

[45] *Journal of A. I. E. E.*, 1923.
[46] Cady, Proceedings of I. R. E., Vol. 10, No. 2, April, 1922.

X. Miscellaneous Applications of Thermionic Vacuum Tubes

56. *The Tube as a Voltmeter.* The three-element tube may be used for the measurement of either d.c or a.c. voltages. In the case of d.c. voltages it is customary to apply the unknown voltage to the plate, counter-balancing this voltage with a known negative potential applied to the grid. Given the μ of the tube, it is then possible to calculate with a fair degree of accuracy the plate potential. The usual procedure is to adjust the negative grid potential to such a point that the plate current just becomes zero. The tube when used in this manner becomes an electrostatic voltmeter, and it is evident that to give accurate readings the tube should have a well-defined cutoff (see Sec. 8, Fig. 10).

In a somewhat similar fashion a.c. peak voltages may readily be compared with known d.c. voltages. A typical circuit is shown in Fig. 69. In operation a fixed plate voltage is applied to the voltmeter

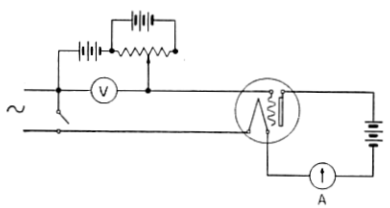

Fig. 69

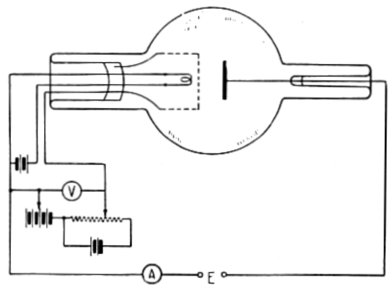

Fig. 70

tube and a steady negative d.c. voltage is applied to the grid which is just sufficient to reduce the plate current to zero. The a.c. voltage is then superimposed in the grid circuit with the result that current flows during the positive halves of the wave. If now the steady grid potential is made more negative until the plate current again just ceases to flow, it is apparent that this change in the steady potential just equals the peak value of the a.c. voltage.

For the measurement of very high voltages a special tube of the design shown in Fig. 70 will be found desirable, the grid being in the form of a screen which surrounds the filament. Such a tube may have a μ as high as 200.

A circuit similar to Fig. 69 may be so employed that the a.c. voltage to be measured causes a change in the space current meter reading, the negative grid potential being preferably so set that the conditions discussed in Sec. 16 are satisfied. The tube, due to its curved characteristic, acts as a detector and as pointed out in Sec. 37, the change in space current is approximately proportional to the square of the a.c. input voltage. For accurate work the circuit requires calibration but the calibration will in general remain good over long periods of time. This method is particularly useful for small voltages.

57. *Power-Limiting Devices.* As pointed out in Sec. 4 the total emission from the filament at a given temperature is fairly sharply defined regardless of the plate voltage, so long as this exceeds the value required to give voltage saturation. The fact that the total emission is limited by the temperature may be used to control the

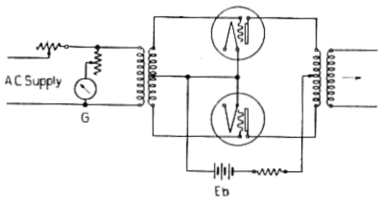

Fig. 71

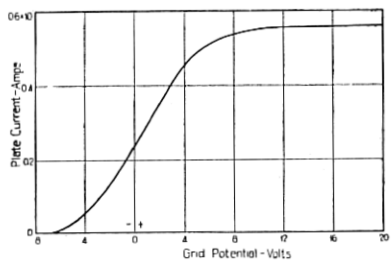

Fig. 72

maximum current in a circuit. As an illustration, Fig. 71 shows its application to an alternating current circuit, the performance of which is illustrated in Fig. 72. The introduction of such a device into an a.c. circuit will, of course, result in the generation of harmonics and may therefore, be objectionable.

There is almost no limit to the number of regulatory circuits which can be devised to employ the three-electrode tube.

