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Use of Tubes Having High Amplification
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Use of Tubes Having High Amplification

A Discussion of the Theory Underlying the Functioning of High-Mu Tubes—A Paper Delivered Before the Radio Club of America

By A. V. LOUGHREN

Research Laboratory, General Electric Company

THE amplifier tube has, within the last two years, undergone a notable change. In 1923 all amplifier tubes were of the general-purpose type and all were alike. To-day, on the other hand, we have, in addition to this general-purpose tube, two distinct groups of special-purpose amplifier tubes.

One of these groups—that having a low amplification factor and low plate-to-filament resistance as its chief characteristics—was brought into being to satisfy the demand for more speech power which arose when reception on the loud speaker became common. The performance of this group of tubes has already been discussed in some detail ("Output Characteristics of Amplifier Tubes," J. C. Warner and A. V. Loughren, *Proceedings Institute of Radio Engineers,* Vol. 14, No. 6, Dec., 1926).

The second group, consisting of tubes having amplification factors of 15 or more, will be treated in the present paper. It should be understood, of course, that tubes with high amplification factors are not at all new, as such tubes have been built since 1912. Some of their uses have not been completely investigated, however, until recently.

Any treatment of the uses of tubes having high amplification factors is of necessity primarily a discussion of their use in resistance-coupled amplifiers. In order to understand their application to this type of amplifier it is necessary to have its underlying theory clearly in mind.

Fig. 1 is a diagram of a two-stage amplifier with resistive-interstage coupling. The operations may be sketched roughly as follows:

When a signal is impressed on the input circuit, consider the phenomena at the instant when the grid potential has reached the highest value occurring during the cycle. In Fig. 2 this condition is represented by the point t_1. At this same instant the plate current reaches a maximum. Now, looking back at Fig. 1, we see that the voltage at the plate of tube No. 1 is equal to the battery voltage minus the IR drop in the resistance R_{p1}. The value of this drop is simply $I_p \times R_{p1}$. Therefore, it is directly proportional to the plate current. Thus, when the plate current is greater, as at t_1, the drop in the coupling resistance, R_{p1}, is greater, and hence the plate voltage on the tube is less. The curve of plate potential in Fig. 2 shows this exactly. Incidentally, it may be noted that the signal has been shifted 180° in phase by going through the first stage.

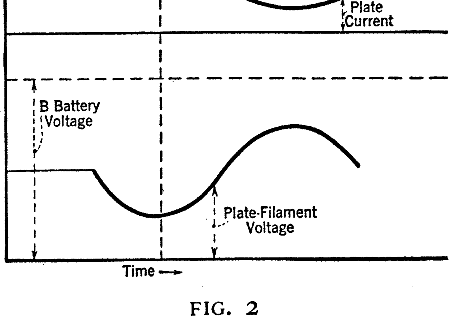


FIG. 2

The alternating component of this plate potential is applied to the grid leak resistance, R_{g2}, of the second tube, while the direct component is kept back by the blocking condenser C_{b2}. The grid of tube No. 2 is so connected that the drop in the grid leak resistance is the alternating component of grid voltage. In this stage the action is exactly like that in the preceding one.

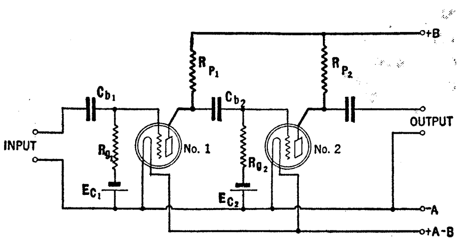


FIG. 1

Now, having a slight familiarity with the circuit and its mode of operation, let us proceed to a more rigorous analysis of the performance. To do this we make use of a fundamental principle of physics which may be stated as follows: With circuit elements whose coefficients are constants, the circuit response to a complex emf. may be determined by evaluating the respective responses to each of the (simple) component emf's. and taking the summation, if desired. In the present case this principle permits us to analyze the performance of the amplifier circuit for the alternating quantities alone, neglecting entirely the direct components.

