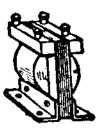
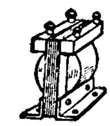
Overloading the Audio Amplifier

By SYLVAN HARRIS

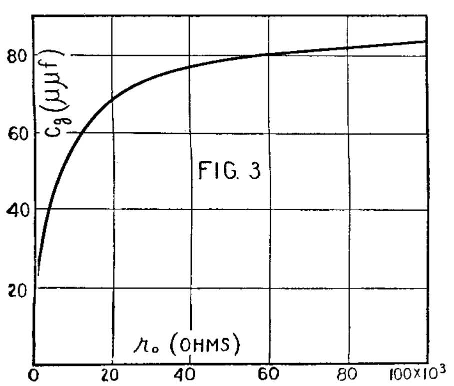



Continuing the series by Mr. Harris, this article discusses some of the conditions that are met in the design and operation of audio-frequency amplifiers. The salient point here expressed is that, contrary to the general assumption, audio amplifiers do not work into open circuits, but into surprisingly low impedances.

WHEN this series of articles on audio amplifiers was begun the writer did not stop to think how complex it would turn out to be. The study is leading us into many questions which have never occurred to us before; this is just as well, however, for the research is turning out to be very interesting, and very much worth while.

The readers of this series of articles (of which this is the fourth) may be beginning to wonder: "When are we going to read about the construction and design of amplifiers?" It is probable that the study of the characteristics of the different kinds of amplifiers will be begun in the next issue of RADIO NEWS.

But, before discussing the amplifier characteristics, it is necessary that we should completely understand what is required of an amplifier and what difficulties we may meet, in both its design and its operation. It is for this reason that we have discussed at such length the subjects of overtones or harmonics, distortion, means of illustrating the characteristics, etc., in our previous articles. In this article we will discuss the causes of *overloading* the amplifier, the effect of this overloading on the quality of reproduction, and consider somewhat the nature of the load as it affects the output of the amplifier coupling device.

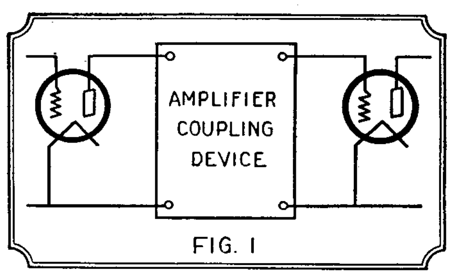


The input capacity of a tube depends on the resistive load in the plate circuit. How it varies with this resistance, for a 201A tube, is shown in this curve.

The last subject will be dealt with but lightly in this article, for it will be considered more in detail later on when we discuss the amplifier circuits themselves. It is necessary to introduce the subject beforehand in order to make the following article intelligible.

INTERNAL CAPACITY OF A TUBE

To begin, then—let us look at Fig. 1. Here we have two electron tubes coupled by an amplifier coupling device, which may be an audio transformer, or a network of various combinations of resistors, condensers, and impedances. The action of the complete amplifier is so complicated that, in order to simplify the problem, assumptions are generally made on the basis of ideal operation. To be specific, since in the *ideal electron-tube repeater* (or amplifier) no current is supposed to flow between the grid and filament of the tube, it is supposed that the input impedance of the tube is *infinite*.



An amplifier coupling device is connected at its input side to the impedance of the plate circuit of the tube preceding; on its output side to the impedance of the grid circuit of the succeeding tube.

In general, the grid of the tube is made sufficiently negative, by means of biasing batteries, so that no *convection current* flows between the grid and filament. This biasing does not, however, prevent the flow of alternating current through the condenser formed by the grid and the filament. In other words, the grid and filament can be considered as two plates of a condenser; and it is well known that current will flow through such a condenser when an alternating potential, such as the signal voltage, is impressed across its terminals.

It has been shown (J. M. Miller, U. S. Bureau of Standards, Scientific Paper 351) that the input impedance of an electron tube may be represented by a capacity in series with a resistance. Furthermore, it has been shown (ibid.) that this capacity is not the simple electrostatic capacity existing between the filament and grid, but is much greater; as the capacity existing between the grid and plate and that between the plate and filament have an effect on the input capacity. The idea is illustrated in Fig. 2A and the equivalent electrical network in Fig. 2B. The voltage μe_g shown in Fig. 2B is the voltage developed in the plate circuit of Fig. 2A by an alternating input voltage e_g.

