PROCEEDINGS
of the
RADIO CLUB OF AMERICA

A. C. as a Filament Supply Source

A Paper Delivered Before the Radio Club of America on September 15, 1926

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Volume 3, No. 12 December, 1926

The Radio Club of America

Bryant Park Building, Room 469
55 West 42nd Street, New York, N. Y.
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A. C. As a Filament Supply Source

The Problems of Filament Heating With Alternating Current—Determining the Cause of and Remedying Undesirable Hum—The Best Tubes to Use

By B. F. MIESSNER

Chief Engineer, Garod Corporation

RADIO receivers and tubes have, since the beginning, been designed and developed for operation on absolutely steady direct current, such as that delivered by batteries. To operate a receiver from machine-generated direct current presents some problems, and to operate it from alternating current presents problems of a much higher order. Because operation from direct-current mains was easier, direct-current receivers of this type were the first to make their appearance in spite of the fact that fully 90 per cent. of electrically wired homes are provided with alternating current, and only between 5 and 10 per cent. with direct current suitable for use with radio receivers, that is, 110-volt current.

With battery operation, it is customary to connect filaments in parallel with a heavy-current A-battery source. When, however, the direct current lighting mains are used it has been found necessary to connect the filaments in series and to add resistance to this series circuit which, when connected across the 110-volt circuit, would provide a current of proper value for the filaments of the tubes. A simplified circuit arrangement of the general type used for this purpose is shown in Fig. 1.

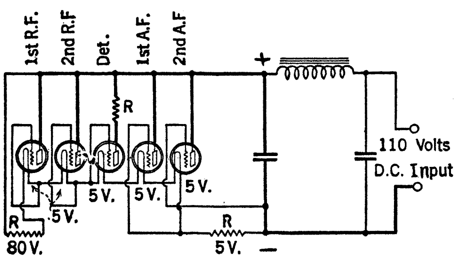

FIG. 1

The next step in electric power receiver development was the substitution, in a circuit of this type, of an a. c. line with a suitable rectifier for supplying the direct current.

In Fig. 2, it will be noted that the vacuum-tube supply circuits are preceded by a filter device, that the vacuum tube filaments are connected in series with a resistance across the rectified current line, and that the grids are biased by voltage drops in filaments more negative than the filament of the tube whose grid requires a negative bias. The first receivers of this type were designed for 201–A tubes requiring 250 milliamperes in the filament and an additional plate load of perhaps 25 milliamperes. To provide this rectified power output of 250 milliamperes at approximately 100 volts, a full-wave rectifier consisting of two Tungar gas type rectifier tubes was used together with a heavy-duty filter, consisting of very large inductances and very large capacities.

With the introduction of 60-milliampere filament tubes and also 60-milliampere rectifier tubes of the Kenotron type, by the Radio Corporation of America, came the possibility of using the same general receiver scheme with such rectifier and radio tubes. This is shown in Fig. 3. A simplification in the power conversion system was made possible with such a scheme because the output load of the converter was reduced to approximately 30 per cent. of that required by 201–A tubes. Even then, two such rectifier tubes were required to take care of the filament and plate current loads unless a single rectifier tube were to be considerably overloaded.

The ideal scheme for eliminating batteries in receivers is one which will use standard tubes of the larger types, without the necessity of developing rectified current specially for the heating of their filaments, and one which will also provide the large power so necessary for the development of high quality and plenty of volume.

A receiver which will operate satisfactorily with raw a. c. filament supply will require less than half the rectified current required when rectified current is applied throughout. For example, if the small dry-cell tubes are used with filaments in series across the rectified current output, their filament supply will be 60 milliamperes, which is more than the necessary plate supply.

If 201–A type tubes are used, the filament consumption is 250 milliamperes in excess of the plate current load. If still larger tubes, such as the 112, are used, the rectified power must necessarily be still further increased to provide the additional filament heating current. The cost of current-supply devices of this type varies nearly in proportion with the rectified output power for which they are designed; their size, weight, complexity and upkeep cost vary in like proportion.

