NOTES ON ELECTRONICS

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VALVES

THE THERMIONIC VALVE

In 1884 Edison discovered that an electric current flowed between the hot filament of an electric lamp and any other conductor maintained positive with respect to the filament and contained within the evacuated envelope. It was Fleming who, in 1904, after the discovery of the electron by Sir J.J.Thomson, experimented with this first "thermionic valve" and discovered that the current was actually a flow of electrons.

THE DIODE

Many advances have been made since the experiments of Fleming, but the essential features of the valve remain unchanged. The modern equivalent of Fleming's original valve is called the DIODE, because it possesses two electrodes, a CATHODE and an ANODE. The hot wire emitting the electrons is the cathode and the conductor collecting them is the anode, these electrodes being contained in an evacuated glass envelope.

The cathode is constructed from tungsten containing a very small amount of thorium oxide. The addition of thorium oxide has been found to produce not only a change in the structure of the tungsten, giving it greater strength, but also an increased power of emitting electrons. It is beleived that the thorium oxide decomposes to give a surface layer of thorium, and it is this thorium layer that is the electron emitter and not the tungsten. Other oxides, including those of strontium, barium, and calcium, are very good emitters of electrons at red heat, and these are more often used in the construction of the cathode, particularly as they do not have to be heated to so high a temperature as "tungsten" in order to emit electrons freely. For this reason they are known as "dull" emitters and "tungsten" cathodes as "bright" emitters. The latter occur commonly only in large transmitting valves.

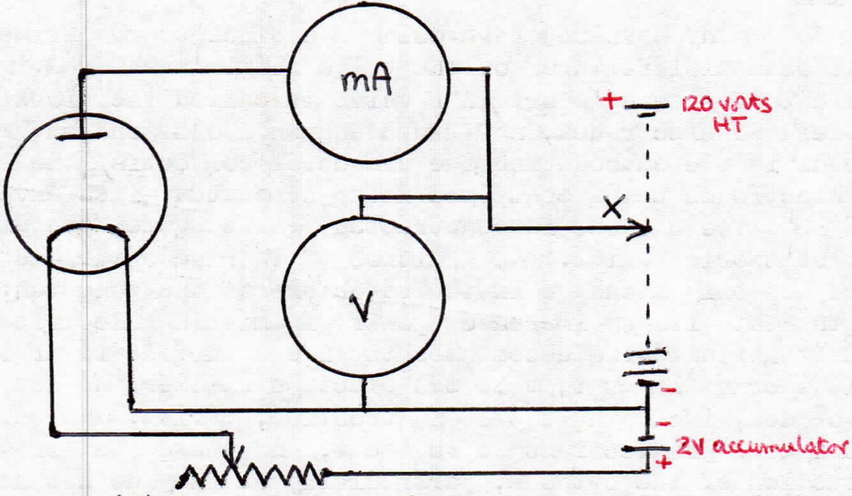
The cathode is sometimes heated by passing a current through it from an accumulator or dry battery, a valve heated in this way being known as a directly heated valve.

In modern valves it is usually required to heat the cathode by means of an alternating current and, since the passage of such a current through the cathode itself would cause variations in the cathode emission, this current is passed through a filament mounted near to, but insulated from, the cathode so that as the filament becomes heated so does the cathode. This type of valve is known as an indirectly heated valve, and the cathode in it normally takes the form of a tube surrounding the filament. The anode is made of nickel or molybdenum, since these, of the various metals which could be used, have the least tendency to occlude gases within them which would gradually spoil the vacuum of the valve. The anode is often in the shape of a cylinder surrounding the cathode assembly.

The emission of electrons from a hot wire is very similarto the evaporation of a liquid from its surface. If the surface area is increased the rate of emission increases, and if the temperature is increased the emission increases rapidly. Also, as a liquid will evaporate more rapidly if the external pressure on its surface is decreased, in the same way does electron emission froma hot wire increase with decreasing external pressure. The cathode emission may be kept at a high value by enclosing the electrode assembly in an envelope the interior of which is at a pressure of about 10^{-5} mm. of mercury. By increasing the temperature of the cathode, the emission is increased, but if this is carried too far the cathode disintegrates. As in electric lamp bulbs, a fairly high degree of vacuum and the exclusion of oxygen is needed, anyway, to avoid oxidation of the material of the cathode.

CHARACTERISTICS OF THE DIODE

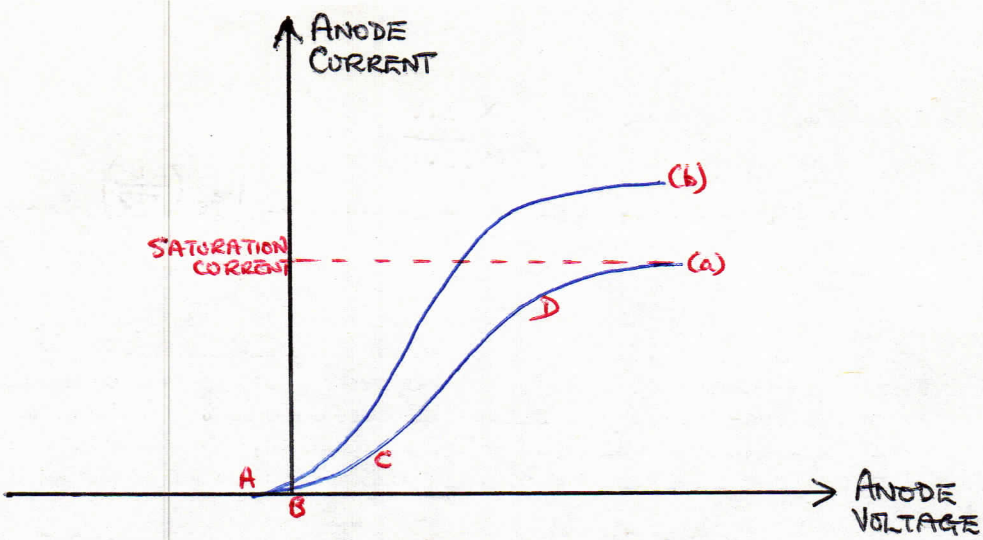
If a diode is connected up as shown below, by placing X in various tappings on the battery, a graph can be drawn of the current flowing through the valve against the voltage between the cathode and anode, which is causing this current to flow.



The graph (a) is called the anode characteristic of the diode and is the graph of anode current against anode potential (i.e.) the potential difference between the anode and the cathode.

The space between the anode and the cathode contains swarms of electrons, and these are more dense near the cathode. Now these electrons constitute what is known as a space charge which tends to repel electrons coming towards it. There is, therefore, in the neighbourhood of the cathode, a fairly strong force tending to repel electrons passing from cathode to anode, a force which in fact causes some of the electrons to return to the cathode again. When the anode is at a low potential with respect to the cathode, only those electrons which are emitted with fairly high velocities will be able to traverse the cathode-to-anode space and be collected by the anode as anode current. As the potential of the anode increases, however, more electrons will be enabled to traverse this space. Eventually a potential of the anode will be reached at which all the electrins emitted from the cathode are able to travel to the anode and be collected, and when this state has been reached the maximum anode current possible, for emission from the cathode at that temperature, has been reached. This si known as the saturation current of the valve, and it can only be increased by increasing the temperature of the cathode. The graph (b) shows the characteristic when the temperature of the cathode has been increased by increasing the current through it.

Consider graph (a). The portion BC of the curve shows the effect of space-charge in reducing the flow of electrons when only a small anode potential exists, whilst the portion CD shows the increase in anode potential overcoming the space charge. At D the curve flattens out horizontally as the saturation current of the valve is reached.



Notice the presence of the very small current represented by B, when the anode voltage is zero. This is the result of the energy given to the electrons during the thermionic emission.

Since it is possible for electrons to flow through the valve only from the cathode to the anode the valve will, in effect, appear as a fairly low resistance path to current flowing from cathode to anode, but as a very high resistance path to current flowing in the other direction.

This is a very important property of the diode which is used frequently in rectification and detection circuits.

RICHARDSON'S LAW

There are two laws of interest concerning the diode. The first is Richardson's Law, which gives a relationship between the electron emission and the temperature of the emitter, the cathode. Richardson deduced from pure thermodynamical reasoning that the relationship is of the form

$$i = KT^2 e^{-\epsilon\phi/kT}$$

where i is the anode current, K a constant, T the absolute temperature of the cathode, ϵ the electronic charge, ϕ a potential diff. constant, and k is Boltzmann's constant. The product ϕ is a quantity of energy, and if ϕ is in volts, will be so many electron volts (ev). If we take logarithms across in Richardson's equation above, we obtain

$$\log_e (1/T^2) \propto 1/T$$

Thus, a graph of $\log_e(1/T^2)$ against 1/T roughly confirms the law if the graph is a straight line. It is not easy to measure the temperature of the cathode, but it is easily shown that T^2 is approx. proportional to $\sqrt{I.V}$ where I is the filament current and V is the filament voltage.

The rate at which energy is supplied to the filament is proportional to I.V. But the rate at which energy is radiated is, by Stefan's law, proportional to T^4. (If T is very much larger than the temperature of the surroundings the heat received back from the surroundings may be neglected).

Thus approximately $T^4 \propto I.V$

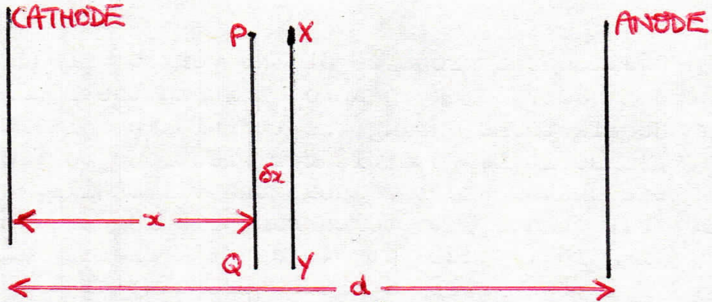
$$T^2 \propto \sqrt{I.V}$$

To verify the law, a graph is plotted of $\log_e\left(\frac{i}{\sqrt{IV}}\right)$ against $\frac{1}{\sqrt[4]{IV}}$

3/2 POWER LAW

The second law of the diode gives the relation between the anode current and the anode voltage for the curved part of the characteristic. It is known as the three-halves power law and corresponds to Ohm's Law.

To make the deduction of the law simpler, consider the cathode and the anode asstwo parallel plates of unit cross-sectional area at a distance d apart.



Consider a section of thickness δx situated between the electrodes and distant x from the cathode. Let n electrons be the number contained in unit volume of the section and let m be the mass of the electron, ϵ its charge and v its velocity when traversing the section, this being assumed the same for all electrons. Let i be the current flowing across the section, then

$$i = n\epsilon v$$

$$\epsilon V = \tfrac{1}{2}mv^2$$

where V is the potential at the surface PQ

Thus $$n = i\sqrt{\frac{m}{2\epsilon^3 V}}$$

Across PQ the electric field intensity is $E_1 = -dV/dx$ and this, since the medium is air, must be the total normal imduction entering the section.

Let the potential at the surface XY be $V + \delta V$

Across XY the electric field intensity is $E_2 = -\frac{d}{dx}(V + \delta V)$

$$= -\frac{\partial}{\partial x}\left(V + \frac{dV}{dx}\cdot\delta x\right)$$

$$= -\frac{\partial V}{\partial x} - \frac{\partial^2 V}{\partial x^2}\cdot\delta x$$

and this is the total normal induction leaving the section.

Thusthe total normal induction ending in the section must be

$$E_2 - E_1 = -\frac{\partial^2 V}{\partial x^2}\cdot\delta x$$

Now by Gauss' theorem the total normal induction over a closed surface is 4π x (the total charge within the surface). Now the total number of electrons in the section is $n\delta x$ and the total charge present is therefore $-\epsilon n\delta x$

Thus $$-\frac{\partial^2 V}{\partial x^2}\delta x = -4\pi\epsilon n\,\delta x$$

$$\frac{\partial^2 V}{\partial x^2} = 4\pi n e$$

$$\therefore \qquad = 4\pi i\sqrt{\frac{m}{2e}}\,V^{-1/2}$$

Integrating, $$2\frac{dV}{dx}\cdot\frac{d^2V}{dx^2} = 8\pi i\sqrt{\frac{m}{2e}}\,V^{-1/2}\,\frac{dV}{dx}$$

$$\left(\frac{\partial V}{\partial x}\right)^2 = 16\pi i\sqrt{\frac{m}{2e}}\,V^{1/2} + \text{const.}$$

$$\frac{dV}{\partial x} = 0 \text{ when } V=0, \quad \therefore \text{ const} = 0$$

$$\therefore \quad \frac{dV}{dx} = \sqrt{16\pi i\sqrt{\frac{m}{2e}}\,V^{1/2}}$$

$$\text{or} \quad \int_0^{\mathcal{V}} V^{-1/4}\,dV = \sqrt{16\pi i\sqrt{\frac{m}{2e}}}\int_0^d dx$$

$\mathcal{V}$ = potential diffce. between cathode and anode.

$$\therefore \quad \frac{4}{3}\mathcal{V}^{3/4} = \sqrt{16\pi i\sqrt{\frac{m}{2e}}}\; d$$

$$\therefore \quad i = \frac{\mathcal{V}^{3/2}}{9\pi \partial^2}\sqrt{\frac{2e}{m}}$$

$$\underline{\underline{i \propto \mathcal{V}^{3/2}}}$$

This theory is not quite accurate, mainly because we have assumed all the electrons to travel with the same velocity.