FORMULA OF INPUT CAPACITY

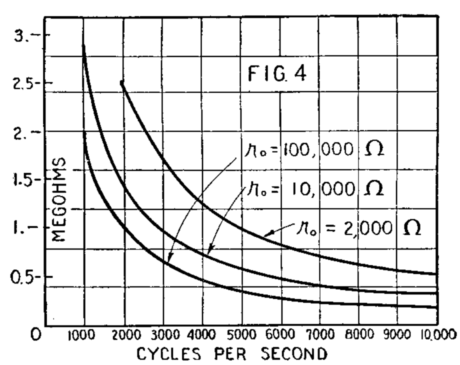
If the capacity of the network be measured between the points a and b (Fig. 2B), the apparent input capacity of the tube will not be merely C_1 but will be

$$C_g = C_1 + C_3 \left(1 + \frac{\mu r_o}{r_p + r_o}\right)$$

in which C_g is the apparent input capacity, C_1 is the grid-filament capacity, C_3 is the grid-plate capacity, μ is the *voltage amplification constant* of the tube, r_p is the plate resistance of the tube, and r_o is the resistance of the load in the plate circuit. This load is not shown in the figure; in a resistance-coupled amplifier r_o would be the resistance connected between the plate and the "B" battery; in a transformer-coupled amplifier it would be the *resistance* (not impedance) of the transformer.

Now, to investigate the magnitude of this input capacity for the UX-201A tube, the following constants have been assumed for the sake of argument:

C_1	10 $\mu\mu$f.
C_3	10 $\mu\mu$f.
μ	7
C_p	10,000 ohms



This curve shows how the reactance, due to the input capacity of a tube, varies with the frequency, for various resistive loads in the plate circuit. Note that over the most important part of the acoustic-frequency range, the reactance may be less than one megohm.

These values are likely to vary in different tubes, and with different plate voltages; but they will at least give us a fair idea of the magnitude of the input capacity, when substituted in the expression given above. From these values the curve of Fig. 3 was computed for different values of load resistance, varying from zero to 100,000 ohms. The latter value of the resistance is probably the greatest that is used in resistance-capacity-coupled amplifiers; and of course zero resistance is much lower than the resistance of transformers. It is evident, then, that this curve covers all practical cases for the tube in question; and it shows that the input capacity may be as high as eighty micro-

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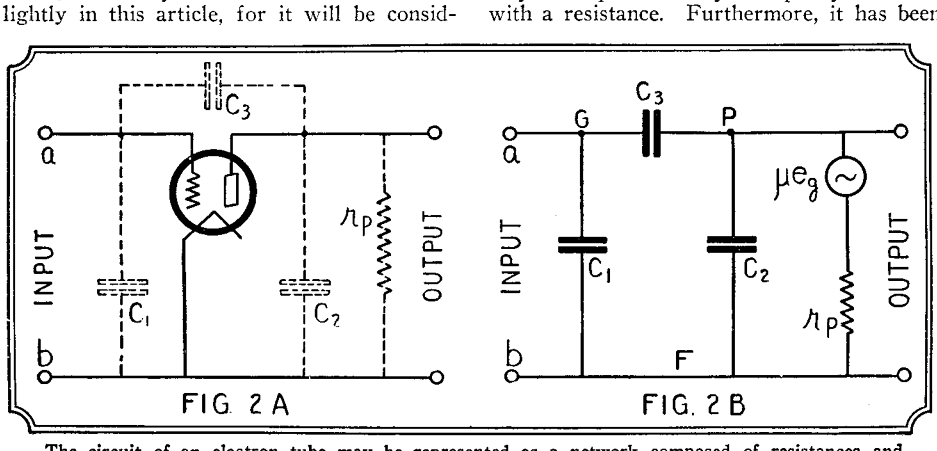

The circuit of an electron tube may be represented as a network composed of resistances and capacities. C_1 is the grid-filament capacity, C_2 the plate-filament capacity, C_3 the grid-plate capacity, r_p is the internal-output impedance (or, simply, the plate resistance of the tube), and μe_g is the emf developed in the plate circuit by the alternating voltage on the grid.

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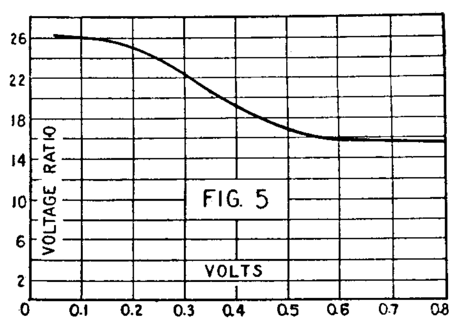
microfarads (80 $\mu\mu$f.) and in some cases higher. We will consider later on the particular values which apply to the different types of amplifiers.

EFFECT OF FREQUENCIES

It has been mentioned before that the input of the tube can be regarded as a condenser in series with a resistance. Expressions for the resistance are also given by Miller; but a few brief calculations will show that this resistance is small compared with the reactance due to the capacity, so we will neglect it. The input impedance of the tube is therefore the reactance of the input capacity, and this is shown in Fig. 4 for several different resistances in the plate circuit. The range of frequencies covered by this curve is the audible range, for we are considering audio amplifiers.