It will be understood, therefore, that a receiver so designed as to permit the use of standard tubes of proved design with a. c. current excitation of their filaments represents probably the ultimate and ideal type of design for operation from home lighting circuits. The only rectified power required in such a receiver is that used for the plate circuits of the receiver, and the alternating current required for the filament lighting is obtained from a single winding of a few turns of wire on the power transformer used with the B power rectifier. The A power, therefore, requires none of the complex, costly, and bulky elimination apparatus, and the B power requirements are such that the rectifier and filter apparatus is small and inexpensive.

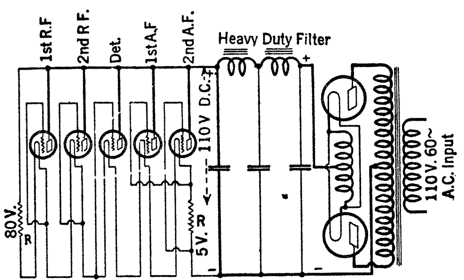

FIG. 2

In the author's receiver plan, the filaments of the amplifier tubes are heated by a. c., and the plate circuits are energized by rectified a. c. The filament of the detector tube is lighted by the B current of all the other tubes which is regulated to the 60 milliamperes required by this filament. By the use of this scheme, therefore, a single 216–B rectifier tube provides ample plate power for all of the tubes, including the powerful 210 second audio tube. The filament power for the detector tube, and the C voltage for all the tubes requiring a grid bias, are also supplied from the 216–B rectifier tube.

AN INTERESTING EXPERIMENT

LET us now consider a two-element vacuum tube connected as shown in Fig. 4. The filament of the tube is excited by a. c. The plate is connected through a telephone or other indicating device to one leg of the filament without any external source of potential included in its path. If we listen at the telephone in this circuit, we will hear a humming noise in which a trained hear can discern a mixture of tone frequencies including 60 cycles, 120 cycles, and some other higher harmonic frequencies. This may appear strange, inasmuch as the plate circuit is not provided with any source of potential for attracting the electrons emitted by the filament.

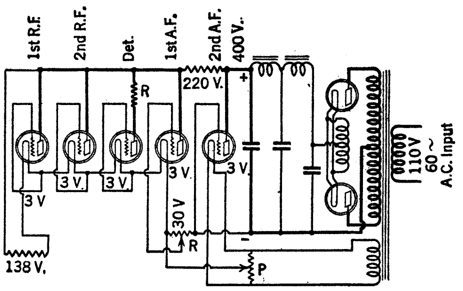

FIG. 3

We realize, however, on examination of the diagram, that the plate is connected to the filament at a point of potential variation. The plate itself has at all times the same potential with respect to the rest of the filament as the leg to which it is connected. It is clear that, when the plate and its leg of the filament is positive with respect to the other leg, the plate and this leg both may, by virtue of this positive potential, attract electrons emitted from the negative leg of the filament. In fact, we may conceive of the negative leg as repelling electrons from it while the positive leg is not only holding within it the electrons attempting to escape, by virtue of the releasing effect of the filament temperature, but in addition, this positive leg, along with the plate electrode connected to it, is attracting some of the electrons liberated from the negative leg. Thus we have impressed upon the plate electrode a 60-cycle voltage variation by its connection to the filament circuit, and it functions as a single-wave rectifier under these conditions.