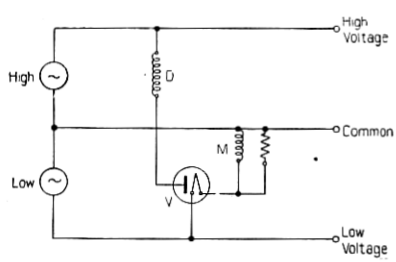

Fig. 73

58. *Voltage and Current Regulation of Generators.* The two-electrode tube with tungsten filament has been used to great advantage as a voltage regulator for a special airplane generator designed to deliver both 28 volts and 300 volts. The circuit arrangement is illustrated

in Fig. 73 in which *M* represents the main field winding, and *D* the differential winding which opposes *M*. The high voltage given by the generator when applied to the plate of the valve is sufficient to produce a condition of voltage saturation. As the speed of the generator increases, the current through the main field winding and

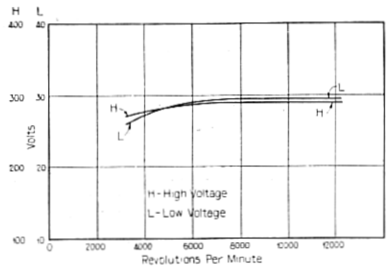

Fig. 74

the filament increases, thereby giving rise to greater emission from the filament and a larger current through the differential winding. It was found possible to so design the valve as to yield the very close regulation illustrated in Fig. 74.[47]

The three-electrode tube can also be used as a voltage regulator for a generator as shown in Fig. 75. It is apparent that an increase

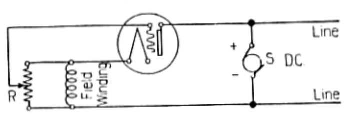

Fig. 75

in the voltage across the line tends to increase the current through the tube and resistance *R*. This in turn lowers the grid potential and tends to prevent an increase in current through the field winding.

The circuit shown in Fig. 76 illustrates an arrangement for main-

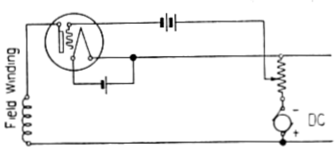

Fig. 76

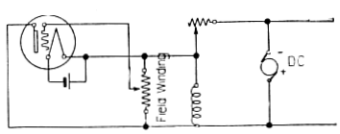

Fig. 77

taining a constant current from a generator. The operation of the device is apparent.

Fig. 77 shows another arrangement for maintaining a constant generator voltage. In this circuit an increase in voltage tends to

[47] Radio Telephony by Craft & Colpitts, Trans. A. I. E. E., Vol. 38, p. 330, 1919

make the grid less negative, thereby reducing the resistance shunted across the field winding.

A somewhat similar arrangement can readily be applied to regulate the voltage delivered by a battery. Fig. 78 illustrates such a circuit. An increase in E_1 raises the grid potential, thereby increasing the current through the tube and the resistance r_3. By a choice of regulating tube and resistances such that

$$r_3 = \frac{r_1 + r_2}{r_1} \frac{dE_g}{dI_p},$$

it may readily be shown that the voltage E_2 remains constant. Since the regulation effected by this circuit is independent of frequency it

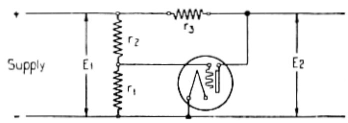

Fig. 78

may also be applied to a generator supply for elimination of commutator noise as well as voltage fluctuations due to changes in speed.

59. *The Ionization Manometer.* When gas is present in a three-electrode tube in quantities not sufficient to seriously affect the activity of the filament, and the plate voltage exceeds a value sufficient to produce ionization by collision, it has been found that the number of ions produced is proportional both to the pressure of the gas and to the electron current passing through the gas to the anode.[48] If now a small negative potential be applied to the grid, a certain fraction of the positive ions will be drawn to it and their number can be accurately measured by the current flowing in the grid circuit. The best arrangement is to apply the positive potential, not to the plate in the usual fashion, but to the grid, and apply the negative potential to the plate making it the collector of the positive ions. Dimensions of a satisfactory tube are given in Fig. 79. The values $E_g = 110$ volts and $E_p = -2$ volts have been found to give very satisfactory results, the electron current being .02 ampere, and K being equal to 0.10 for nitrogen and having approximately this value for air. The gauge equation may be put in the form,

$$P = K \frac{I+}{I-},$$

in which P is the pressure, K a constant depending upon the design

[48] O. E. Buckley, Procd. Nat. Acad., Vol. 2, p. 683, 1916.

of the tube, $I+$ the positive ion current, and $I-$ the electron current.

As it is necessary to know the value of $I-$, and since the emission from the filament is liable to vary somewhat with the kind of gas and its pressure, it will be found advantageous, if many readings are to be made, to place in the $I-$ circuit, the coils of a relay which is adjusted to close at a definite value of $I-$, and which, when closed, cuts in a shunt around the filament which will reduce its heating current.