Fig. 3 is drawn in this way. It may be noted that only the quantities entering into the alternating-current phenomena are shown. The interstage coupling resistor, R_p, is shown connected from the plate back to the filament. In practice it is connected to the positive terminal of the B battery and through the latter to the filament, but here we do not need to show the battery. The representation of a tube by a generator and the series resistance r_p is quite common in analyses of tube output characteristics.

By the use of Kirchoff's Laws for alternating current circuits an expression may be worked out for the relation between e_{g2}, the output voltage of the network, and μe_{g1}, the input voltage. The first voltage corresponds to the alternating voltage on the grid of the second tube while the second is proportional to that on the grid of the first tube. The steps of the mathematics are hardly worth showing in detail. The final expression is that given in Fig. 3. This expression contains a group of terms independent of frequency, and two terms containing the quantity P, where P = 2 π x frequency, which are dependent on frequency. The first of these latter is directly proportional to frequency and thus may be expected to interfere with the amplifier performance more at higher frequencies; the second, on the contrary, is important at low frequencies since it is inversely proportional to frequency.

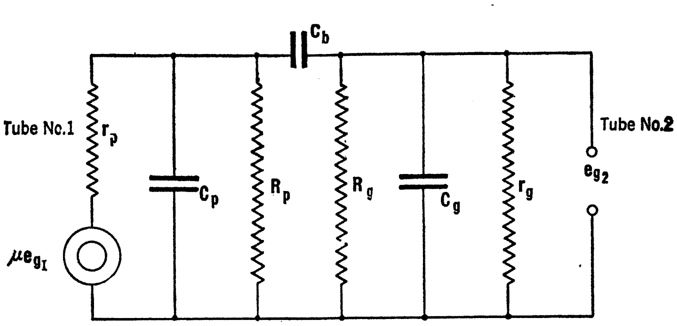
Before investigating the magnitudes of these two frequency effects we must see what the values of the various circuit coefficients are. Certain of them are quite familiar to radio workers, such as the internal plate circuit resistance r_p, the coupling resistance R_p, the grid leak R_g, and the blocking condenser C_b. The quantities C_p, C_g, and r_g have not been in common use, so a word about their magnitudes will hardly be amiss.

The plate-to-ground capacity, C_p, is very nearly the sum of the following:

(1.) Tube inter-electrode plate-filament capacity.
(2.) Tube inter-electrode plate-grid capacity.
(3.) Stray capacities in wiring.

For the Radiotron UX-240 the first two are 1.5 and 8.8 micro-microfarads, respectively.

The quantities r_g and C_g cannot be treated rigorously without going beyond the scope of the present paper. Their magnitudes are de_



SOLUTION:

$$\mu e_{g_1} = e_{g_2}\left[1+\frac{C_g}{C_b}+\frac{r_p}{R_p}+\frac{r_p}{R_g}+\frac{r_p}{r_g}+\frac{r_g C_g}{R_p C_b}+\frac{r_p C_p}{r_g C_b}+\frac{r_p C_p}{R_g C_b} + jPr_p\left(C_g+C_p+\frac{C_p C_g}{C_b}\right)+\frac{1}{jPC_b}\left(\frac{r_p}{R_p}+1\right)\left(\frac{1}{R_g}+\frac{1}{r_g}\right)\right]$$