If now we change the connection of the plate

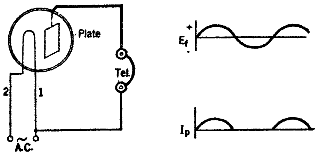

FIG. 4

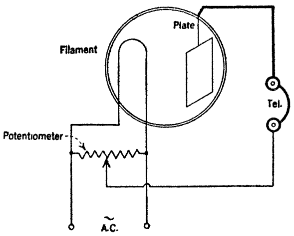

FIG. 5

circuit to the filament circuit as indicated in Fig. 5, so as to reach a point which is neither positive nor negative with respect to the two ends of the filament, the plate will never be positive or negative with respect to the filament as a whole, and it will, therefore, not have the positive potentials applied to it as in the preceding case. If we listen, however, with such an arrangement, we will still hear a humming signal in the telephone. This signal is of a 120-cycle frequency, or in general terms, double that of the exciting frequency. If we include a battery in the plate circuit so connected as to make the plate negative with respect to the filament, we will find that a potential of several volts is required to stop the hum signal. With the 201–A type tube, a negative plate voltage of about 9 volts is necessary to stop this signal. With the 199 type tube, a negative voltage of about 3 volts on the plate will accomplish the same result. One might ask many questions concerning the cause of this phenomenon. It might be due to a bicyclic thermo electromotive force set up between plate and filament by a bicyclic temperature variation of the latter; it might be a bicyclic contact electromotive force; it might be photo-electromotive force, or a magnet electromotive force emanating from the filament current.

Possibly the best explanation is that there is a bicyclic variation in initial emission velocity. We know that when a cathode is heated, it allows a freer swing to the natural vibration of the electrons within it and we know that the higher the temperature of the cathode, the greater the velocity of emergence of the electrons liberated by the heating. If then the temperature of the cathode is varying under the varying heat-producing electric current, the velocity of emergence will vary. Consequently the plate electrode, with no attractive force of its own for these electrons, will receive a mild bombardment of them which varies (in number of electrons striking it) with their emission velocity. We see, therefore, according to this explanation, that electrons reach the plate through no attractive force of its own and with a bicyclic variation following the temperature variations of the filament itself. This temperature effect, along with the effects of the voltage on the plate due to the latter's connection with one side of the filament, as shown in Fig. 4, occur simultaneously. We should not forget in this connection that the positive voltage of one leg of the filament is attempting to equalize the emission reaching the plate by stealing from the negative leg a portion of the excess electrons liberated at the periods of higher temperature. That is, while the negative leg tends to emit more electrons, due both to its rising temperature and to its rising repulsive negative potential, the potential of the positive leg is rising also and attracting to it an increasing number of freed electrons. Thus, the effect of the positive leg which we shall call "voltage effect," is in direct opposition to the "temperature effect" and tends therefore to stabilize the electron flow to the plate electrode. These effects are shown in Fig. 6. In this diagram, curve A represents the exciting voltage applied to the filament of the tube. Curve B indicates the temperature of the filament and shows that the temperature variation is bicyclic with reference to the exciting current. Curve C indicates that the plate current also is bicyclic although the definite relation between temperature and emission is not indicated in this curve. Curve D indicates the voltage variation on the positive leg of the filament insofar as its action as a plate electrode is concerned. The numerals 1 and 2 indicate that during the first cycle one leg of the filament is the positive leg and that during the other half cycle the second leg acts as the positive plate electrode, so that, irrespective of the fact that a given leg of the filament is alternately positive and negative, one or the other of the legs is positive during all periods except when the exciting voltage passes through the zero point, and therefore one or the other leg is constantly acting as a plate electrode of variable potential. The effect upon an otherwise steady emission to the plate electrode of the vacuum tube is shown in curve E, which indicates that the voltage effect of the filament causes a periodic decrease in the electron flow to the plate. When the two effects shown in curve C and E are present simultaneously in the same tube, one tending to increase the emission to the plate and the other tending to decrease it, both of these effects are constantly opposed and a neutralization results which has the effect of stabilizing the plate current, as shown in curve F.

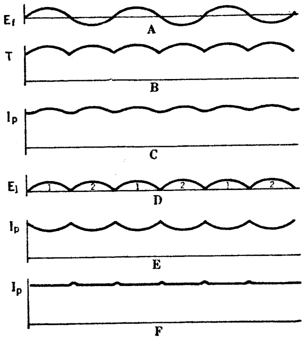

FIG. 6

While these curves indicate the tendencies toward plate current stabilization, they are not meant to represent exactly the effects found experimentally. To determine exactly the precise amount of hum signal developed in the plate circuit of various types of vacuum tubes under more normal operating conditions, a series of measurements have been made upon different types of tubes under different operating conditions. In order to obtain this information, a vacuum tube with direct current plate potential and with steady grid bias was set up for alternating current filament excitation.