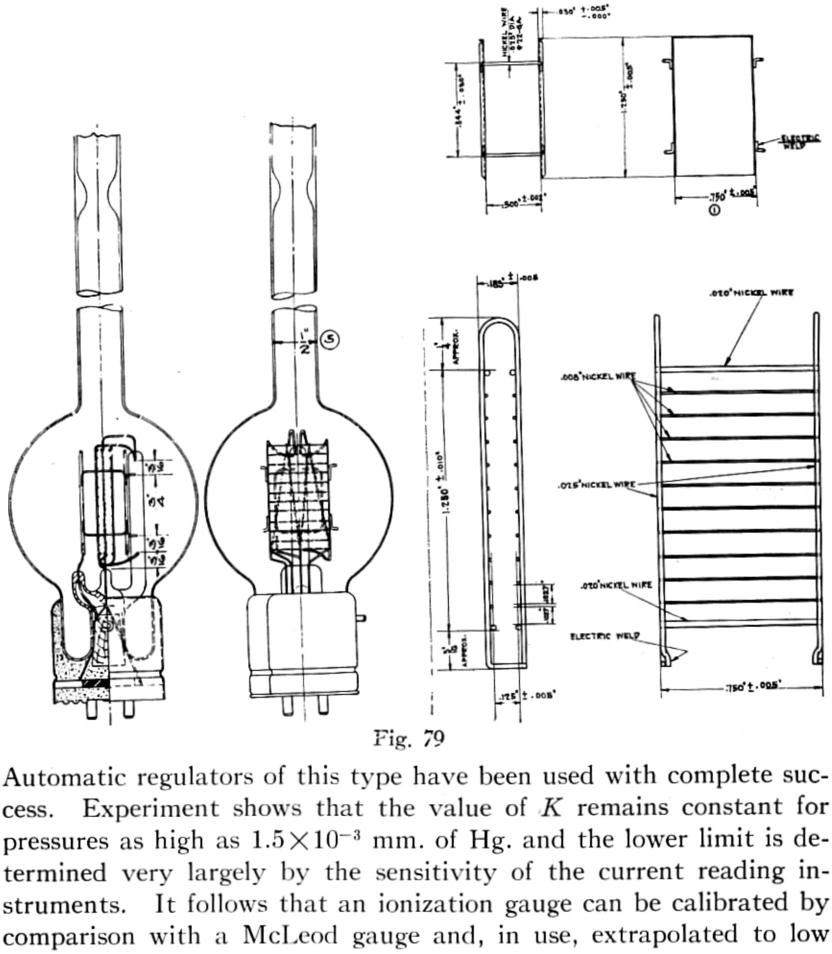

Fig. 79

Automatic regulators of this type have been used with complete success. Experiment shows that the value of K remains constant for pressures as high as 1.5×10^{-3} mm. of Hg. and the lower limit is determined very largely by the sensitivity of the current reading instruments. It follows that an ionization gauge can be calibrated by comparison with a McLeod gauge and, in use, extrapolated to low pressures.[49]

60. *Heterodyne Method of Generating Currents of Very Low Frequencies.* By impressing upon the grid of a detector tube two frequencies which differ by a very small amount (e.g., 99 and 100 cycles),

[49] Dushman, *Phys. Rev.*, Oct., 1920, p. 854.

it is possible to obtain from the output of the detector the difference frequency of one cycle per second. This low frequency may be readily separated by means of a filter. It is apparent, however, that to maintain this difference frequency constant requires that the input frequencies be held within a very narrow range of variation.

61. *Thermionic Valve as a High Tension Switch.* If the plate circuit of a valve is inserted in a high tension circuit, the flow of current in the circuit may readily be stopped by cutting off the filament heating supply, thus making unnecessary the breaking of any contacts in the high tension circuit. In case the transmission of current in both directions is necessary, two valves may be used.

62. *Devices Employing Secondary Emission.* As pointed out in Sec. 9, the grid current in a three-element tube shows a negative resistance characteristic for a certain range of voltage, and various uses of this fact have been pointed out.[50]

63. *Electron Tube Oscillograph.* A special type of thermionic tube designed for oscillographic uses is of great importance as a laboratory instrument. These tubes, using the hot filament as a source of electrons, have certain marked advantages over the Braun tube with its gaseous discharge.[51] One of the very successful thermionic oscillographs has the following properties: anode potential 300–400 volts, sharp focus of electron beam, sensitivity of 1 mm. per volt between deflection plates and 1 mm. per ampere-turn when using magnetic deflection. Photographic recording is possible with relatively short exposures by using suitable fluorescent material.

[49] Dushman, *Phys. Rev.*, Oct., 1920, p. 854.
[50] See footnote 21.
[51] See J. B. Johnson, *J. of Opt. Soc. of Amer.*, Sept., 1922, or *Bell System Technical Journal*, Nov., 1922.