Does Resistance Coupling Give Best Quality?

Results Are Dependent on Resistance and Capacity Values

By SYLVAN HARRIS

THE title of this article may come as a surprise to many of those who will read it. There is a general feeling that, if one desires the best quality of production from his radio receiver, all he has to do is to use resistance coupling in his audio amplifier in preference to any other type. This idea has been played up by many radio publications and in many advertisements, but as far as the writer is aware, no one has publicly raised the question which furnishes a title for this article.

There are two sides to every question—is it so, or is it not? And, if not, then why not? These are questions which will be discussed in this article in connection with the resistance-coupled amplifier. The presentation of facts is based on a paper written by the present writer, published in the December, 1926, issue of *Proceedings of the I.R.E.*

ELEMENTS OF THE CIRCUIT

Before we discuss these questions, let us consider some of the advantages of resistance coupling. First of all, the circuit of a complete resistance-coupled amplifier is shown in Fig. 1. The development of this type of amplifier has been described in detail in an article by the writer, entitled, "Types of Audio Amplifiers," published in the October, 1926, issue of RADIO NEWS. The plate current for the various tubes in the amplifier flows through resistances marked r1 in the diagram. In order to prevent the high positive voltage of the "B" battery from charging the grids of the succeeding tubes, it is necessary to use blocking condensers, marked C in Fig. 1. Then, since this would leave the grids of the tubes "free," it is necessary to connect across the grid and filament of each tube a grid-leak resistance, marked rg in the diagram. This completes the amplifier, as far as the circuit arrangement is concerned. But the action of the amplifier, with regard both to its amplification and to its ability to reproduce with good quality, depends upon the values of the resistances and condensers used.

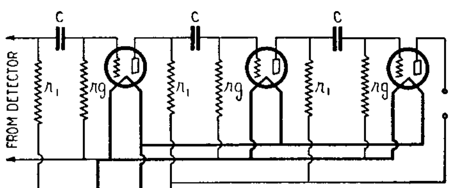

FIG. 1

The circuit diagram of a typical resistance-coupled audio-frequency amplifier.

This circuit has advantages which are not possessed by transformer-coupled amplifiers. At the same time do not forget that there are advantages possessed by transformer-coupled amplifiers and not by resistance-coupled amplifiers. A very important advantage of the resistance amplifier is the fact that there are no such things as resonance peaks, which often occur in transformers having considerable coil capacity.

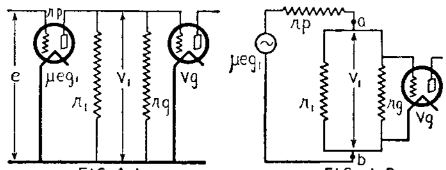

FIG. 4-A FIG. 4-B

When the capacity of C (Fig. 2A) is high or the frequency is high, then the diagrams of Fig. 2 become those above.

Another advantage is that the resistances r1 and rg (Fig. 1) function independently of the frequency. In transformers, at very low frequencies, say 60 cycles, the impedance is very much lower than the impedance at higher frequencies, say 1,000 cycles. Consequently the bass notes of the organ or other music are not amplified as much as the high notes, and in some cases are lost altogether. This matter has been discussed in great detail by the writer in his series of articles on amplifiers in general, in RADIO NEWS.

SOME DISADVANTAGES

Such are the claims for all resistance-coupled circuits, but there are features which are too often neglected. One of the most important of these is that the presence of the blocking condenser in the circuit makes the resistance-coupled amplifier susceptible to a drop in amplification at the low frequencies of the bass notes, just the same as that we encounter in the transformers. We will understand how important this is, later on, and will find that in order to obtain good reproduction it is necessary to use much larger condensers than are ordinarily provided for resistance-coupled amplifiers.

The resistance-coupled amplifier has other disadvantages which must be weighed against its advantages, besides the important one mentioned. One of these is the low amplification, per stage, which is possible. The maximum amplification *theoretically* obtainable is equal to the voltage amplification factor of the tube. Using the 201A type of tube, therefore, the most we could ever hope to get in the way of amplification per stage is about 7, as contrasted with from 20 to 30 for the transformer-coupled amplifier.

ANALYSIS OF THE ACTION

Of course it is not possible to obtain the maximum theoretical amplification. The actual amplification is always lower than this. We can see why if we look at Fig. 2. In Fig. 2A we have shown one stage of the resistance-coupled amplifier of Fig. 1. In this circuit is indicated the plate resistance of the tube, which is marked rp. Alongside, in Fig. 2B, is shown the equivalent circuit, that is, one which is equivalent in every respect to the circuit of Fig. 2A, excepting that the first tube has been replaced by an alternator which delivers an alternating voltage of µeg1 and the latter is in series with rp. The voltage µeg1 is the voltage developed at the plate of the first tube when a signal voltage e is impressed on the input of the first tube of Fig. 2A.