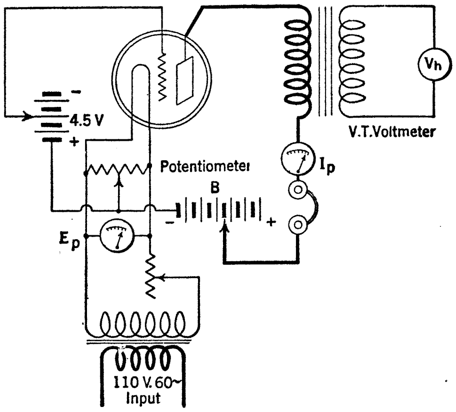

FIG. 7

FURTHER EXPERIMENTS

IN FIG. 7, the circuit arrangement employed for making these measurements is shown. It will be noticed that the filament of the vacuum tube is energized from a 110-volt 60-cycle lighting circuit through a step-down transformer and controlling resistance. A voltmeter across the terminals of the filament indicates the voltage impressed thereon. A milliameter in series with the plate circuit indicates the plate current therein, while a telephone in the same circuit serves as an aural indicator of hum signals. An output transformer primary is also connected in this plate circuit and its secondary is connected to the terminals of a vacuum tube voltmeter, whose function it is to measure the peak voltage of the alternating currents produced by hum causes within the vacuum tube. There is no input to the grid circuit other than the grid biasing C battery. The grid- and plate-circuit filament returns are made to the central point of the potentiometer shown connected across the filament terminals. The plan of measurement here is to fix the grid and plate voltages at some definite values and then to vary the filament voltage through definite steps and to measure the hum signal as well as the plate current for each such filament voltage.

Curves are then drawn with the filament voltage as abcissae and the hum signals as ordinates for one curve and the plate current as ordinates for another curve. These two curves are plotted together and various sets of this type are obtained under varying plate and grid voltage conditions. In Fig. 8 are shown two such curves obtained with an UX–112 type tube with a plate voltage of 135 and a grid voltage of 4.5 volts. The filament voltage was varied from approximately two to six volts and the plate current and hum voltage curves were obtained as indicated. We are impressed at once with the unexpected fact that the hum does not increase uniformly with the filament voltage as would a grid impressed signal voltage under the same conditions. There is, strangely, a rather pro-