Now the current through the diode is controlled almost entirely by the space charge, so that we can alter the shape of the electrodes from the simple parallel plates without greatly altering the above theory. This means that in all diodes constructed in this manner, high voltages will be needed in order to produce currents which are only of the order of milliamps, for substituting amps and volts for e.s.u. in the equation (2) above, we obtain

$$i\,(\text{amps}) = \frac{\mathcal{V}^{3/2}(\text{volts})}{d^2} \times 2.33 \times 10^{-6}$$

Thus for an anode potential of 100 volts the current through the diode will be only 2.33 mA for each sq,cm. of cathode and anode, assuming d to be 1 cm., which is a reasonable value. If the diode is required to carry a high current something must be done to decrease the effect of the space charge. This is easily effected by introducing positive ions of a gas such as argon which, being heavier than the electrons, will have correspondingly slower speeds, remaining longer therefore near the cathode and reducing the space charge in correspondence.

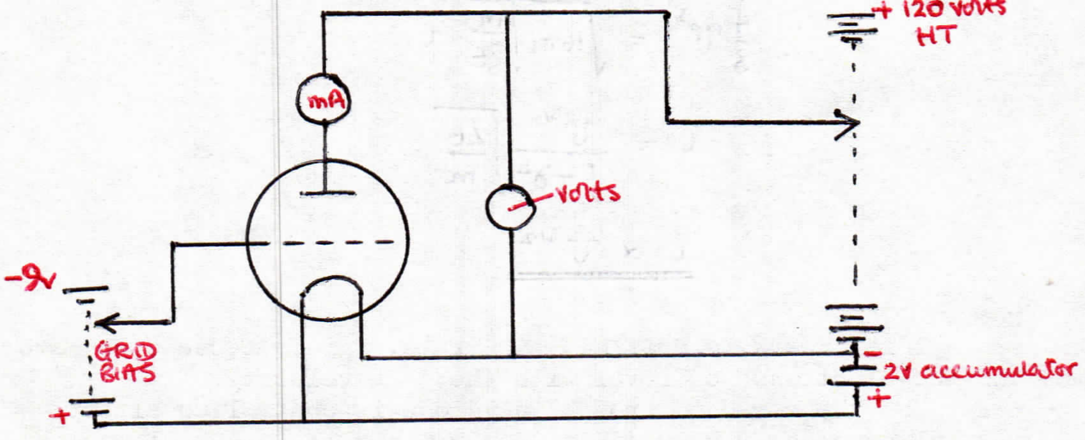
These gas-filled diodes are often used for the rectification of AC when a considerable current is required.

THE TRIODE

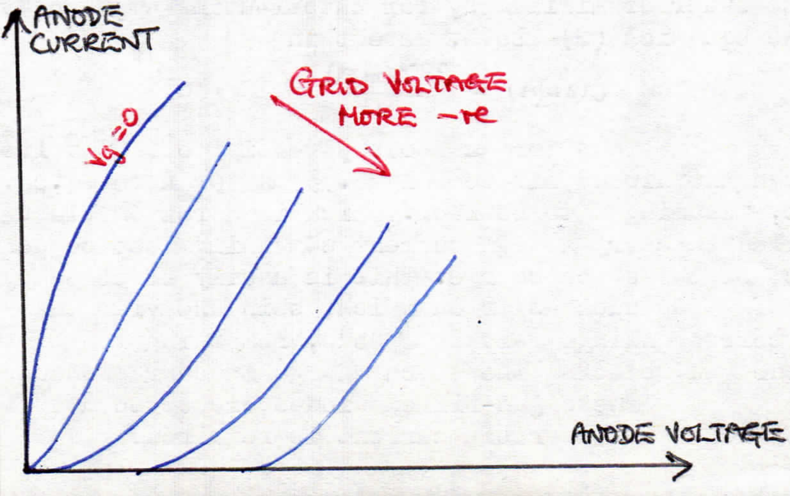
The triode valve is similar in construction to the diode, but a cylindrical wire mesh, called a GRID, is inserted between the cathode and the anode. The effect of this open mesh is that it allows electrons to pass through it, though if its potential is different from that of the cathode it exerts a force on the electrons exactly similar to that exerted by the space charge. The effect of making the grid positive with respect to the cathode is therefore to reduce the effect of the space charge and hence to increase the anode current. Similarly, if the potential of the grid is negative with respect to the cathode it will increase the effect of the space charge and decrease the anode current.

CHARACTERISTICS OF THE TRIODE

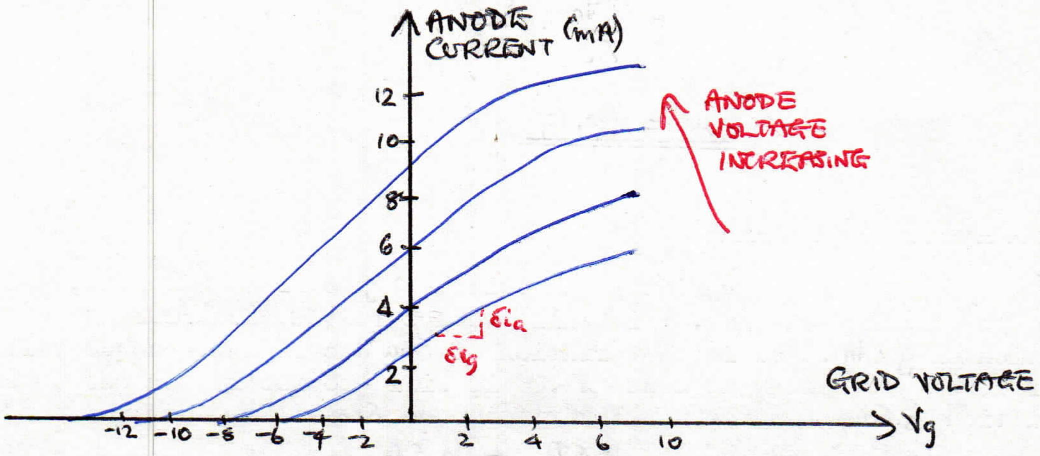
Two sets of characteristics are usually drawn for the triode: the anode characteristics, which are graphs of the anode current against the anode voltage for fixed values of the grid voltage, and the mutual characteristics, which are graphs of the anode current against the grid voltage for fixed values of the anode voltage. The curcuit shown below is used for finding the characteristics.



With fixed values of the grid potential, graphs are drawn of the variation in anode current as the anode voltage is changed. These anode characteristics are shown below:



Again, with fixed values of anode potential, graphs are drawn of the variation of anode current with grid potential. These are the mutual characteristics and are shown below:



These two sets of characteristics are called the static characteristics of the valve. It can be seen from these two sets of curves that a change in potential on the grid produces a far greater change in anode current than the same change in potential of the anode. The grid is in fact practically the sole controller of the current going to the anode. It will be noticed that in both sets of curves there is an appreciable portion of each that is straight. It is on this straight portion of the characteristic that the valve is normally operated.

CONSTANTS OF THE TRIODE

Consider one of the mutual characteristics. The lowest part of the curve follows the three-halves power law, the curve then becoming straight until it finally bends over, becoming horizontal to the axis as the saturation value of the anode current is approached. Consider the straight portion of the mutual characteristic. The ratio of a small change produced in the anode current to the small change in grid potential producing it, the anode potential remaining constant, is called the mutual conductance of the valve. Thus if δi_a is the small variation in i_a produced as a result of the small variation δV_g in V_g, then the mutual conductance is given by $\delta i_a/\delta V_g$. This is usually denoted by g_m and is expressed in mA per volt.

Now consider the straight portion of the anode characteristic. A small variation in V_a of δV_a produces in i_a a small variation δi_a, the grid potential remaining constant, and the ratio $\delta V_a/\delta i_a$ is called the differential resistance of the valve, and is denoted by ρ. Notice that this is the resistance of the valve to variations in current only and for this reason it is often called the AC Resistance of the valve. The resistance offered to the valve to DC is not constant, but varies all along the characteristic, whereas the differential resistance remains constant along the straight part of the characteristic.

We have already said that a variation in voltage on the grid of the triode produces a far greater variation in the anode current than the same variation in anode voltage. The ratio of the variation of anode voltage to the variation in grid voltage which would give the same variation in anode current is called the <u>amplification factor</u> of the valve and is denoted by μ .

Thus
$$\mu = \delta V_a / \delta V_g$$
$$= \frac{\delta V_a}{\delta i_a} \cdot \frac{\delta i_a}{\delta V_g}$$
$$\underline{\underline{\mu = \rho . g}}$$

THE EQUATION OF THE TRIODE

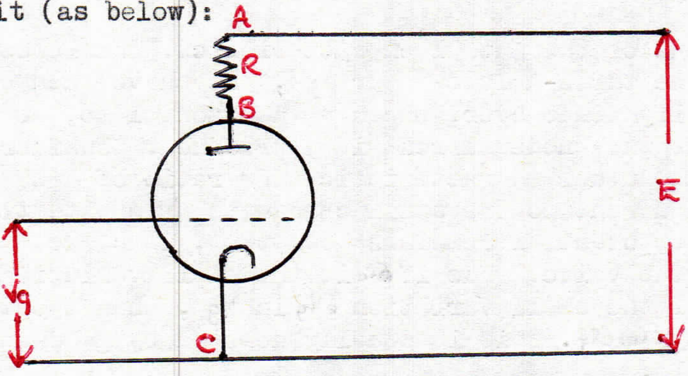
Let a variation of voltage δV_g occur on the grid, the anode voltage remaining constant. This will produce in the anode current a variation of $g . \delta V_g$. Now let a variation of δV_a occur in the anode voltage, the grid voltage remaining constant. This will prodice in the anode current a variation $\frac{1}{\rho} . \delta V_a$. Let the total variation be δi_a

Then
$$\delta i_a = \frac{1}{\rho}\delta V_a + g\,\delta V_g$$
$$= \underline{\underline{\frac{1}{\rho}(\delta V_a + \mu \delta V_g)}}$$

This is the equation of the triode, and represents the variation that occurs in the anode current for simultaneous variation in grid voltage and anode voltage.

THE TRIODE AS AN AMPLIFIER

Now let us consider the effect of a resistance in the anode circuit (as below):



Let the steady anode current which is flowing be i_a when the grid voltage is V_g, then:
$$V_a = E - R i_a$$

where V_a is the voltage of the anode and E is the voltage of the H.T. supply. Differentiation of this equation gives
$$\delta V_a = -R\,\delta i_a \quad (3)$$

Now let a variation of voltage δV_g occur on the grid, with a consequent variation of δi_a in the anode current; then for anode load, R,
$$\delta V_R = R\,\delta i_a \quad (4)$$

where δV_R is the variation produced in the voltage across R.

From these expressions it can be seen that the voltage variation between A and B, i.e. across the anode load, is the same as that between B and C, i.e. across the valve. That across the anode load acts from B to A (conventional direction) but that across the valve from B to C, since they are opposite in sign but of the same magnitude. Thus, as far as the variations are concerned, the anode load and the valve appear to be in parallel, the points A and C being at the same potential and the H.T. a short circuit. But notice that this is only so for the variations which are occurring in the curcuit.

Consider the equation of the triode:

$$\delta i_a = \frac{1}{\rho}(\delta V_a + \mu \delta V_g)$$

Combining this with (4) we obtain

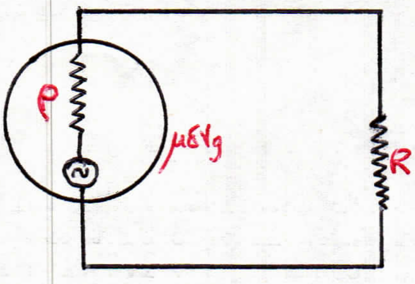
$$\frac{\delta V_R}{R} = \frac{1}{\rho}(-\delta V_R + \mu \delta V_g)$$

$$\frac{\delta V_R}{\delta V_g} = \frac{\mu R}{R+\rho}$$

and this is the voltage amplification produced by the circuit. It is the ratio of the varying voltage between A and B (or between B and C) to the varying voltage on the grid producing it.