FIG. 3

pendent on the constants of the plate circuit of the second tube. For our purpose it will be sufficiently accurate to consider r_g infinite as long as the second tube is biased sufficiently. C_g may be expressed as:

$$C_g = C_{gf} + C_{gp}\,(A_V + 1)$$

The reason for the appearance of the quantity $(A_V + 1)$ where A_V is the voltage amplification actually obtained between grid and plate of the second tube, is explained in the appendix on page 240. In practice C_{gf} is usually 3 to 4 mmfd. and C_{gp} 8 to 10 mmfd. while A_V may be between 2 and 25 or more. Accordingly C_g will vary over the range from 20 to perhaps 300 mmfd. The figures given, by the way, do not include the stray capacities in the wiring. It should further be noted that there is no marked difference in the values of these capacities for low and high amplification tubes; that is, the Radiotron UX-201-A for which $\mu = 8$ and the Radiotron UX-240 for which $\mu = 30$, have substantially the same inter-electrode capacities. The Radiotron UX-171 has nearly the same grid-to-plate capacity as the others, but as it has twice their filament surface its grid-filament capacity is somewhat greater.

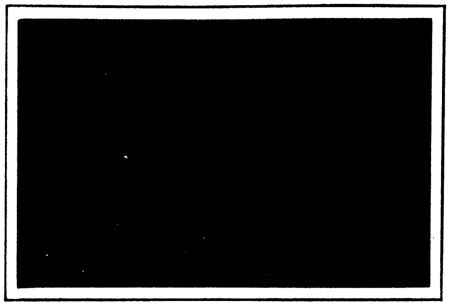


FIG. 6

The frequency characteristic of each individual stage may be calculated by the relation shown in Fig. 3. The frequency characteristic of the complete amplifier is equal, of course, to the product of the frequency characteristics of the individual circuits. Fig. 4 shows certain of these overall frequency characteristics. It should be noted that the use of higher value coupling resistances increases the amplification, but that these increases are always less in magnitude at the upper end of the frequency characteristic than in other portions of the range. Accordingly, the frequency characteristic becomes poorer as the coupling resistance is increased.

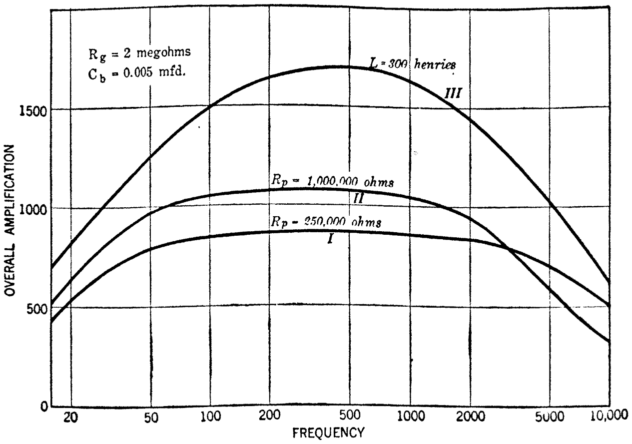


FIG. 4

CHOICE OF AMPLIFICATION FACTOR

THIS is an excellent point in the discussion to take up the question of the choice of the amplification factor. It should be pointed out that this factor is completely under the control of the tube designer so that there is little difficulty in building tubes having values anywhere between 0.5 and 500. Any increase in the amplification factor, however, involves an increase in the plate resistance of the tube, if the filament and plate dimensions and the spacings are kept the same. Fig. 5 shows this variation in plate resistance with amplification for tubes similar to the UX-201-A in plate and filament structures. It may be shown from the mathematical expression in Fig. 3 that any increase in the plate resistance r_p leads to a loss of amplification which will be more pronounced at the high frequencies than elsewhere. Further, as the actual voltage amplification of tube No. 2 is increased, the capacity C_g of Fig. 3 is increased almost directly, as may be seen from the expression already given for it; this capacity increase also tends to make the amplifier "lose" higher frequencies.