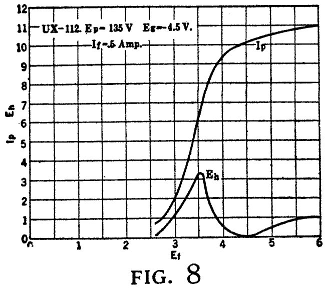

FIG. 8

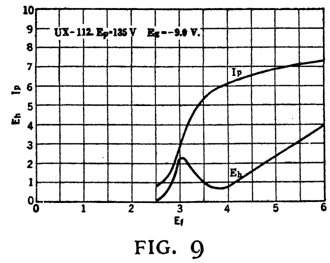

FIG. 9

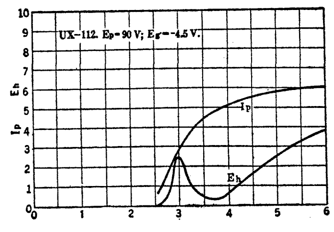

FIG. 10

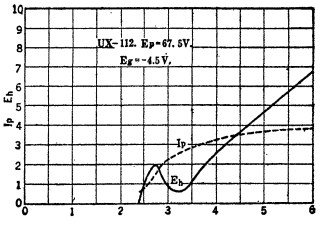

FIG. 11

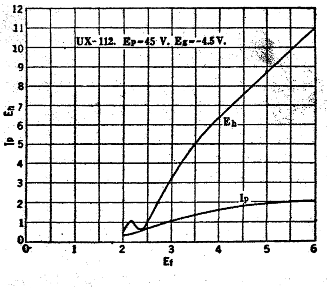

FIG. 12

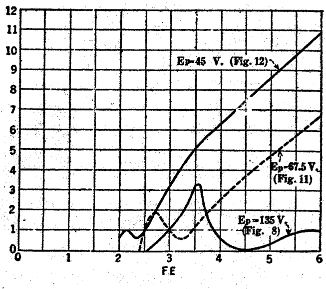

FIG. 13

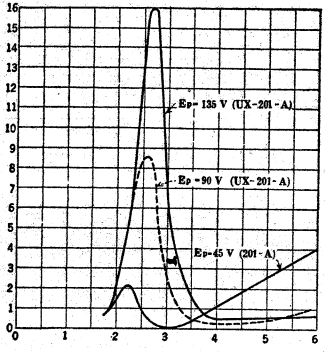

FIG. 14

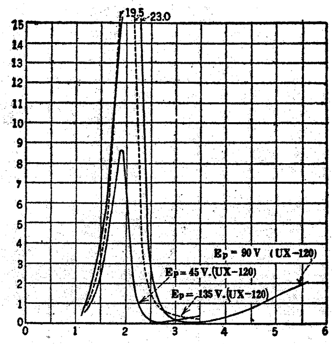

FIG. 15

nounced peak in the hum voltage at a point of about half the normal filament voltage, and there is a very definite minimum at a voltage of about 15 per cent. below the normal voltage of 5 for this tube, and again a definite rise as the normal voltage is approached and exceeded.

If now we change the operating conditions only by doubling the grid voltage, we obtain the curve shown in Fig. 9. Here we note that the hum peak has remained about the same, that the minimum point has risen to a considerable value, and that the upper maximum has increased about four times. If, instead of doubling the grid voltage, we leave the grid voltage at 4.5 volts and decrease the plate voltage to 90, we obtain a curve, shown in Fig. 10, similar to that for the nine-volt grid bias and 135-volt plate voltage. If we now reduce the plate voltage still further, to 67.5 volts (see Fig. 11), we notice a slight decrease in the lower peak, a further rise in the minimum portion, and a decided rise in the maximum portion. Going down to 45 volts we note in Fig. 12 that the lower peak has almost disappeared while the upper maximum has risen to a comparatively high value.

If we now compare the hum curves of Figs. 8, 11, and 12, by drawing them together on one curve sheet, as shown in Fig. 13, we can at once see the general nature of the variation in the curves under the changing plate voltage conditions. With high plate voltage, the hum peak is predominant, and as the plate voltage is lowered, this hum peak decreases in amplitude while the upper maximum steadily increases.

It may be observed in these curves that the peak of the hum curve always coincides with the point of maximum steepness in the filament voltage-plate curve curves drawn with them. This appears to identify definitely this hum peak with a temperature variation cause. Since a given amount of filament voltage variation at the steepest point of this static plate-current curve produces the maximum change of plate current, it is quite reasonable to expect that, under dynamic conditions, the complete change from maximum to zero of the filament voltage would produce a periodic change in plate current whose frequency is double that of the filament exciting current frequency. And, since the greatest variation in plate current is produced at this filament voltage, it is obvious that the greatest amount of hum disturbance would occur also at this point. We have, therefore, rather definitely identified the lower voltage peak with the temperature variation of the filament. This identification is still further strengthened by the fact that this hum peak corresponds fairly well in amplitude with the slope of the filament voltage plate-current curve.

The filament voltage of the 201-A type tube is the same as that of the 112, whose characteristics have just been shown. However, its filament is made of thoriated tungsten designed for a 0.25-ampere operating current, while the 112 tube has an oxide coated platinum filament designed for an operating current of 0.5 ampere.

HUM CURVES

IN FIG. 14 are plotted three hum curves of the UV-201-A representing the two extremes and middle conditions as far as plate voltage is concerned. By an inspection of the curves it is easy to visualize very clearly the changes in hum characteristics with variations in plate voltage, and again indentify this hum with the filament temperature variation cause. It will also be noticed that the hum peaks are much higher than those obtained for the 112 type of tube. Similar curves for the 120 tube are given in Fig. 15.