EQUIVALENT CIRCUIT OF THE TRIODE

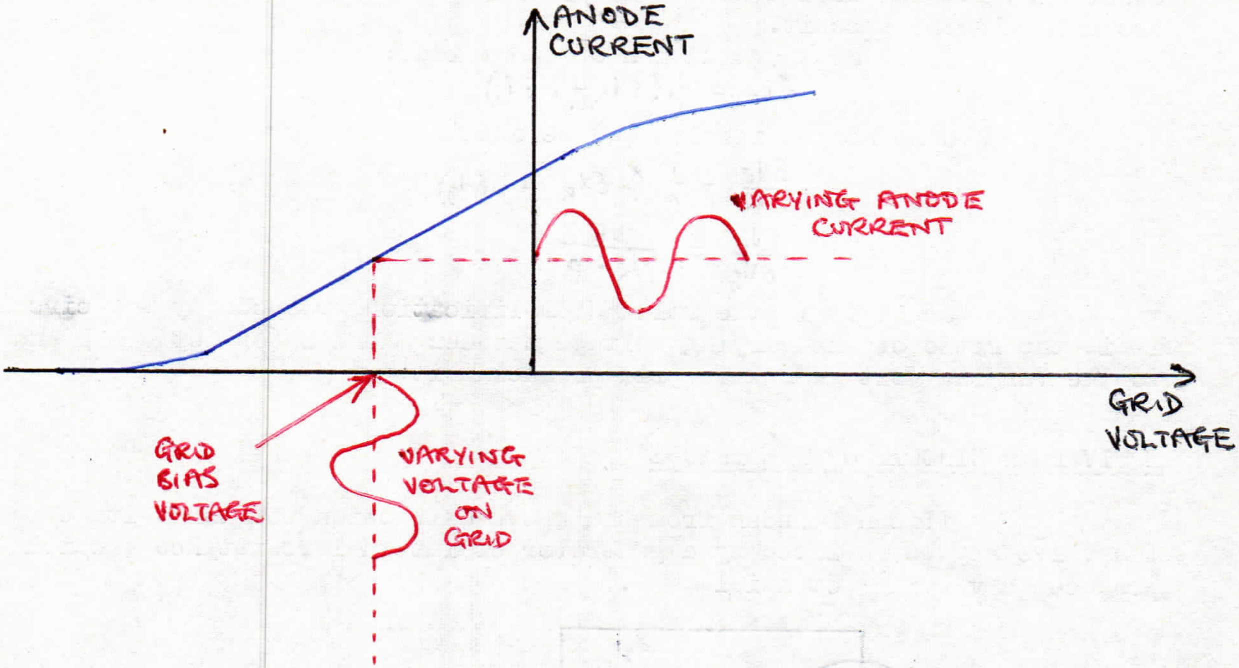
It can be seen from the above expression for the voltage that the valve may be replaced by a generator of internal resistance which produces a varying potential .



GRID BIAS

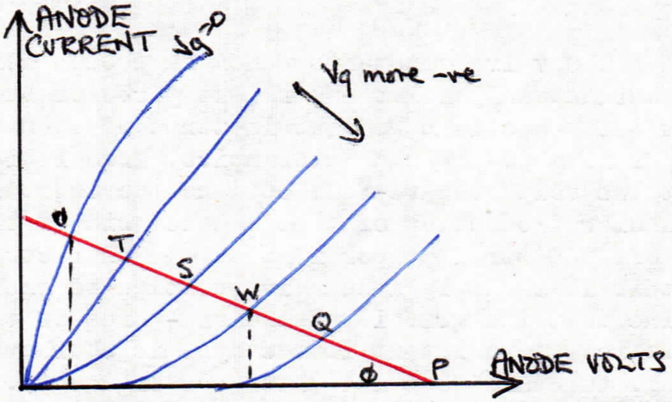
The valve constants which have been defined for the triode have been defined only for the straight parts of the characteristics. This means that the deductions we make in terms of them are true only for the straight portions of the characteristics. Also it is clear from the diagram below that the voltage wave-form obtained across the anode load will only be a faithful reproduction of that on the grid if the grid variations do not swing off the straight portions of the characteristics. The method of ensuring this is to apply a negative voltage to the grid of the valve of such a value that the grid is at the mid-point of the straight part of the characteristic. (Actually it is the dynamic characteristic that we should be considering, but this does not alter the argument).

The voltage applied to the grid in order to do this is the grid bias. The point X represents the grid when no variations are applied to it. When variations are applied their amplitude must be such that they do not swing off the straight portion of the characteristic, nor swing into that region which makes the grid positive with respect to the cathode and so cause grid current to flow. If grid current flows the effect is the same as placing a resistance across the grid circuit, since the valve between grid and cathode is now conducting current, and the waveform on the grid will be distorted owing to the damping introduced. The distortion produced by the grid voltage swinging too negative, into the lower curved portion of the characteristic, is called anode bend distortion, that due to grid current being called grid current distortion.



THE LOAD LINE AND DYNAMIC CHARACTERISTIC

The characteristics so far described for a valve are called the static characteristics and have not taken into account the circuit in which the valve may be operating. Let us consider a valve with resistive load, R, in the anode lead. A set of static anode characteristics for the valve are shown below:



Let the point P be the point at which anode current i_a is zero, then there will be under these conditions an anode potential E, where E is the H.T. supply potential, and a grid voltage V_g (which will be negative of course). Let the grid voltage be varied so that an anode current i_a flows. This current will flow through the anode load, R, causing a drop in potential across R of Ri_a. The anode voltage thus becomes $E - Ri_a$. Imagine the point

W on the graph represents these new conditions. If a straight line PW is drawn, let it cut the characteristics at Q, S, T, and U, as shown. Now from the graph it is clear that the ratio of the voltage drop across the anode load at any moment to the corresponding anode current is a constant, thus, using the letters on the graph,

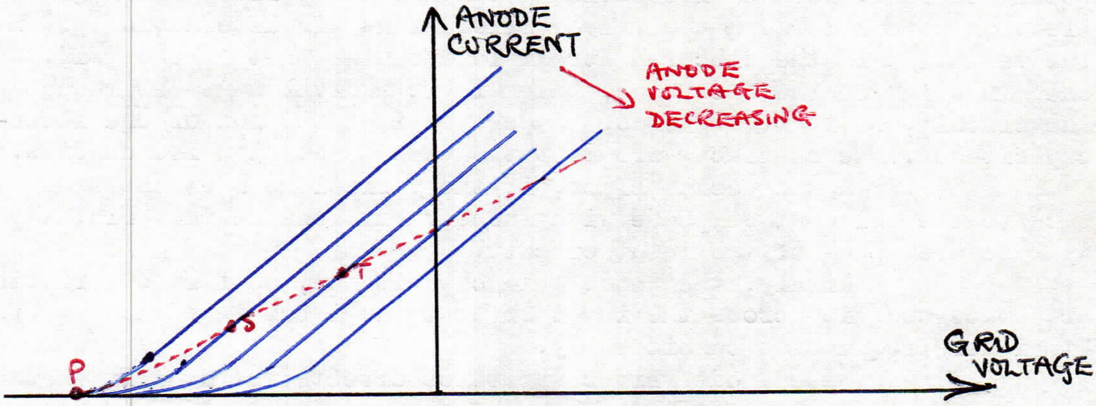
$$\frac{Ri_a}{i_a} = \frac{BP}{WB}$$

$$R = \cot\phi$$

Now since R is constant, so is Ø, so that as the grid voltage swings between W and U the corresponding values of anode voltage and anode current are represented by the appropriate points on the line PQWSTU. Such a line is called a <u>load line</u> and is characteristic of the circuit as a whole and not of the valve alone.

Now when a valve is used as an amplifier, the grid voltage is adjusted to some predetermined value. i.e. the grid bias voltage. As the grid swings about this point owing to an oscillatory input voltage applied to it, the resulting swing of anode current will be determined by the load line. It is easy to see that changes in grid voltage can only produce equal changes in the anode current if the load line makes equal intercepts with all the characteristics. In an amplifier circuit, then, for undistorted output, the arrangement must be such that the load line does make equal intercepts with all the characteristics.

Let us now consider a set of mutual characteristics for the valve. Proceeding as before when the valve is in the resistive-load circuit, the grid bias is adjusted to a negative value sufficient to reduce the anode current to zero, when the anode voltage will be that of the H.T. supply,E, and represented on the graph by a point P (see below)



Now if the grid voltage is adjusted so such a value that an anode current i_a flows, then there will be a drop of potential $R.i_a$ across R and the anode voltage will become $E - Ri_a$. Let this be represented by the point S. Reducing the grid voltage further causes a further increase in i_a but a drop in V_a. Let this be represented by the point T. The join of the points P, S, and T represents the mutual characteristic when the valve is in this circuit. This characteristic is called the dynamic characteristic. Notice that the dynamic characteristic will be a stright line only if the mutual characteristics are equally spaced parallel lines.

It is the dynamic characteristic which must be considered when, for example, investigating the circuit as an amplifier, and not the static characteristic of the valve alone.

SECONDARY EMISSION

When the electrons emitted by the cathode of a triode valve impinge on the anode or the grid, they may cause the emission of further electrons from these electrodes. This further emission is known as secondary emission. Now the quantity of the secondary emission may well exceed that of the primary emission from the cathode, but, since most of the electrons emitted in this way fall back into the electrode, their effect is not always observed. If however the grid is at a high potential, so that the emission is correspondingly high, the secondary electrons may pass to the anode and cause undesirable variations in the anode current. This is a defect of the triode which is very difficult to overcome.

INTER-ELECTRODE CAPACITANCE

It is clear that the various electrodes in the triode will act as small condensers. There will be a certain capacitance between the cathode and the grid, between the cathode and the anode, and between the grid and the anode. Now the existence of these capacitances produces various undesirable effects, the worst, perhaps, being the electrical path between anode and grid caused by the grid to anode capacitance.

In the first place, variations on the anode are enabled to be fed back on to the grid, where, if they arrive in phase with the grid oscillations, will reinforce the grid variations so that they build up more and more. The valve is then oscillating. Furthermore, these inter-electrode capacitances are not constant while the valve is working. There is a certain value of grid to anode capacitance when the valve is conducting a steady current. Let an alternating potential be applied to the grid. The electron stream through the valve varies with this alternating potential, but the variation in the electron stream lags behind that of the grid, owing to the "inertia" of the electrons, and this is equivalent to an inductance in the circuit, or in other words, a decrease in the value of the inter-electrode capacitance. These effects are most troublesome at high frequencies.

In the second place, if the variations from the anode are fed back to the grid out of phase with those variations on the grid, the effect will be a damping of the input circuit.

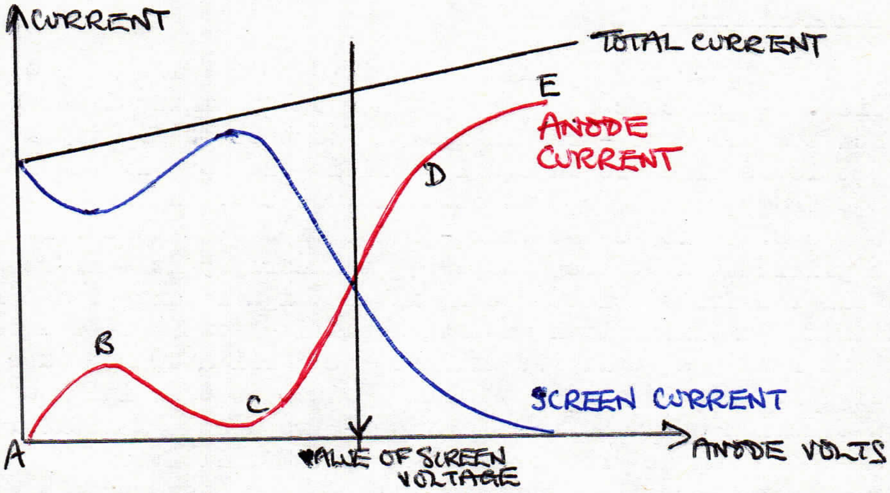
Thirdly, the anode/grid capacitance, as far as variations are concerned, is across the input so that the input impedance is affected, at higher frequencies considerably.

These anode/grid capacitance effects are usually known as the Miller Effect. It is to overcome the effects of inter-electrode capacitances and secondary emission that the various screen valves, to be described, have been introduced.