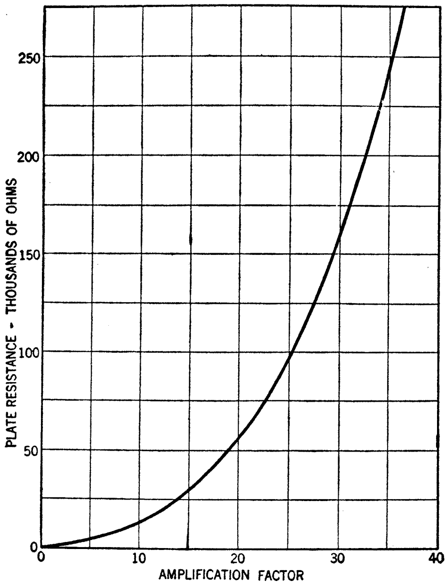


FIG. 5

Accordingly, the choice of the proper amplification factor for a tube for resistance-coupled amplification should be the highest value which is consistent with a satisfactorily flat frequency characteristic. Of course, opinions on frequency characteristics differ, but it is felt that in the design of Radiotron UX-240 the greatest value of amplification factor that should be used in a high-quality receiver has been chosen.

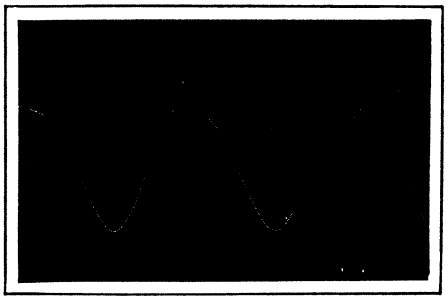


FIG. 7

One of the curves of Fig. 4 shows an experimentally determined overall frequency characteristic when iron-core inductances are used for interstage coupling. The units used have unusually high inductance, but the loss of amplification at low frequencies shows that, even so, impedance coupling was unsatisfactory.

So far we have assumed that the circuit coefficients are constants. Actually this may or may not be a valid assumption in a practical case. The two circuit coefficients which may