Proceeding now to the UV-199 tube with a three-volt filament, taking only 60 milliamperes, we obtain curves such as shown in Fig. 16 and Fig. 17. With 90 volts on the plate and a negative grid voltage of 4.5 (Fig. 16), the plate current characteristic is comparatively flat, while curiously enough the hum peak is very pronounced at the normal operating voltage of the filament. If we decrease the plate voltage to 45 and maintain the same grid voltage as before, we get an extremely flat plate-current characteristic, a very low hum peak, and a definite indication of a minimum point at about 2.5 volts on the filament. See Fig. 17.

Finally, we have two curves for the WD-12 type of tube. This tube has the lowest operating voltage of all, while the filament current is the same as for the 201-A, or 0.25 ampere. It has, however, an oxide-coated platinum filament as has the 112 tube, and operates at comparatively low temperatures. The first curve taken on this tube is shown in Fig. 18, with a plate voltage of 135, and 9 volts negative bias on the grid. The plate current curve is much steeper than any we have yet considered, while the hum peak is about the same as for the 201-A. At a point near or beyond the normal filament voltage, the hum curve is still quite high and there is little indication of a minimum point. In Fig. 19 a curve is given with a plate voltage of 90 and a negative grid voltage of 4.5. A reduced hum peak is obtained, but in general the same hum and plate current characteristics are present. Curiously, there is a steep bulge in about the middle of the plate current characteristic that has not been noted on any of the other tubes under discussion.

If we consider the grid and voltage ratings of the filament as indications of the thickness of the filaments, and consider that a thick filament will not fluctuate in temperature so much as a thin filament, we may compare filaments so far as their temperature variation hum characteristics are concerned on a basis which we may call the "thermal inertia" of the filament itself. This is a time temperature factor which is determined by the thermal characteristics of the filament. The cubical contents of the filament, its specific heat, its radiation constant, the conduction effects through lead-in wires, and some other factors, determine the value of this thermal inertia factor for any given filament. With a given material it is, of course, highest for a cylindrical type of filament, as compared for example, with a flat strip type of filament. It is greater for a material with high specific heat than it is for one with a lower value. It is greater for a filament having a surface with low radiation constant than it is for one having high radiation properties. It is greater for a filament of low temperature than it is for one of high temperature, because the radiation factor increases rapidly with high temperatures. If, therefore, we classify the various tubes we have thus far studied with reference to their filaments and select two extremes and a medium, we will have the 112 tube at the one extreme with highest thermal inertia, the 201-A with medium thermal inertia, and the 199 with the smallest thermal inertia.

THERMAL INERTIA

IF WE plot the hum curves of these three tubes for the same plate and grid voltages, that is, 90 volts plate and negative 4.5 grid volts, as shown in Fig. 20, we may compare their hum characteristics directly as a function of the ther-

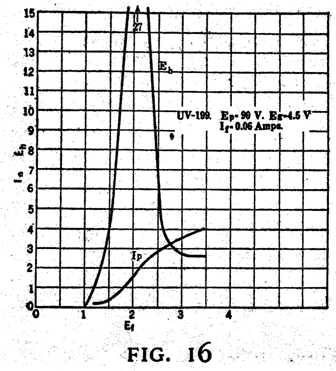

FIG. 16

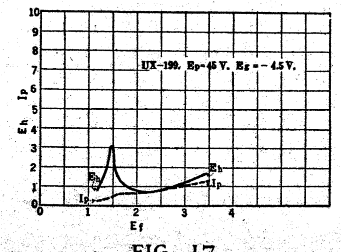

FIG. 17

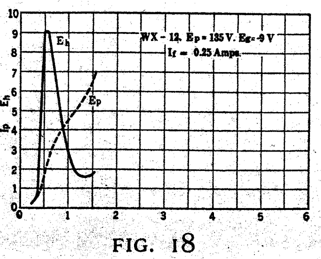

FIG. 18

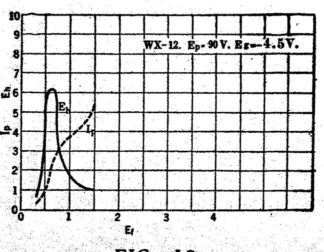

FIG. 19

mal inertia of the filament itself. This comparison indicates very clearly that the hum peak is always found below normal filament voltage, and has a very definite relation in its magnitude to the thickness and thermal characteristics of the filament.