THE TETRODE

The tetrode is the simplest attempt to overcome the grid to anode capacitance of the triode. Another grid, similar in design to that of the triode, is interposed between that of the control grid and the anode. This second grid is called the <u>screen grid</u>. Its effect is easily understood. Consider the lines of electric force which are passing between the control grid and the anode in virtue of the fact that a difference of potential exists between them, the screen grid being unconnected. Now raise the screen grid to a potential higher than that of the anode. All the lines of force will now end on the screen, none of them reaching the anode. Now, if no lines of force pass between the control grid and the anode there can be no ~~potential~~

capacitance between them. If the potential of the screen is slightly less than that of the anode, most of the lines will terminate on the screen, although a few will reach the anode. The grid to anode capacitance now has a value, but it is considerably reduced, in fact negligible at all but the highest frequencies. The electrons, however, have considerable velocities on reaching the screen, and since this is in the form of an open mesh, are able to travel through, come under the influence of the anode field, and be collected by the anode. The screen grid valve is therefore similar to the triode but with the grid to anode capacitance much reduced. The introduction of this screen grid gives the tetrode characteristics quite different from those of the triode. The shape of the anode and screen characteristics is shown below.



The screen voltage and the grid voltage have been kept constant, while the anode voltage has been varied.

Consider the curve of anode current: this clearly falls into four main divisions. The part AB shows that the anode current increases with increase of anode voltage, until a point is reached, the point B, at which the electrons travelling to the anode impinge with sufficient velocity to cause secondary emission. The electrons thus emitted are attracted towards the screen, which is at a potential considerably higher than the anode. This continues with increasing effect until the point C is reached where the anode voltage is producing sufficient field to attract the electrons back to itself. From this point onwards increasing anode voltage produces increasing anode current in a manner similar to that of the triode.

The mutual characteristivs of the tetrode are very similar to those of the triode. The tetrode, then, can be used in place of the triode if the voltage on the screen is less than that on the anode. In practice a screen voltage about two-thirds that of the anode is generally used.

THE PENTODE

It can be seen on the diagram above that the anode characteristic of the tetrode is fairly straight over the portion CD but changes abruptly at C and D. The result of this will be that a variation in voltage on the grid will not produce a similar variation in anode current, when operating as an amplifier, except within the very narrow range of anode voltages over which the linear portion, CD, extends. It is to eliminate these sudden changes in the characteristic that a third grid is introduced between the screen grid of the tetrode and the anode. The new valve is called a pentode, and the grids moving outwards from the cathode are called the ~~screen grid,~~ control grid, the screen grid, and the suppressor grid. The suppressor grid is connected to the cathode, normally externally to the valve, and suppresses the secondary emission which would otherwise take place from the anode. The resulting anode characteristic for the pentode is not unlike that of the triode, and the pentode becomes a very useful valve for amplification purposes.

SOME WIRELESS CIRCUITS

SIMPLE AMPLIFICATION

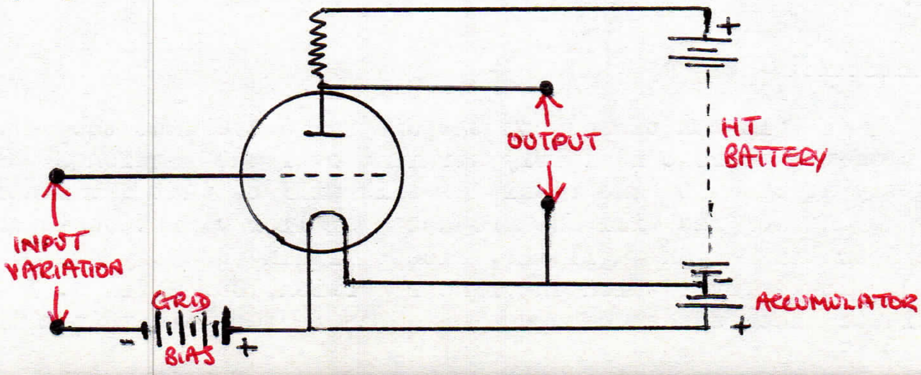
Generally speaking, amplification falls into one of two categories. We are concerned with either the amplification of modulation frequencies or of radio-frequencies. If we wish to amplify audio-frequencies then what is required is an equal amplification of all the frequencies in the range from about 20 c/s to about 16,000 c/s, and in some cases as high as 20,000 c/s. If it is the video-frequencies of a television signal, then equal amplification of frequencies up to nearly 5 Mc/s is required. In other words, all the frequencies present in the signal which is applied to the amplifier for amplification must be amplified to the same extent otherwise the output from the amplifier will not be a faithful reproduction of the input signal. This is one of the main points to bear in mind when considering the construction of an audio- or video- frequency amplifier.

When we are considering the amplification of radio-frequencies, however, we are normally concerned with the amplification of the modulated radio frequency which has been picked up by an aerial for application to a detector. In this case, a small band of frequencies, on either side of the carrier frequency, is being amplified, so that a radio-frequency amplifier will be designed for the reception of this band only. Before we consider the particular points in the design of an amplifier tor either audio-frequency or radio-frequency work, let us first consider the action of a triode as an amplifier.

We have seen above how variations of voltage on the grid of a triode produce large variations in the anode current through the valve, and that these variations passing through a resistance in the anode circuit produce across it voltage variations of greater amplitude than those on the grid. The expression for the voltage amplification produced by the valve was shown to be

$$\frac{\partial V_R}{\partial V_g} = \frac{\mu R}{R+\rho}$$

Now the circuit below represents the essentials of a one-stage amplifier employing a triode:



In general, more than one stage of amplification is needed, so that it is necessary to investigate the methods that are used for coupling the various stages together. Before doing this, let us notice that the input stage of the amplifier, i.e. the grid, requires maximum voltage swing. For the last stage of the amplifier, however, which is feeding a "current device", such as a loudspeaker, we are concerned with the maximum power that can be delivered. There is then this essential difference between the last stage of an amplifier and the previous stages, that the last stage is required to deliver power, the previous stages to deliver voltages. This is not the whole story, however, for although we require the maximum amplification that the circuit can give us, we do not want this amplification to be at the expense of a faithful reproduction of the wave-form to be amplified. In general, we have to bear two point in mind when designing an amplifier and coupling together the various stages of it, first of all to obtain a faithful reproduction of the signal to be amplified, and secondly to get the maximum amplification that we can, consistent with this fidelity.

The condition for maximum voltage amplification can be seen from the expression

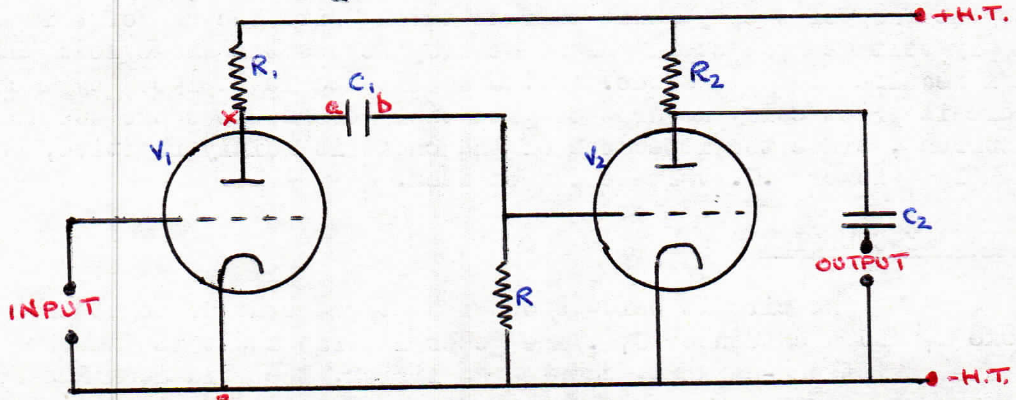
$$\frac{\delta V_R}{\delta V_g} = \frac{\mu R}{R+\rho}$$

to be when R is very large compared with ρ , when the voltage amplification approaches the amplification factor of the valve. But if the resistance of the anode load is made very large, the steady voltage developed across it by the steady anode current flowing through it will be very large, with a consequent difficulty in obtaining sufficient steady anode voltage to operate the valve satisfactorily. A mean has to be met, where the resistance of the anode load is large, but not so large that the steady voltage drop across it is too great. The optimum value for the resistance of the anode load is usually about three or four times that of the differential resistance of the valve.

As we have said, in order to get a greater amplification than that obtainable from one valve only, several valves may be connected together in cascade. We shall now discuss the various ways in which this can be done and the advantages to be drawn from any particular method.

RESISTANCE-CAPACITY COUPLING

In the circuit below it is desired to impress the voltage variations across the anode load R_1 of the first valve V_1 onto the grid of the second valve V_2 in order to obtain further amplification.



If the point x is connected to the grid of V_2 then the variations of voltage across R_1 are applied between the grid and cathode of V_2 , since the point 'y' is identical with the point 'z' as far as variations are concerned. But in addition to the variations of voltage the steady volts drop across R_1 , due to the steady anode current through it, is also applied to the grid of V_2 . Now this steady voltage would alter the bias on the grid voltage of V_2 (for simplicity the bias voltage has been omitted from the diagram), and this would introduce distortion since grid current would flow in V_2 owing to the positive potential on its grid. To prevent this the blocking condenser C_1 is introduced, its capacitance being such that the variations pass through it more or less unimpeded to the grid of V_2 , and the steady potential is unable to affect the grid. With C_1 alone, however, a positive charge would build up on the plate 'a' and a negative charge on the plate 'b' so that the valve V_2 would "cut off" and conduct no current. The grid leak R is connected between the grid and the H.T. as shown, so that the charge can leak away.

Of course the values of C_1 and R must be chosen to be such that the wave-form is not distorted, remembering that the action of such a capacity and resistance combination tends to cause asymmetry in the wave-form, a fact which will be made use of in detection. The values of C_1 and R will depend on the frequencies to be amplified, in other words, on whether the amplifier is to be a radio-frequency or audio-frequency amplifier. In this respect, other considerations need to be taken into account.

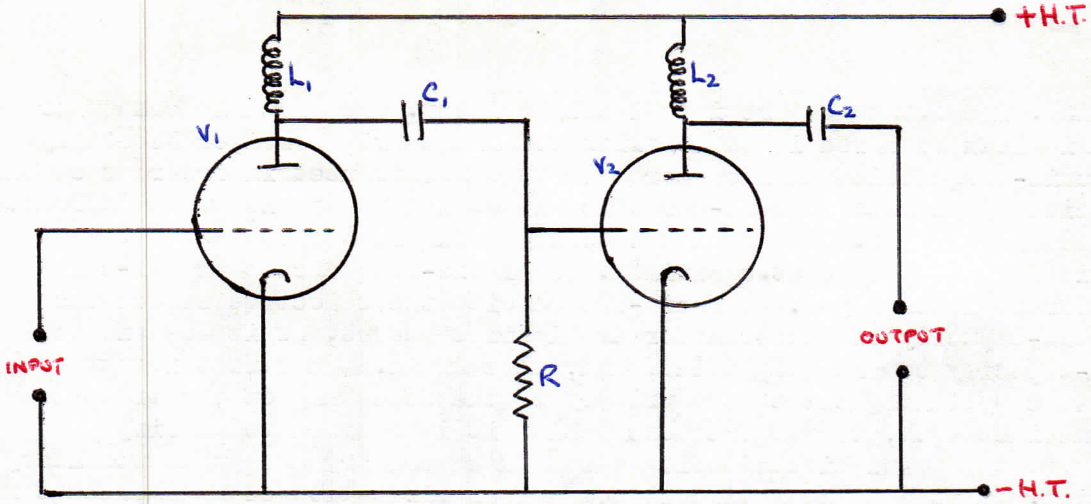
We have said that for audio-frequency amplification, faithful response is required over a range of audio-frequencies. Now the condenser C_1 , if its capacitance is large (about 0.1 μF) will offer nearly equal impedance to all the audio-frequencies across it, so that if the value of the resistance R is large compared with the impedance of C_1 , the amplification of the resistance-capacity coupled amplifier will be the same for all frequencies.

For radio-frequencies, however, this coupling is rarely used, because at the higher frequencies the impedance due to the self-capacitance of the resistance R and that due to the valve capacitances become comparable with the resistance, and of course vary with the frequency so that marked falling-off in amplification occurs as the frequency is increased. Another point regarding the radio-frequency amplification is that we are usually only concerned with the amplification of one frequency band and other means of coupling give a means of tuning to this particular frequency band with a consequent increase in the selectivity of the receiver in which it is used.

One last disadvantage of the resistance-capacity coupling lies in the voltage drop across the resistive anode load R_1 of the valve owing to the flow of steady anode current through it. Because of this the H.T. supply voltage must supply both the drop across the anode load and the potential required for the anode. If the resistance is replaced by a choke then there is practically no drop of potential across the choke due to the steady current, since the impedance of the choke is mainly reactive, and consequently a lower H.T. voltage can be used.

CHOKE-CAPACITY COUPLING

The circuit below shows two stages coupled together by means of a choke L_1 and a condenser C_1 . The general arrangement is the same as that of the resistance-capacity coupled amplifier, the grid leak R serving the same purpose as there. The values of C_1 and R are determined in the same way.