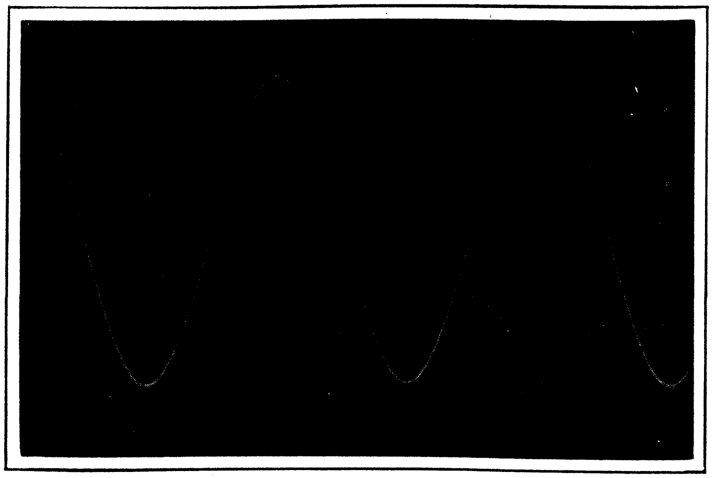


FIG. 8

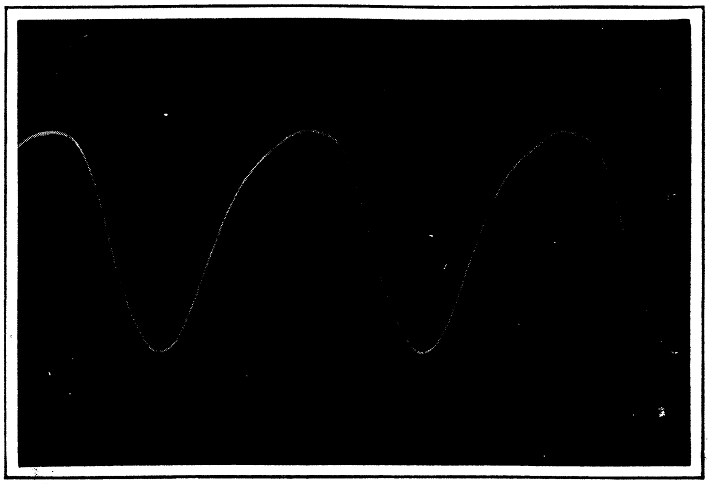


FIG. 9

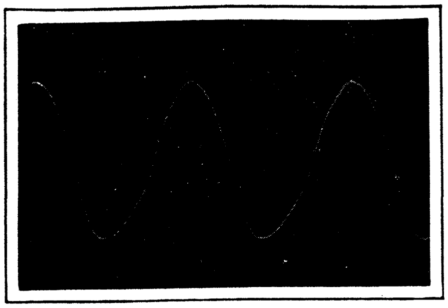


FIG. 10

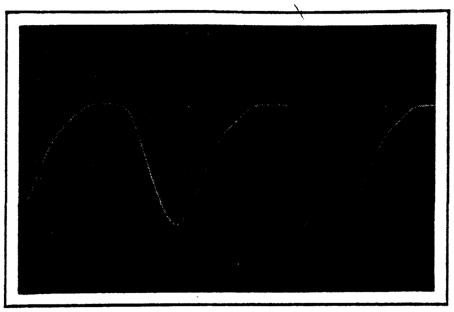


FIG. 11

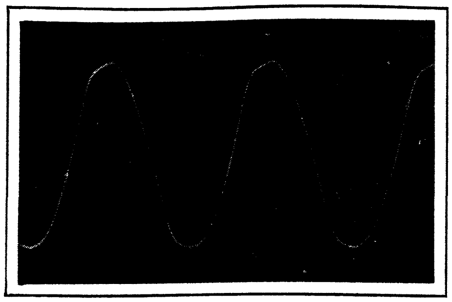


FIG. 12

vary appreciably in practice are the plate resistance and the grid resistance.

Variation of the plate resistance becomes a matter of importance if the plate current is permitted to decrease to too low a value at any time during the cycle. The effect of this may be seen by comparing the oscillograms of Figs. 6 and 7. Fig. 6 shows the output of the UX-240 when operating normally, while in Fig. 7 the negative bias on the grid is excessive. The resulting distortion on the lower half of the plate-current wave is quite objectionable.

Variation of the grid resistance is negligible in magnitude when the grid potential is negative. When the grid becomes positive, however, its resistance falls quite rapidly, and it may, under some conditions, introduce appreciable distortion. If the source of the signal voltage has good regulation there is little likelihood of distortion occurring; the oscillogram of Fig. 8 demonstrates this. It shows the output of the UX-240 for the same signal voltage as in Fig. 6 and 7; that is, 1.06 volts effective, this time with no bias at all. The plate current is obviously undistorted. Fig. 9 shows the rather poor results obtained when the regulation of the signal source is unsatisfactory.

If the tube is operating with a blocking condenser and grid leak and receives sufficient signal to make the grid positive, the electrons which flow from the filament to the grid must continue through the leak and back to the filament. In doing so they will develop a voltage drop across the leak which will bias the grid negative; the trouble will thus be largely self-correcting. Fig. 10, which illustrates this point, was made under the same conditions as Fig. 9 except that a blocking condenser of 0.015 mfd. was interposed in the lead from the grid to the signal source and a grid leak of 1 megohm was connected from grid to filament. The improvement in output wave form over that of the preceding oscillogram is quite striking.