From the preceding data the fact is well established that one very prominent kind of hum in tubes is due to the temperature variation of the filament. It has been further established that there is usually to be found a filament voltage within the operating characteristics of the tube at which the total hum from whatever cause developed by the tube is at a minimum. It has been shown that at voltages near, and in excess of the normal operating voltages, there is usually a considerable rise in hum output of the tube.

We will now endeavor to explain the cause of these phenomena. If we go back to our discussion on the two-element tube, wherein we indicated that there was present within a tube a voltage effect and a temperature effect, which tend to neutralize each other so as to cause a stabilization of the plate current under varying filament emission, the explanation of these hum effects will be made clear.

Let us consider for a moment a tube which, with normal filament, grid, and plate voltages, has a filament sufficiently thick to prevent any appreciable temperature variations due to its high thermal inertia. With such a tube, we will have no hum peak due to temperature variations, but we will have a hum of another type due to the voltage effect previously discussed.

Remembering that the positive leg of the filament is acting as a plate electrode and attracting electrons from the negative leg, we can understand that, irrespective of the fact that the emission from the filament is constant, due to constant temperature, there is still a hum due to the "stealing" effect, which causes a hum of double the frequency of the exciting current, because of this periodic subtraction from the flow to the plate by the periodic flow to the filament legs. With such a tube we will secure a hum characteristic such as that shown in Fig. 21. We can see therefore, that by merely increasing the thickness of the filament we have not eliminated all of the hum causes within a tube.

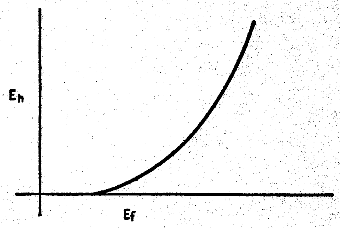

FIG. 21

If now we consider another type of tube in which the filament has a very low thermal inertia and a negligible voltage effect, so that a strong variation of temperature and plate current results, we will obtain a curve of the type shown in Fig. 22, in which the voltage effect is absent.

The 199 type of tube, with but three volts across its filament and the ends far spaced in this straight filament form, is almost a perfect example of this type of tube, as you may remember from the appearance of the hum characteristic which showed a very high temperature peak and no appreciable voltage effect.

In Fig. 22, it will be noted that the hum curve does not drop to zero, at the higher filament voltages, but that it retains a fairly uniform value which, from a comparison of all the curves so far presented, indicates that its value at this point bears a definite relation to the slope of the plate current characteristic in the same filament voltage region. The hum curve, therefore, should never drop to zero unless the plate current curve is parallel to the filament voltage axis.

If we now combine the temperature effect and the voltage effect in a single tube, we may expect a neutralizing action between them, which, under suitable conditions, may make it possible to operate a tube with alternating current on the filament and with a stable plate current. By combining the pure voltage hum characteristic of Fig. 21 with the pure temperature characteristic of Fig. 22, we can understand how this neutralization takes place and what should be the form of the resultant hum curve.

This combination is shown in Fig. 23, wherein the upper curve represents the temperature characteristic and the lower curve the voltage characteristic. The algebraic addition of these two factors, Eht and Ehv, gives the resultant curve shown in the dotted line. This dotted curve shows that, at the point where the two neutralizing effects are equal, zero hum results, and that where the temperature effect is predominant, that is, at voltages below this zero point, we have a temperature type of hum, and at voltages above this point, where the voltage effect becomes predominant, we have a voltage type of hum.

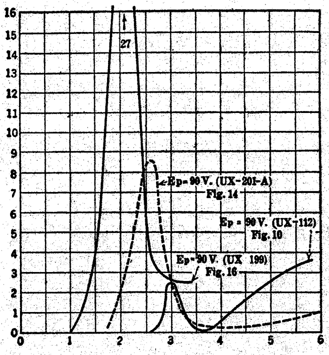

FIG. 20

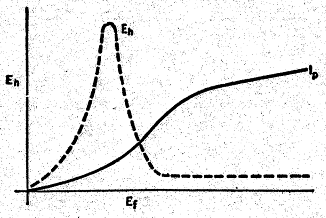

FIG. 22

Of course, in the measuring apparatus used for taking the hum curves previously shown, this reversal in the nature of the two types of hums on the two sides of the minimum point, does not appear, with the result that the portion of the dotted curve below the filament voltage axis turns upward instead of downward in the curves shown. It is necessary to show it as it is indicated in Fig. 23 to arrive at the algebraic sum of the curves, and this form is more exact.