The curves of Fig. 4 show plainly that, for frequencies higher than above 2,000 cycles per second, the input impedance of the tube may be less than one megohm, and for frequencies even higher than this, or for large-load resistances, may be as low or lower than a half a megohm. It is evident, therefore, that we have no right to assume that the transformer or other coupling device works into an open circuit; for since the input impedance of the tube is not infinite, but in some cases relatively low,



Showing the change in a tube-transformer amplifier's voltage ratio at a constant frequency. Note how the ratio falls off as the input increases.

it may present an appreciable load on the coupling device.

The effect of this load on the operation of the transformer, impedance or other coupling device may also be quite appreciable, in that it may effect the voltage regulation. By the term "voltage regulation" we mean the drop in secondary voltage that occurs, at a given frequency and for a given voltage input to the coupling device, when a load is placed on the output. In other words, suppose we have a certain voltage impressed at a certain frequency on the primary of a transformer. When there is no load on the secondary, that is, when the secondary is working into an open circuit, there will be a certain voltage across the secondary terminals. If, now, a load is applied to the secondary the voltage at the terminals of the latter will drop. The percentage drop in voltage is the voltage regulation. The same idea applies to any type of coupling device if we replace the word primary by the word "input" and the word secondary by the word "output."

OVERLOADING THE GRID

Another serious effect occurring in amplifiers is overloading the grid. Suppose the path from the grid to the filament outside the tube has a very high resistance; as, for instance, in the case of a resistance-capacity-coupled amplifier in which the grid-leak re-

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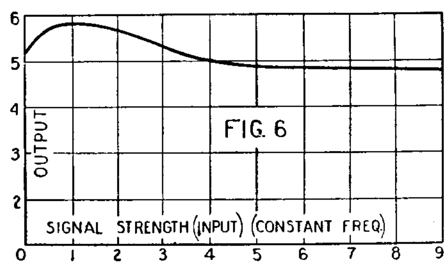
sistance is too high. As everyone knows, the grid will collect electrons, since it is in the path of the electrons flowing from the filament to the plate. The accumulation of electrons on the grid, when the leak-resistance is very high, may cause the grid to assume a relatively high potential. When this potential becomes sufficiently high the charge on the grid will leak off through the leak resistance, and we will have periodic charges and discharges of the grid, giving rise to the effect we often notice when we have an "open grid."

The number of these discharges per second, that is, their frequency, depends on the constants of the circuit, and may be anything, from a very low frequency producing a click, to an inaudibly-high frequency. Whether the click is audible or inaudible, it will have its effect on the quality of reproduction; for the clicks of inaudible frequency may combine with, or modulate, the voltages of audible frequency which we wish to amplify.

To illustrate the effect we are discussing, the voltage ratio of a well-known transformer working with a tube was measured at a constant frequency under varying impressed voltages. The results of the meas-



The effect of overloading on the output of an amplifier; it actually diminishes as the signal strength increases.

urements are shown in Fig. 5. The horizontal scale represents the input voltage and the vertical scale represents the ratio of the output to the input voltage; or, in other words, the voltage ratio of the combination of tube and transformer. It will be noted that the voltage ratio of the combination does not remain constant for different impressed voltages, as it should for ideal operation. Furthermore, notice that it drops off at about 0.2-volt input.

OPERATION OF LOUD SPEAKERS

This raises some interesting questions as to the voltages required to operate loud speakers. If we take a transformer having a ratio of 3 to 1 and a tube having an amplification constant of 7, the total voltage ratio of the combination will be 3×7 or 21; and this multiplied by 0.2 volt gives about 4 volts as the maximum to be impressed on the loud speaker, without overloading this particular transformer.

To test the effect of this voltage on the volume output of the loud speaker, a potential of 4 volts at the output of an audio-frequency oscillator was impressed directly upon various loud speakers at various frequencies. In some cases great volume resulted; in other cases not so much; depending upon the particular loud speaker used. The test indicated, however, that to operate good loud speakers much lower voltages are required than ordinarily imagined.

In Fig. 6 we have shown the overloading effect on a resistance-capacity-coupled amplifier, the curve of which was obtained in a different manner. A radio-frequency oscillator, modulated by a 1,000-cycle tuning fork, was set at various distances from a non-regenerative receiver employing a detector tube and three stages of resistance-coupled amplification. The frequency of the oscillator was kept constant. Connected to the output of the amplifier was an indicating device. In arbitrary units, therefore, the

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horizontal scale of Fig. 6 represents the distance between the oscillator and the receiver (or the signal strength) and the vertical scale represents the output of the amplifier. It will be noted that, after a certain maximum signal strength has been attained, the output of the amplifier not only ceases to increase as the oscillator is brought closer to the receiver, but is actually diminished, due to the overloading.

The effect of such overloading is evident. If we are listening to a concert and amplify up to the point of overloading, the shading of the music will be lost. *Piano* and *Forte* will mean nothing; strong fundamentals will be amplified less than the weaker overtones; the timbre will not be true, and the interpretation of the artists will be lost.