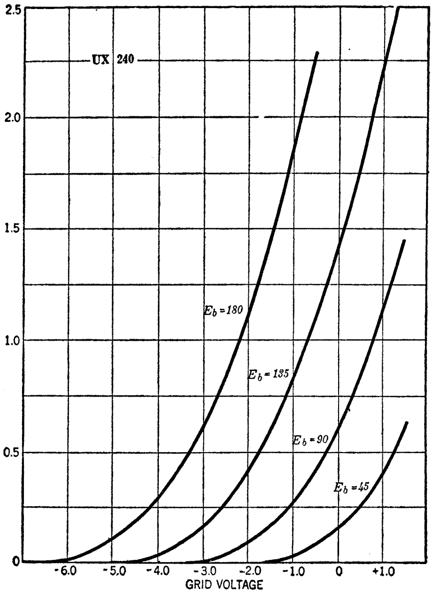


FIG. 13

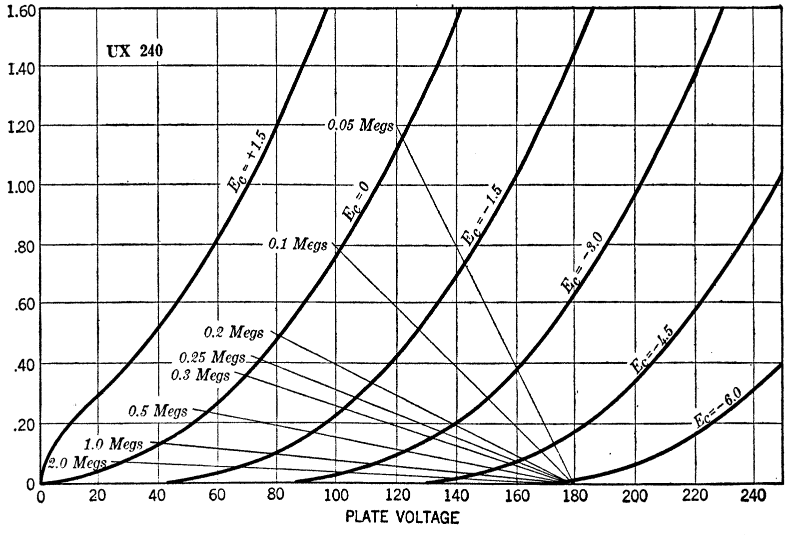


FIG. 14

Fig. 11 shows the distortion that occurs with no bias and the same signal amplitude as before, when the signal is supplied from another tube through an interstage transformer. Here the grid current cannot bias the tube appreciably as it has a low-resistance return to the filament and hence produces only a negligible IR drop. In the record of Fig. 12 this condition has been corrected by the introduction of a suitable bias.

Perhaps a word about the UX-240, the tube on which our work is based, would not be amiss. In external appearance this tube is identical with the UX-201-A. The filament characteristics and ratings are also identical. Normal operating conditions for the tube are 1.5 to 3 volts grid bias, 135 to 180 volts plate supply voltage, with a 250,000 ohm resistance in series with the plate. Under these conditions the actual voltage amplification will be between 15 and 20, representing better than 50 per cent. utilization of the tube's inherent amplification factor of 30.

Fig. 13 shows the mutual characteristics of the tube and Fig. 14 shows a family of plate characteristics. These are the two forms in which static characteristics are conventionally shown and are reproduced for that reason.

APPENDIX

THE change in grid-to-ground capacity introduced by the plate and plate circuit of the tube may be treated as follows: In the case of a resistance-coupled circuit having substantially unity power factor, so that there is no appreciable phase shift, let us observe what happens when the grid is raised in potential 1 volt. The plate potential falls by an amount A_V volts, where A_V is the actual voltage amplification which the stage is furnishing. Now, across the direct grid-filament capacity we have introduced a net change in potential difference of 1 volt, and accordingly the quantity of electricity which will raise this potential difference 1 volt is added to that already providing the electro-static field between grid and filament. Across the direct grid-plate capacity we have introduced voltage changes of 1 volt at the grid side and of A_V volts at the plate side, the two changes being of the same sign insofar as their effect on the electrostatic phenomena is concerned. As a result, a quantity of electricity sufficient to change the grid-plate capacity to $1 + A_V$ volts must flow on the grid.

By combining these two terms we find that the effective capacity from grid to ground is:

$$C = C_{gf} + C_{gp}\,(1 + A_V)$$

It should be noted that a general treatment of this capacity effect is, ipso facto, a study of regeneration due to inter-electrode capacity.