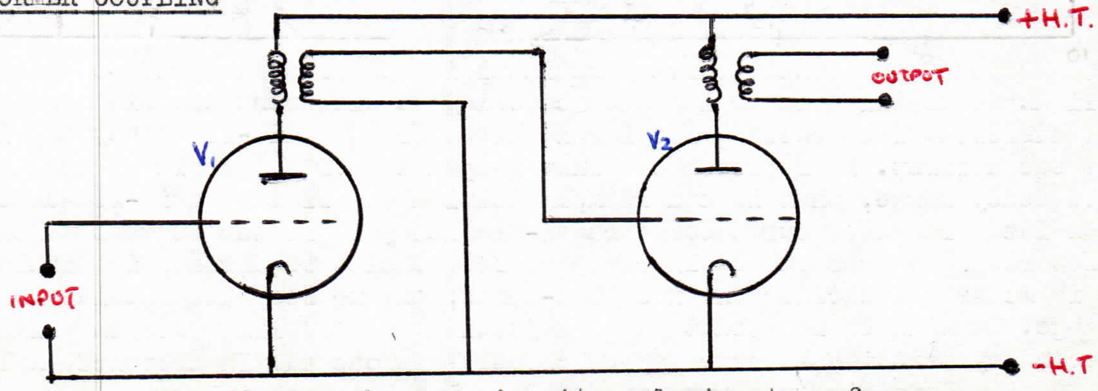


The value of L_1 will depend on the frequencies to be amplified. If an audio-frequency amplifier is required, then L_1 will be large (about 20 henries) in order that the anode current variations may produce sufficiently large voltage variations in it. In practice a choke of this inductance would have to be iron-cored. Now the presence of the iron core introduces a certain amount of distortion, due essentially to the hysteresis effects of the iron. The effect on the wave-form is to change it in a way very similar to that which would be effected by the superposition of the second harmonic of the fundamental. This distortion is therefore termed <u>second harmonic distortion</u>.

If the amplifier is to be used for radio-frequencies the value of the inductance required is much less and the choke may be air-cored, a point in its favour as second-harmonic distortion is not then produced. It is clear that the impedance of the anode load will vary with frequency so that unequal amplification of the different frequencies will occur. This is, in general, a disadvantage.

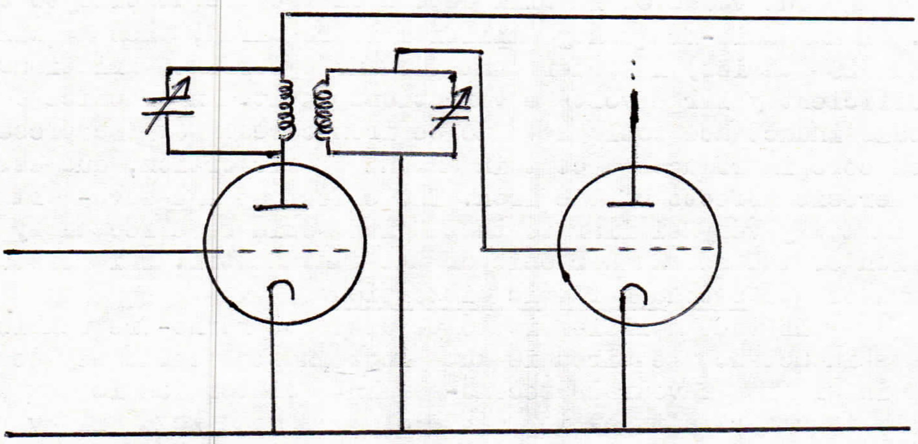
Apart from the variation of anode load impedance, the self-capacitance of the choke itself may form a parallel resonant circuit with its inductance at one particular frequency and give exceptionally good amplification at this frequency. This selective amplification can be put to good use in radio-frequency amplifiers where the amplification of one particular radio frequency is normally wanted. This "tuned choke coupling" is effected by putting a condenser across the choke, the capacitance of the condenser being such that resonance occurs at the desired frequency. The principle are the same as tuned transformer coupling and we will discuss them there.

TRANSFORMER COUPLING

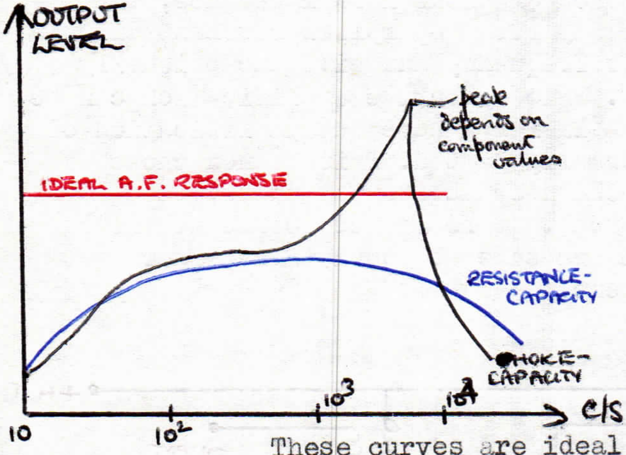


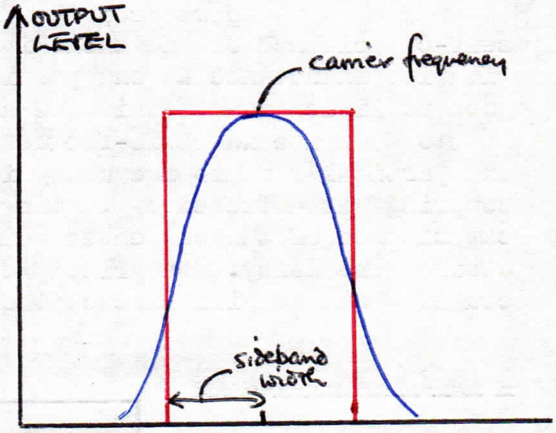
The diagram shows a circuit employing transformer coupling. Theadvantages are immediately evident. The blocking condenser and the grid leak required in the earlier couplings are no longer necessary. For audio-frequencies an iron-cored transformer is used in order to obtain sufficient impedance. Second-harmonic distortion is liable to be introduced as a result of this, and in high fidelity work great care has to be exercised to keep this at a minimum. For radio-frequencies an air-cored transformer is employed. At radio-frequencies the selective effect due to the self-capacity of the transformer windings occurs, as it does in the choke-capacity coupled amplifier, and, here again, the effect is put to advantage by tuning either the primary or the secondary of the transformer, or sometimes both, to the frequency which it is desired to amplify.

The circuit below shows tuned primary and tuned secondary coupling. It is a typical circuit for the amplification of a wireless carrier wave previous to detection.



Next, a series of response curves is drawn for variously coupled amplifiers.





These curves are ideal in so far as they do not show the slight peaks which occur in practice owing to different circuit resonances at different frequencies. The ideal curve for an audio-frequency amplifier is shown first. It represents a flat response over the whole of the audio-frequency range, that is equal amplification of all the audio-frequencies. The ideal response curve for a radio-frequency amplifier is that which gives flat response over the small range of frequencies required ; in wireless work this means the carrier and its side-bands, but no response outside this range. It will be noticed that by adjusting the coupling between primary and secondary this ideal curve may be closely approached. In practice an amplifier is designed to give response as near the ideal as possible consistent with cost.

POWER AMPLIFICATION

We will now calculate the condition for maximum amplification by a triode when it is the last stage of an amplifier. The maximum amplification will occur when there is maximum transference of power from the valve circuit to the loudspeaker (say) which is being driven. Using the same symbols as before, the power developed by the valve in the anode load is $R(\delta i_a)^2$

Now $R(\delta i_a)^2 = \mu^2(\delta V_g)^2 . R / (R+\rho)^2$

Since $\delta V_R = R.\delta i_a$

And $\frac{\delta V_R}{\delta V_g} = \frac{\mu R}{R+\rho}$

Let this power be W. $\frac{dW}{dR} = 0$ will give the value of R for which this power is a maximum.

Now $\frac{dW}{dR} = \mu^2(\delta V_g)^2 \left[\frac{(R+\rho)^2 - 2R(R+\rho)}{(R+\rho)^4} \right]$

When $\frac{dW}{dR} = 0, \quad (R+\rho)^2 = 2R(R+\rho)$

i.e. $\underline{R = \rho}$

The condition for maximum power to be developed in the external circuit, then, is that the value of R shall be the same as that of the differential resistance of the valve.

We have assumed in the above arguments that the anode load is purely resistive. The same results apply if this is not so, the anode load impedance taking the place of the resistance we have considered.

As we have said already, the circuit arrangement for maximum power delivery may not be the best arrangement for faithful reproduction of the signal to be amplified. It can be shown that the condition for maximum power and, at the same time, minimum distortion of the wave-form is that the impedance of the anode load should be twice the differential resistance of the valve. The maximum power output available with minimum distortion is, of course, less than that available if distortion of the wave-form is permitted.

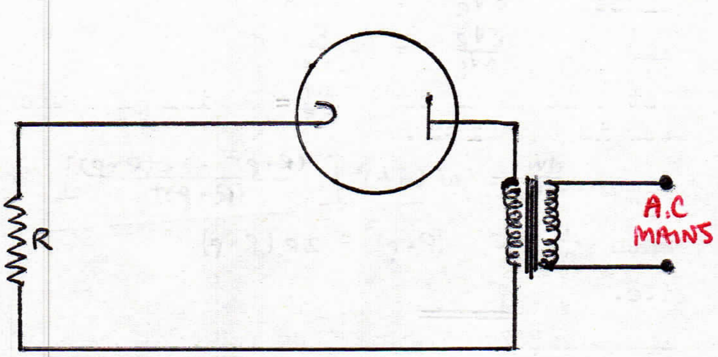
RECTIFICATION

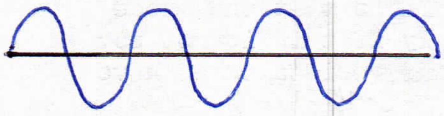
In a "battery" receiver the current required to heat the cathodes of the valves is obtained from an accumulator, the higher voltages for the anodes from a battery consisting of many dry cells in series, and the voltage required to bias the grids from a few dry cells in series. If the mains supply is D.C., this can be used directly, the required voltages being obtained by using resistances in series with the supply so that the voltage is dropped to the required values. Special valves are usually employed whose heaters, when connected in series, are of the correct resistance for direct connexion to the supply. If the supply is A.C. then it is necessary to convert this into a D.C. supply at the required voltage level by rectification. It is only necessary to rectify the H.T. supply to the valves since, by using indirectly heated valves, A.C. can be used to heat the filament, and, as will be seen later, grid bias can be obtained automatically.

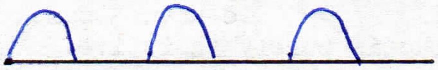
THE DIODE RECTIFIER

It has been seen that a diode permits the flow of current in one direction only. In actual fact when the cathode becomes positive with respect to the anode a slight reverse current does flow, so that the diode is not a perfect one-way conductor, although it is normally near enough so in practice. We shall consider it a perfect one-way conductor when discussing its applications.

The circuit below represents a half-wave rectifier:




(a)

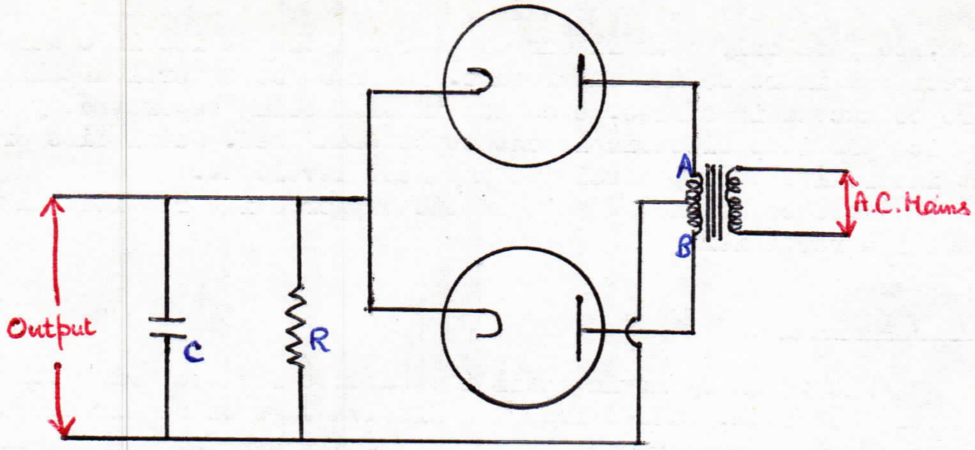

(b)

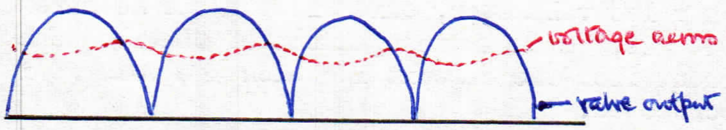
The waveform of the alternating mains input is shown in (a) andsince the diode will allow current to pass through it in one direction only, the waveform across the resistance R, produced by the half sinusoidal pulses of current through it, will be that shown in (b).