If you will compare the two circuits you will find that they are electrically equivalent. Of course, we have omitted the "A" and "B" battery connections because we are concerned only with the action of the alternating voltages. Now we are interested in comparing the value of the grid voltage on the second tube with that of the voltage developed in the plate of the first tube. That is, we want vg to be as large as possible compared with µeg1. It is evident that vg can never be as as great as µeg1.

We shall see why directly. In the first place it will be seen that the voltage impressed on the second tube, vg, is only a part of the voltage across the resistance rg and the condenser C. This voltage is marked V1 in Fig. 2B. The reason for this is that part of the voltage V1 is used up in the condenser C, where it does no good. The only voltage that does any good is that which gets to the input of the second tube.

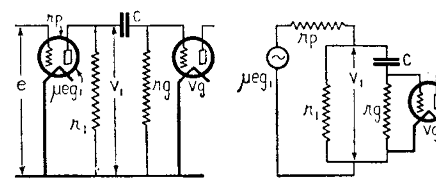

FIG. 2-A FIG. 2-B

These circuits are the equivalent of a single stage of the amplifier in Fig. 1.

Going a step further we notice that the voltage V1 is only a part of the total voltage developed at the plate of the first tube (µeg1), for a part of the total voltage is used up in the plate resistance rp of that tube. It is evident, therefore, that there is no amplification in the coupling device, but on the contrary there is attenuation; which is a polite way of saying that there is a loss instead of a gain. We amplify, say, seven times in the tube, and then lose perhaps 20 per cent. of this in the coupling device, bringing our net amplification per stage down to perhaps five or a little more. The ampli-

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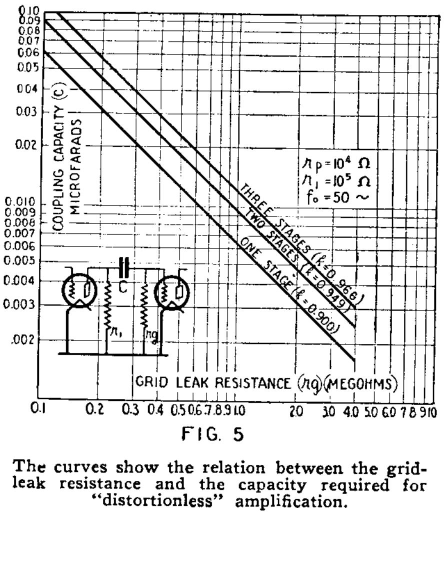
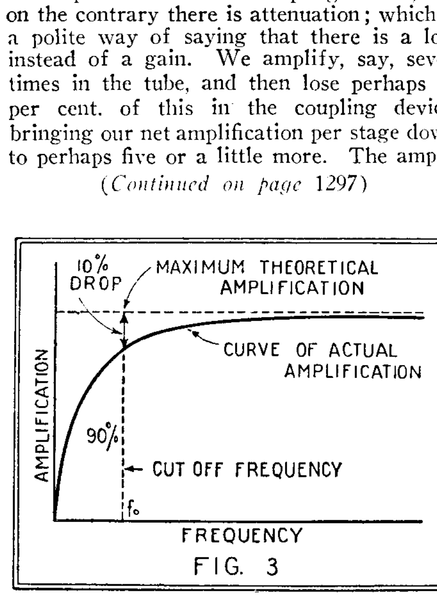


FIG. 5

The curves show the relation between the grid-leak resistance and the capacity required for "distortionless" amplification.



The above curve shows the actual amplification obtained in a resistance-coupled amplifier.

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fication we lose in the coupling unit depends on the design, as well as the frequency which we are amplifying, but we may take these figures as fair for the average resistance amplifier at frequencies not too low.

All this would be well if there were no other complications. We might convince ourselves that we can stand a loss of this amount to obtain better quality. Better to use an extra tube or two to bring the volume up, than use amplifiers of poor quality, giving high amplification but music not worth listening to. But we must not forget the condenser in the circuit. If none of the elements in the circuit varied with the frequency, we would be able to obtain perfectly undistorted reproduction out of the amplifier. The amplification would be exactly the same, no matter what the frequency of the note we wanted to amplify—bass-note, or otherwise.