112 TUBE BEST

THE 112 type of tube has been found best for use in audio and radio frequency amplifying circuits because there is more complete neutralization of the two hum causes within this tube than there is in other tubes. Again, while some of the other tubes show quite low minimum hums, at operative filament voltages there are nevertheless, present within the tube, hum causes of the two types of considerable magnitude. These, while they almost completely stabilize the plate current, nevertheless introduce other effects. A tube of the 199 type, while its hum output at about 3.5 volts is quite low, is practically useless for radio frequency amplification when its filament is excited by alternating current, due to the fact that its filament temperature is varying considerably. The amplification constant of the tube is varying with the temperature variations of the filament irrespective of the fact that the plate current is very nearly stable so that, as a result, a constant amplitude radio frequency voltage impressed upon the grid circuit of such a tube will possess a strong 120-cycle modulation frequency in its plate circuit. A receiver using such tubes may be made to operate very quietly so long as signals are not received, but when signals, especially strong ones, are received, this modulation effect introduces a strong 120-cycle hum which completely ruins reception.

The 112 type of tube, because of its very heavy filament, introduces only a very slight hum of this modulation type and, in addition, its plate current is practically without ripple, due to the very close neutralization of the temperature and voltage effect hums. The ideal type of tube, should have an oxide-coated low-temperature filament of the straight type operating with perhaps one volt and two amperes. The filament should be round so as to provide the greatest thermal inertia with a given mass of filament material. It should be straight, and the voltage across its ends should be low so that the voltage effect is reduced to a negligible factor.

It should be possible, as the writer's experiments with special tubes have shown, to use such tubes indiscriminately for radio frequency amplification, detection, and audio amplification with the introduction of no objectional hum in the loud speaker output.

In receivers deriving filament, plate, and grid voltages from alternating-current sources, there are other forms of hum than those introduced by the filament excitation within the tubes themselves. A certain amount of ripple is always present in B-supply rectifiers, and this will introduce a hum, particularly if any considerable amount of it is present in the detector or first audio stages, with subsequent amplification behind it. Instead of the usual procedure in bringing the grid and plate circuit returns to the filament at the center of a potentiometer connected across the filament, some of the B ripple hum can be eliminated by introducing a ripple into the grid circuit of one or more of the vacuum tubes in a receiver by displacing the potentiometer from its usual central position. In this way a 60-cycle grid voltage of very small magnitude is made to neutralize a 60-cycle plate voltage variation of larger magnitude.

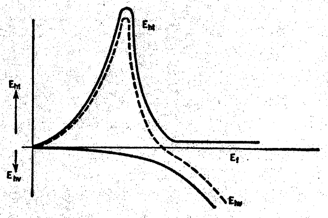

FIG. 23

Another method of eliminating B ripple consists in utilizing, for the grid bias of the vacuum tubes in the receiver, a voltage drop through a resistance carrying some or all of the B current in the receiver. In this way the grid has applied to it a somewhat unsteady biasing voltage with variations of correct phase and amplitude for neutralizing, at least in part, the plate voltage variations from the B supply.

An article in next month's RADIO BROADCAST will give a description of a commercial broadcast receiver in which the principles of hum elimination herein described are employed. This receiver was introduced to the public in May, 1926, and has thus far enjoyed a very successful commercial exploitation.

(This Paper Will be Concluded in the Next Issue of the Club Proceedings)

Forthcoming Papers

The Committee on Papers announces the following schedule for forthcoming papers:

Feb. 9, 1927—C. R. Runyon—Short Wave Transmitter
Mar. 9, 1927—D. F. Whiting—Audio Amplification
Apr. 13, 1927—A. V. Loughren—Modern Vacuum Tubes

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