If connexions are made to the secondary winding of a transformer in the way shown on the next page, then, at any instant, the voltage between the centre tap and the point A is opposite in phase to that between the centre tap and point B. For instance, if the flow of current during one half-cycle is from A to B, then A is negative with respect to the centre tap and B is positive with respect to the centre tap. During the next half-cycle, this state of affairs is reversed.

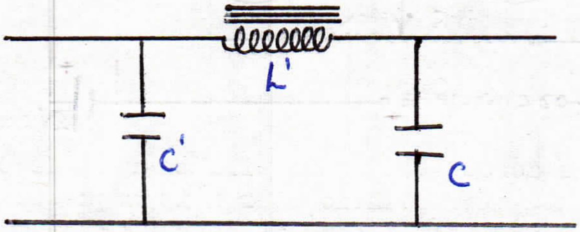
Thus, if we arrange two diodes as shown in the diagram, it can be seen that one of the diodes will pass current during one set of half-cycles and the other during the reverse half-cycles. By this method we are able to obtain current in one direction only from both the halves of the alternating supply and not from one half only. The supply is being full-wave rectified, and the voltage waveform across the resistance is that shown in blue in the diagram. Notice that now the voltage across the secondary of the supply transformer, needed to give the same amplitude of rectified output, has been doubled. Now although the output voltage from this circuit is uni-directional, it is not a steady D.C. voltage which can be applied to the anode of a valve. By taking this voltage across a reservoir condenser, C, the output becomes one at a constant D.C. level but with a ripple imposed on it at twice the frequency of the supply.

The effect if brought about because the capacitance of the condenser C is such that the time-constant CR is very long, and consequently





the condenser is unable to follow the variations of the waveform. The result is a waveform of the shape shown above. There is a ripple on this waveform, as is clearly seen, and this is eliminated by using the combination of C' and L', which is acting as a filter circuit to this low-frequency ripple. L' offers little impedance to the D.C. component but a high impedance to the ripple; C' offers a low impedance path to any of the ripple which does pass through L'. The output is now a steady D.C. and can be used as the H.T. supply to the valves of any other circuit. The elimination of the ripple by the use of C' and L' is called "smoothing", and if the smoothing is insufficient a hum will be developed in any circuit to which this H.T. is connected, the frequency of the hum being twice that of the supply.



Filter circuit for removing hum

THE METAL RECTIFIER

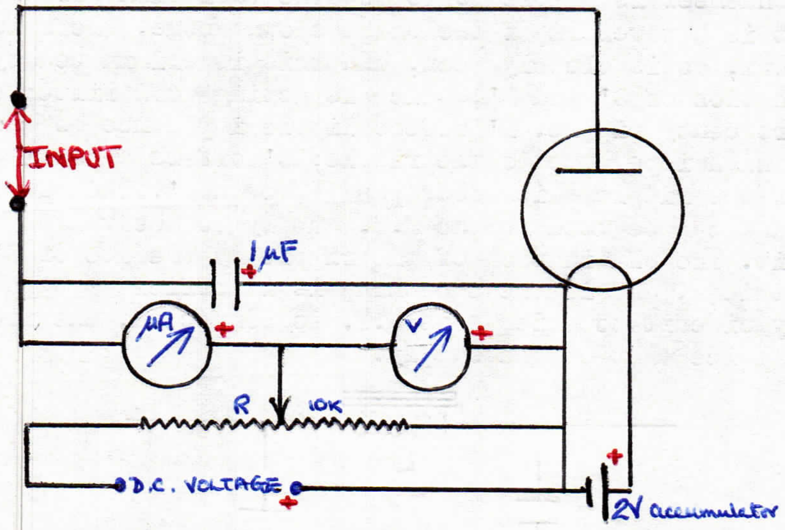
A metal rectifier is often used in place of the valve in the rectifier circuits just described. One type of metal rectifier consists of a disc of copper, one face of which has been oxidised. It is found that the electrical resistance for current passing from the metal to the oxide is considerably greater than that for current passing in the other direction. Such a device inserted in series with an alternating supply will produce a unidirectional current in exactly the same way as a diode valve. As the temperature of the metal/oxide disc increases, the difference between the electrical conductivities in the two opposite directions decreases, so that the device becomes less efficient. It is important, therefore, to pass only a small current through the device in order to avoid any appreciable increase in temperature. In practice several metal/oxide discs are connected in series, each combination being separated by a lead washer which provides electrical contact between them. Metal fins are interposed at intervals to help dissipate any heat developed.

More common nowadays than the copper/oxide rectifier is the selenium/oxide rectifier.

THE VALVE VOLTMETER

The ordinary moving coil instruments for measuring voltage, although very accurate, suffer from the disadvantage of requiring current for their operation. Furthermore, they are unsuitable for the measurement of A.C. voltage unless in circuit with a rectifier, in which case their accuracy is reduced. The rectifying action of a diode is made use of in the construction of a valve voltmeter, suitable for the measurement of both D.C. and A.C. voltages, which is independent of the frequency of the A.C. and takes no current from the circuit in which the voltage is required and to which it is connected.

The circuit below shows the arrangement:

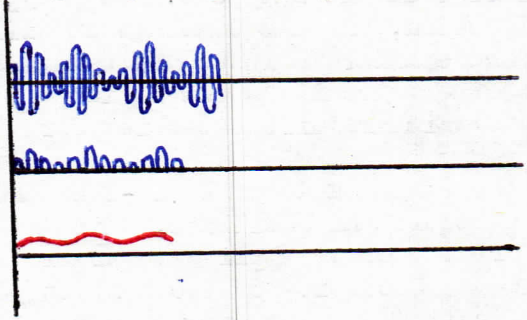


An A.C. voltage across the input will charge the condenser to the peak voltage of the input. The potentiometer R is adjusted until the microammeter records zero, which means there is no current flowing out of the condenser, so the voltage across the condenser must be the same as that across the ptential divider, i.e. that recorded by the voltmeter. Thus, when the value of R is adjusted so as to give zero reading of the current in the microammeter, the voltmeter records the <u>peak</u> voltage of the A.C. input.

A.D.C. voltage, connected with the correct polarity, will be recorded by the voltmeter in the same way. The potential divider is usually calibrated, and when this has been done the voltmeter can be dispensed with.

DETECTION

The voltage and current wave-form is of the form shown in (a) below. It is an amplitude-modulated wave and consists of a radio-frequency wave whose amplitude is varying according to the combination of audio-frequencies it is carrying. The radio-frequency is called the "carrier" and the audio-frequency is generally referred to as the "modulation". Detection, or demodulation as it is sometimes called, is a process whereby the modulation is separated from the radio-frequency carrier, in other words, a process for obtaining the envelope of the radio-frequency wave. The method is to rectify this wave-form, thereby obtaining a wave of the form shown in (b). This rectified wave-form is then taken across a condenser and resistance combination, the time constant of which is large in comparison with the period of the carrier, but small with the period of the modulation. The effect of this can be seen in two ways. Since thetime constant is large compared with the period of the carrier, the voltage across the condenser will not be that of the radio-frequency, because the condenser cannot charge and discharge at the rapid rate at which the radio-frequency voltage is changing. The waveform of the voltage across the condenser follows very closely the envelope of the carrier and consequently is that of the audio-frequency which is required. Alternatively the condenser may be regarded as having such a value that it offers a low-impedance path to radio-frequencies but a high-impedance path to audio-frequencies. Thus the radio-frequency component of the carrier develops very little voltage across it but the audio-frequency component produces a voltage and this voltage is that required.



(a) Voltage waveform in an aerial

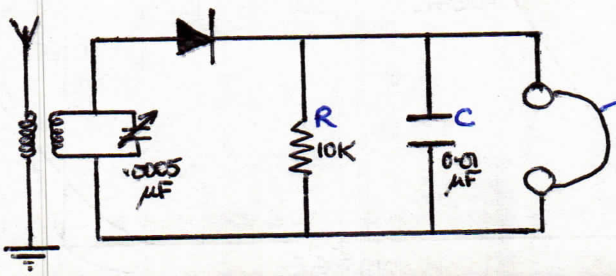
(b) Same waveform rectified

(c) Modulation envelope

CRYSTAL DETECTION

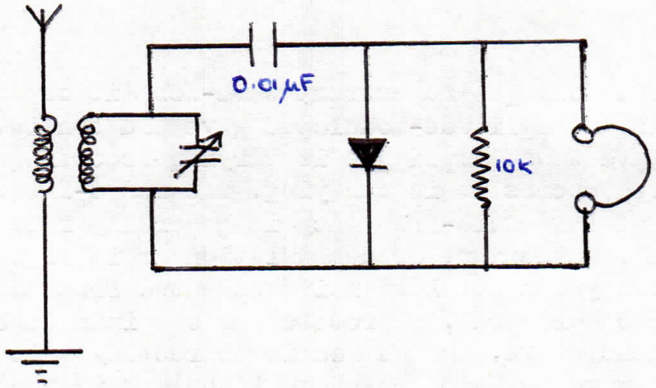
We have alrady seen how the metal to oxide of the metal rectifier allows current to pass through it in one direction only. The very small voltages induced in aerials are not sufficient, however, to operate a metal rectifier, but it is found that a crystal of carborundum, when it has a steel wire in contact with it, allows current to pass through it in one direction only, in other words, it acts as a rectifier. Other crystal-metal combinations act as rectifiers, but this one is perhaps the most common. This device is used for detection in a "crystal set", thecircuit being arranged either as in (a) or (b):

a)



(HEADPHONES INSTEAD OF 10K)

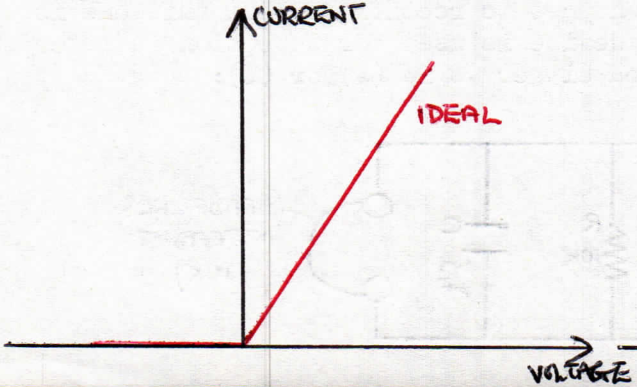
(b)

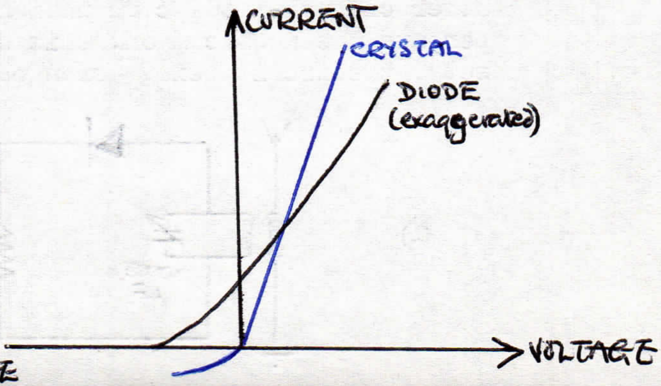


Using either arrangement (a) or arrangement (b) the time constant of the condenser-resistance combination (CR) is such that the voltage across it follows the envelope of the carrier, as has been explained above, and headphones connected across R, or used in place of R, will have the audio-frequency component of the original wave passing through them.

A particular type of metal rectifier which is rapidly replacing the crystal is the germanium diode. In one of its forms it consists, essentially, of two different "forms" of germanium in contact with one another. One possesses free electrons in the same manner as any other metal. Germanium of this form is known as a donor, since it is able to donate electrons, or an "n-" (negative) type of the substance. There is another form of germanium which is actually short of orbital electrons, and this is called an acceptor or "p-" type of germanium. If these two forms are placed in contact, electrons can flow easily across the interface from the n-type to the p-type, but only with difficulty in the opposite direction, and the combination will therefore act as a rectifier. This device, and similar devices, are being used increasingly for detection purposes, and in other circuits where it is advantageous to dispose of as many components which require batteries for their operation as possible.

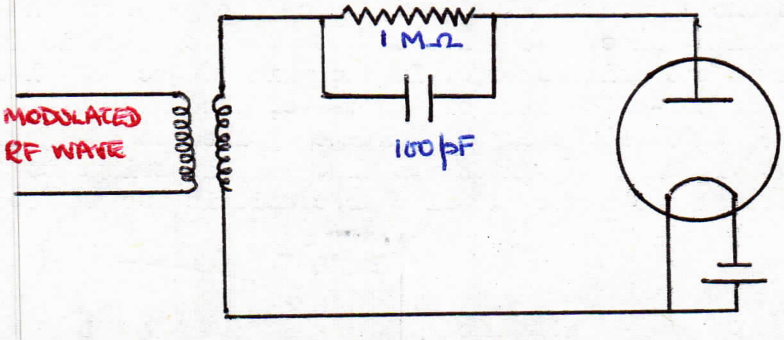
It is always best to avoid too many stages of audio-frequency amplification since such stages may become unstable and oscillate, which means that in a radio receiver it is therefore better to amplify the radio frequency before detection in order to avoid the necessity of too many stages of audio-frequency amplification. Now amplification of theradio-frequency means a much bigger input to the detector. In (a) below is shown the ideal characteristic for a rectifier: no current is passed in one direction, and in the other direction thecurrent passed is linearly proportional to the voltage across the rectifier. In actual rectifiers this can only be approximated to. Diagram (b) shows a crystal (germanium) characteristic and a diode valve characteristic. From these curves it is seen that for small input voltages the crystal is more satisfactory, but it is easily overloaded so that, from what has been said above, the diode is often the more convenient in practice.





THE DIODE AS DETECTOR

A circuit for diode detection is shown below:



It is similar to that for the crystal, the diode having replaced the crystal. The circuit corresponds with circuit (a) shown for the crystal, but a circuit corresponding with (b) above would also suffice.

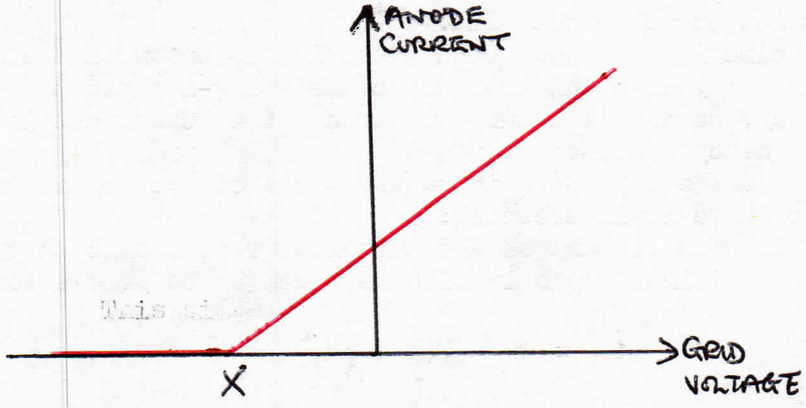
Although diode detection is so simple it is only in recent years that it has been used. The diode requires quite a large voltage variation across it if it is to fundtion linearly, in fact it requires a larger voltage than an aerial alone can supply if it is to function at all. The signal supplied by the aerial has to be amplified before it can be applied to the diode for detection, so that until radio-frequency amplification had become possible diode detection was out of the question. For faithful detection, however, that is for the detected audio-frequency to correspond exactly with the original envelope, the diode is one of the best means.

THE TRIODE AS DETECTOR

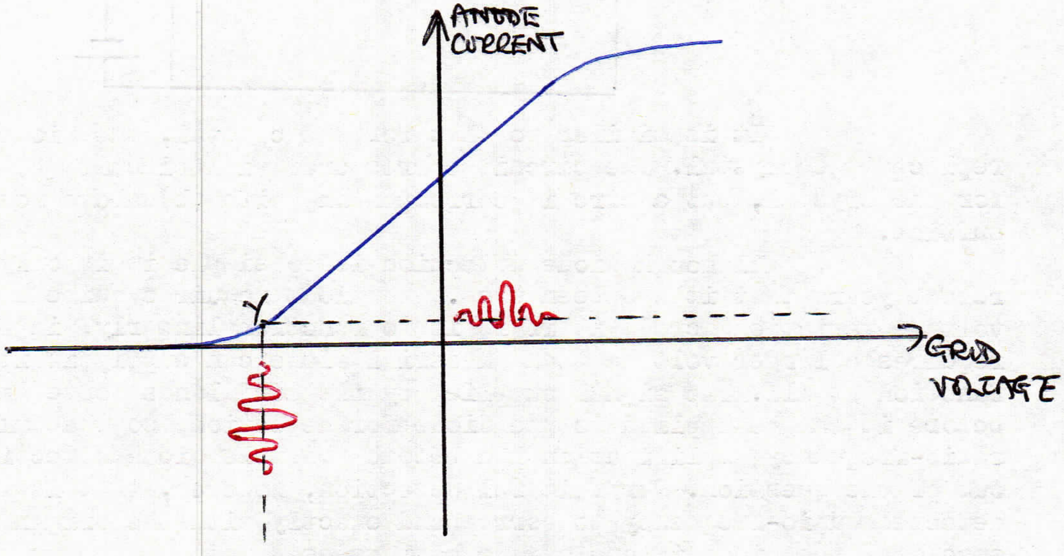
Owing to the large voltage needed to operate the diode valve, the triode was the first adopted. The triode can be used in two ways as a detector and we will deal with each of these in turn.

ANODE BEND DETECTION

This makes use of the fact that the mutual characteristic of the triode is not completely straight, but curves at the lower end. Imagine, first of all, a characteristic of the shape shown below:



This simple ideal characteristic is only approximated to by the triode. The graph shows that for values of grid voltage less than that given by the point X no current flows through the valve, but for values greater than this an anode current flows and, since the graph to the right of this is a straight line, the value of the anode current is linearly proportional to the grid voltage. If the grid of such a valve were biassed back to X, the "cut-off" point of the valve, then it would act as a rectifier, allowing current to flow when the voltage applied to the grid swings to the right but allowing no current to flow when it swings to the left. The diagram below shows the mutual characteristic for an actual triode:



The lower bend on the curve (hence the name "anode bend detection") is not as abrupt as that of the ideal curve, neither is the portion to right of it as straight as that of the ideal curve, but the effect of biassing the grid back to near cut-off and applying a varying voltage to it will be similar to the ideal case. In order to avoid excessive distortion of the anode current the grid is biassed to a point such as Y so that as much as possible of the straight portion of the curve is used, at the same time retaining the rectifying action of the valve. If the bias point moves too far to the right, then the valve will no longer be acting as a rectifier.

Now there is a small current flowing in the opposite direction to that required and this, together with the non-linearity of the lower portion of the characteristic, introduces distortion. In other words, the variations in anode current do not follow faithfully the variations in voltage which occur on the grid.

A circuit for anode bend detection is shown on the next sheet. The condenser C may be considered to act as a low-impedance path to the radio-frequency, so that the current through the headphones is due to the audio-frequency component .

The following approximate treatment of the rectifying action of the valve is interesting:

Over a small part of the mutual characteristic curve, the equation may to a first approximation be taken to be of the form

$$i_a = \alpha + \beta v_g + \gamma v_g^2$$

where α, β, and γ are constants. If the bias voltage on the grid has the value V_b (although nearly zero), the steady current flowing is:

$$i_0 = \alpha + \beta V_b + \gamma V_b^2$$

Now let the varying voltage applied to the grid be of the form $v \sin \omega t$. The total voltage on the grid is $V_b + v \sin \omega t$ and the current flowing is:

$$\begin{aligned} i_a &= \alpha + \beta (V_b + v \sin \omega t) + \gamma (V_b + v \sin \omega t)^2 \\ &= (\alpha + \beta V_b + \gamma V_b^2) + \beta v \sin \omega t + 2\gamma V_b v \sin \omega t + \gamma v^2 \sin^2 \omega t \\ &= i_0 + \beta v \sin \omega t + 2\gamma V_b \sin \omega t + \frac{\gamma v^2}{2}(1 - \cos 2\omega t) \\ &= i_0 + \frac{\gamma v^2}{2} + (\beta v + 2\gamma V_b v) \sin \omega t - \frac{\gamma v^2}{2} \cos 2\omega t \end{aligned}$$

Now the terms in $\sin \omega t$ and $\cos 2\omega t$ represent radio frequencies which will be by-passed through the condenser C, so that the term $\frac{1}{2}\gamma v^2$ represents the variation of the anode current through the headphones as a result of the variations on the grid.

Now $\quad i_a = \alpha + \beta V_g + \gamma V_g^2$

So that $\quad \frac{di_a}{dV_g} = \beta + 2\gamma V_g$

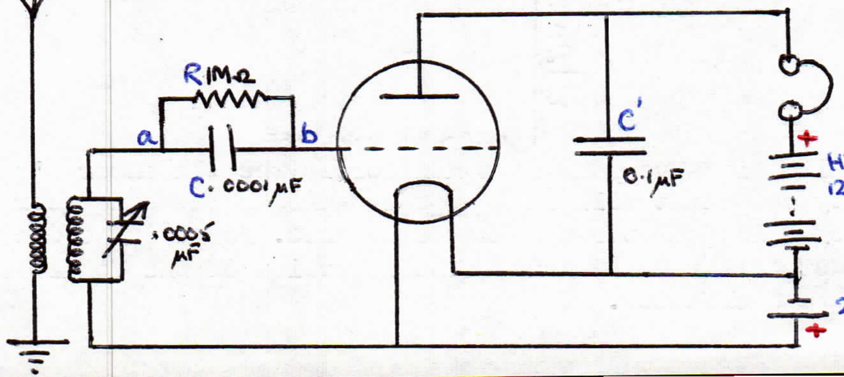
and $\quad \frac{d^2 i_a}{dV_g^2} = 2\gamma$

Thus $\frac{1}{2}\gamma v^2$ may be written $\frac{v^2}{4} \cdot \frac{d^2 i_a}{dV_g^2}$

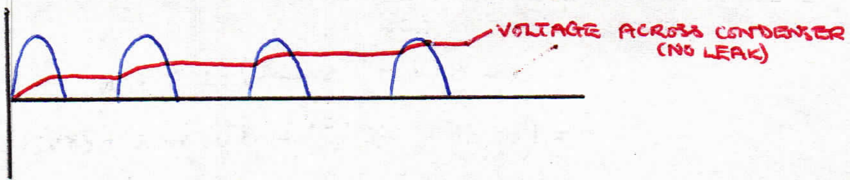
Thus the rectified current which is obtained is proportional to the square of the amplitude of the input variation and proportional also to the rate of change of the slope of the characteristic. This means that if the input signal is small it is best first to amplify it and then apply it to the valve for detection, since if the signal input to the valve is doubled the anode current variation resulting is then quadrupled. Also the most sensitive parts of the characteristic for detection are those at which the rate of change of the slope of the characteristic is most rapid, i.e. the lower bend.

GRID CURRENT DETECTION.

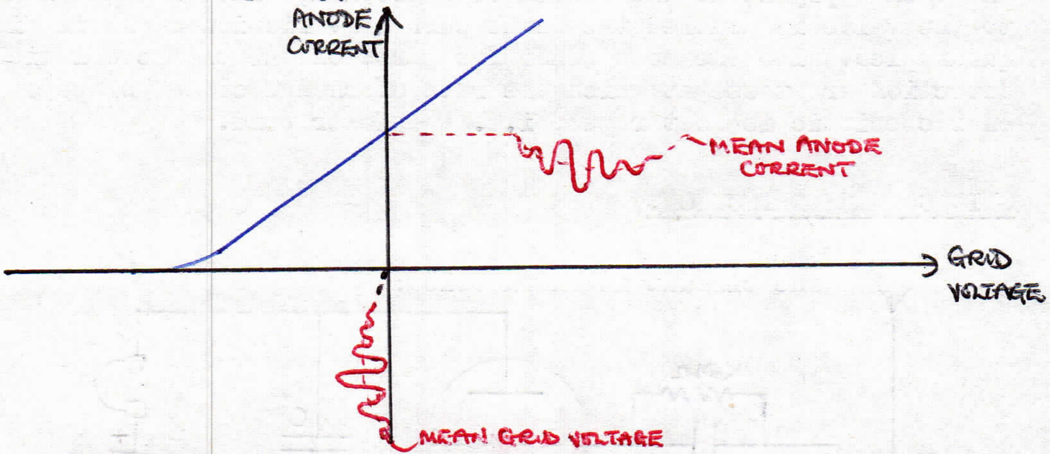
The circuit is shown below:



The grid and cathode of the triode are acting as the two electrodes of a diode valve and the grid circuit can be seen to be similar to the circuit for diode detection. When a modulated radio wave is introduced into the circuit a voltage is established across the condenser C and across the valve from grid to cathode. This can be seen in the diagram below:



The red curve represents the increase in voltage across the condenser due to the radio-frequency wave. It is of this form because the valve is only conducting in one direction. But if there is no path for the flow of current in the reverse direction, the condenser C will charge up to the peak of the incoming signal and remain there. In order that C shall follow the envelope of the curve the resistance R is connected across C, the time constant CR of the combination being such that the combination can follow the envelope but not the radio frequency itself. This resistance through which the condenser can discharge is called the GRID LEAK. It is important that the time constant be of suitable value. If it is too short, the voltage across the condenser will tend to follow the radio frequency, and if it is too long, the condenser will not have discharged, following the modulation envelope, before it is required to charge again. Now the valve is not biassed negatively, as it was in the anode bend detection, so that when no signal is applied to the grid there will be a steady anode current flowing through the valve. When the modulated radio frequency is applied to the circuit, the diode action just described will take place with a constant variation of the potential between the plates of the condenser, i.e. between a and b, which follows the modulation envelope. The potential between a and b is fed between the grid and the cathode of the valve. The potential of the grid is varying in the same way as the potential between the plates a and b, i.e. is following the A.F. of the modulation envelope, and superimposed on this is the radio-frequency. Thus the anode current through the valve, which acts an an amplifier, consists of a radio-frequency varying on an audio-frequency, as shown below:



If this wave-form is taken across the condenser C' the radio-frequency component will be by-passed through the condenser and the audio-frequency will pass through the headphones. For this to occur the value of C' must be large. By this means detection of the modulated radio frequency has been effected.

The expression above becomes:

$$v = E\cos(pt + \delta)$$

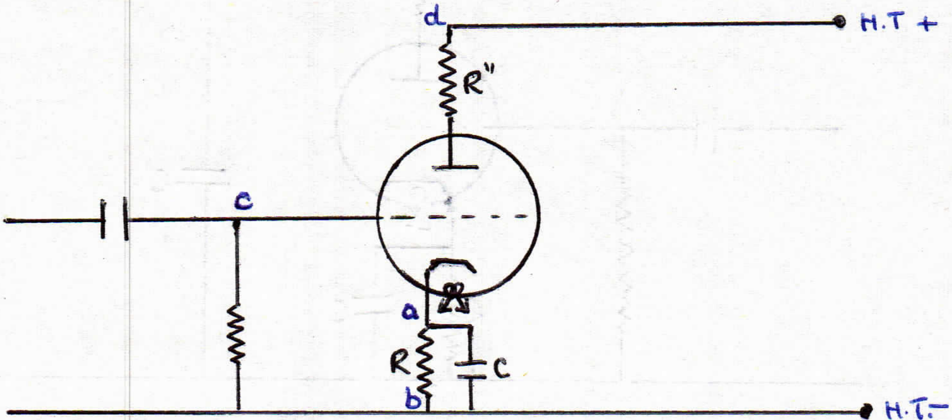
In other words, the time-decay factor has disappeared and oscillations of constant amplitude occur in the circuit. The valve has become a producer of oscillations. In practice, with such a circuit, the switching on of the current gives the circuit a slight electric "shock" and the feeding-back through the coupled circuits P and L builds up oscillations of such an amplitude that the mean value of the resistance of L is zero.

The frequency of the oscillations is seen to be $(2\pi\sqrt{LC})^{-1}$ from the above expression (put R = 0).

The values of L and C are chosen so that oscillations of the desired frequency are produced. In practice, both in A/F and R/F oscillators, either the inductance or the capacitance, or both, is variable.

AUTOMATIC GRID BIAS and DECOUPLING

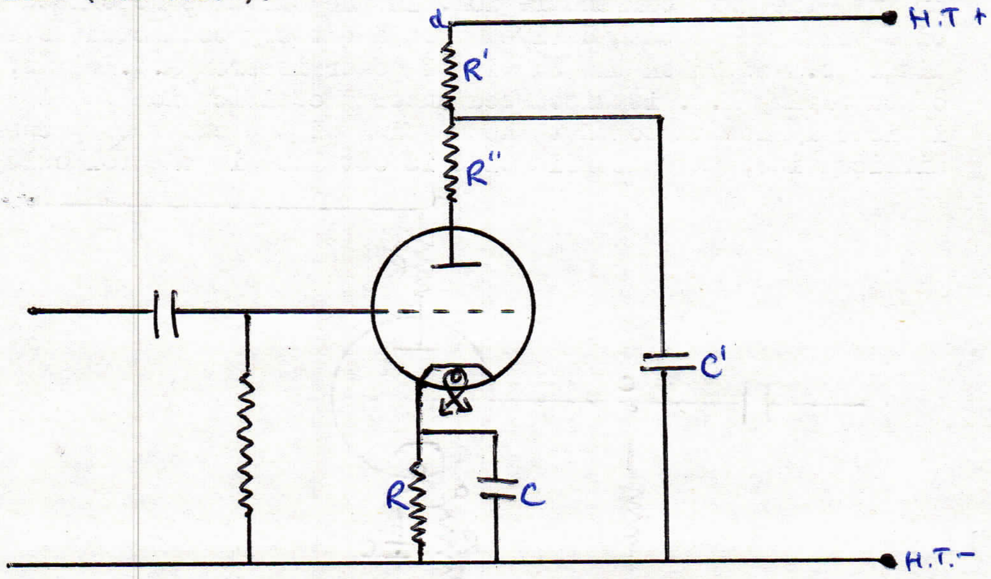
We have seen how it is sometimes necessary to bias the grid of the triode to a negative potential, and to use this "working-point" on the mutual characteristic in such a way that the voltage variations on the grid never swing off the straight part of the characteristic or into the grid current region. In the curcuits described this grid bias voltage has been derived from a battery connected as shown in the diagrams. Now, when the supply of power is from A.C. mains, the method of supplying H.T. is discussed under "Rectification", the valves are indirectly heated so that the heating of the cathodes presents no difficulties, and the grid bias is obtained in the following manner:



A resistor R is connected in the cathode lead. The steady anode current flows through R causing a drop in potential so that a is at a higher potential than b. If there is no grid current flowing in the grid circuit the point c must be at the same potential as the point b, which means that the point a, i.e. the cathode is at a higher potential than the point c, the grid. In other words, the grid is biassed negatively with respect to the cathode. Knowing the steady anode voltage, and consequently the steady anode current through the valve, the value of R is chosen so that the drop of potential across it is equal to the negative bias required on the grid.

If the circuit is left like this, not only the steady anode current passes through R, but also the variations of anode current, due to the variations of voltage on the grid. These, too, would be fed back to the grid and alter the action of the valve. To stop this the condenser C, of large capacity (about 50 F for A/F or 0.1 F for R/F) is connected across R and this condenser provides a low impedance path to the variations, which develop on consequence very little voltage across it. This by-passing of the variations, so that they do not pass through the cathode resistor, is called DECOUPLING the cathode resistor. It might be noticed that a valve with automatic grid bias is "self-compensating",i.e. if the anode voltage increases, causing an increase in anode current, the grid bias voltage increases, making the grid more negative and the valve less conducting.

In order that the valve may operate satisfactorily, a steady H.T. supply is needed. Quite clearly, if the H.T. voltage were to vary, the anode current through the valve would vary. Now not only the steady anode current but also the variations of anode current pass through the circuit made by the anode load, the H.T. impedance and the valve (and any grid bias resistor), and as a result of this the actual potential of the point d in the previous diagram will vary in a manner corresponding exactly to the anode current variations. Now the point d is the H.T. line, so that when the valve is operating it is causing the H.T. line to vary in potential, and this variation will be transmitted to any other valve connected to the same H.T. line, and interfere with its action. To avoid this, some means must be adopted to keep the H.T. voltage constant. This is done by introducing the resistance R' and the condenser C' between the anode load and the H.T. line (see below).



The variations of anode current passing through the anode load R" take the low impedance path through the condenser to earth (or H.T.-), whereas the steady anode current flows through R" and R'. Thus the point d in the first diagram stays at a steady potential unaffected by the variations of anode current through the valve.

In the design of a circuit it essential to ensure adequate decoupling of the cathode resitors and the H.T. line.

It might be noticed that the method of automatic grid bias described is not normally used in battery receivers, although it would be theoretically possible, because a large H.T. voltage is required to provide both the drop across the valve and the drop across the cathode resistor. The 120 volts available from a dry battery are not normally sufficient to do this using normal valves, but will do for miniature valves.

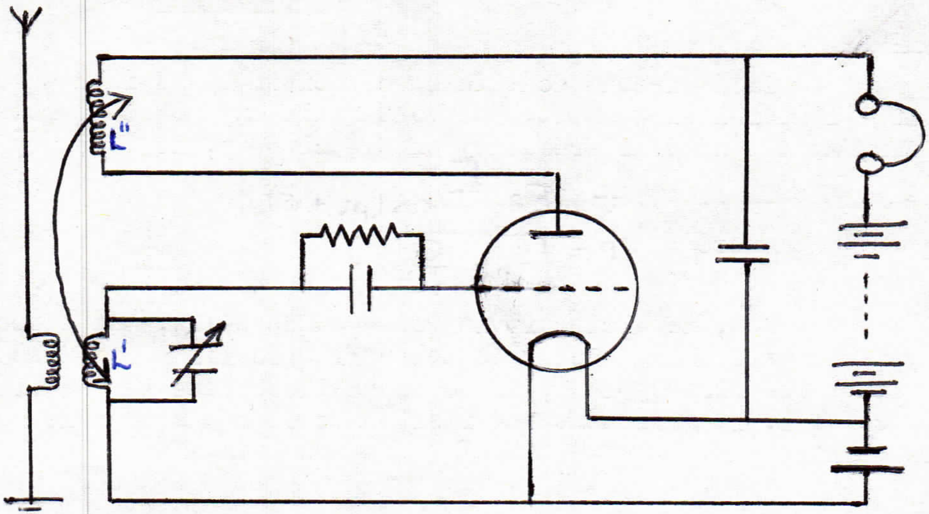
It can be shown, although it is not so simple as in the anode bend method of detection, that here too a square law relates the amplitude of the anode current variation with the amplitude of the grid voltage variation.

These methods of detection, using the triode, although fairly popular, are not satisfactory, since, because of the square law relationship between the anode current variation and the grid voltage variation, there will always be distortion of the signal. Furthermore, in grid current detection, if the amplitude of the incoming signal is large the grid voltage will swing onto the upper bend of the characteristic and introduce further distortion.

The grid current method of detection is also known as CUMULATIVE GRID detection or LEAKY GRID detection.

REGENERATIVE AMPLIFICATION - REACTION

We have seen that the anode current variations produced during detection with a triode consist of both a radio-frequency component and an audio-frequency component. In the circuits described above the radio-frequency was by-passed to earth or H.T.- by a condenser and the audio-frequency component only was put to use. The radio-frequency component can also be usefully employed and a circuit for this is shown below:



This is an adaptation of the one given earlier for grid current detection. A coil L" has been introduced into the anode circuit and the variations of anode current flow through this coil. The coil L" is placed near the coil L', which forms part of the tuned circuit, in a position similar to that shown. The flux through L", produced by the anode current variations, will thread L' and, depending on the direction of the windings, will either help or oppose the variations in L' because of the energy fed back.

In order to see the effect of this feed-back of energy let us first consider the effect of the detector on the tuned circuit. The anode bend detector has no effect, so that this discussion does not apply to it. The grid current detector (and this also applied to the diode detector) produces a considerable damping effect on the tuned circuit, causing the oscillations in it to die away rapidly. When the triode is conducting, as it must be if it is acting as a grid current detector, the necessary grid current causes the path from grid to cathode to change from the nearly infinite resistance ehich it appears to have when no grid current is flowing to the lower finite value which it appears to have when grid current does flow. There is, in effect, an equivalent resistance across the tuned circuit. Again, the grid leak is, in effect, a resistance across the tuned circuit. The result, then, as far as the tuned circuit is concerned, is as if a resistance were across it which damps the amplitude of the oscillations considerably.

The introduction of L" is designed to compensate for this loss of energy by damping, by feeding back into the circuit oscillations which are in phase with those already in L' so that oscillations are maintained in L' despite the damping effect of the detector. This process is called regenerative amplification or retroaction, the latter being contracted to REACTION; the coil L" is called the REACTION COIL.

By introducing the reaction coil into the circuit we have maintained the amplitude of the oscillations induced in the tuned circuit despite the damping effect of the detector - but we have introduced another effect.

The response curve of a parallel tuned circuit is made sharper by decreasing the resistance of the circuit. The effect of the reaction coil is to decrease the effective resistance in the grid circuit, and in consequence of this the response curve will be steeper. In other words, the reaction coil has made the circuit more selective.

OSCILLATORS

In a circuit containing capacitance and inductance and resistance in parallel with it, the voltage at any moment across the condenser, at the natural frequency of the circuit, is given by

$$v = Ee^{-\frac{RT}{2L}} \cos(pt + \delta)$$

where $$p = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

Now, if a circuit is arranged as below, the effect of the coil P, if it is feeding back into the coil L oscillations which are in phase with those already in L, is to cause a decrease in the effective resistance of L. Imagine that the resistance of L has been reduced to zero by this means.