EFFECT OF CONDENSERS

But unfortunately all the elements do not function independently of frequency. The resistances do, but the condensers do not. The condenser has a high reactance at low frequencies, and this decreases as the frequency becomes higher. The voltage V1 in Fig. 2B is divided between the condenser C and the grid-leak resistance rg. At low frequencies, when the reactance of the condenser is high, there may be a greater proportion of the voltage V1 across the condenser, where it does no good, than across the resistance rg, where it is impressed where we want it; that is, on the grid of the second tube.

As the frequency becomes higher, the reactance of the condenser decreases; consequently the voltage across it becomes a smaller and smaller part of the voltage V1, and the part of this voltage across the grid leak resistance becomes greater and greater. In other words, even in the resistance-coupled amplifier we can expect poor amplification at low frequencies, and higher amplification at higher frequencies.

THE BOTTOM FREQUENCIES

The next thing to consider is, "How serious is this variation of the amplification, and what must we do to keep it small?" In order to answer this question let us look at Fig. 3. This shows the shape of the curve of actual amplification obtained in a resistance-coupled amplifier. The shape is very similar to that of a curve for a transformer-coupled amplifier. At the top of this figure is a broken line, which indicates the maximum amplification theoretically obtainable with a given combination of plate and grid resistances.

At very low frequencies the amplification is low, as we have seen before; it rises rapidly at first as the frequency is increased, and then becomes nearly horizontal, gradually approaching the theoretical maximum at very high frequencies. Now let us assume that there is a certain frequency below which we need not amplify. We will call this the "cut-off" frequency. It may be say, 50 or 60 cycles. We rarely encounter musical notes having frequencies lower than this; so it is immaterial whether we amplify them or not, as far as quality of reproduction is concerned.

The problem then resolves itself into this question, "How much drop in amplification can we tolerate at the cut-off frequency?" Dr. Harvey Fletcher of the Bell Telephone Laboratories has answered this for us. In one of his papers in the *Bell System Technical Journal* he has shown that the human ear is sensitive to changes of sound intensity of about 10% and more. We must, therefore, not allow the amplification to drop more than 10% in the entire amplifier, while the frequency is changing from a high value down to the cut-off frequency.

Note that I have said that this must be true of the *entire* amplifier. Where there are three stages used in the amplifier, the drop in amplification that can be tolerated *in each stage* is only 3.4%. This can be understood clearly when we remember that if we have a drop of 10% we must have available 90%, or 0.9 of the maximum voltage amplification. The cube-root of 0.9 is 0.966, which requires that for three stages, 96.6% of the maximum amplification be available in each stage. This means a tolerable drop of 100—96.6, or 3.4%. The requirements are, therefore, more stringent than one would ordinarily think. They are made more so because we have to use three stages in order to obtain sufficient amplification. If we had to use only two stages we could tolerate a drop of about 5% in each stage.

FUNCTIONING OF RESISTANCES

We will come back to this a little later on. Let us now consider the effects of the resistances in the coupling device. The prime requisite of an amplifier is to amplify; hence its name. We should so proportion the circuit elements so as to obtain as much amplification as possible, without introducing difficulties. The amplification can be made to approach the voltage amplification of the tube by

(1) Making the plate resistance r1 high.
(2) Making the grid-leak resistance rg high.

There are involved, in doing these things, limitations which are independent of the blocking condenser. So let us assume for the moment that the blocking condenser is so large that it offers negligible reactance to the alternating currents, or that the frequency is high, which amounts to the same thing. We should then have the conditions for maximum amplification with given combination of resistances. When either the condenser is large or the frequency is high, the circuit then reduces to that shown in Fig. 4A, for the reactance of the condenser is small and may be neglected. The equivalent circuit is shown in Fig. 4B. Note that 4B is the same as Fig. 2B with the condenser C short-circuited.

The whole of the voltage V1 is then impressed on the input of the second tube; that is, vg is equal to V1. This shows very clearly the effect of the condenser in influencing the amplification. The circuit is therefore the equivalent of an alternator in series with a resistance rp and a parallel arrangement of r1 and rg. From this arrangement it is possible to determine the maximum amplification possible with a given combination of resistances. This maximum theoretical amplification is equal to the resistance between the points *a* and *b* of Fig. 4B, divided by the sum of this resistance and the plate resistance rp, multiplied by the "mu" (amplification factor) of the tube. This gives the overall maximum amplification with this combination of resistances.

We may increase the plate resistance r1, in order to increase the amplification, but the limitation to this lies in the "B" battery. When the plate resistance is high we are forced to use a very high-voltage "B" battery, which becomes unwieldy and costly. The value of r1 which has been found to work satisfactorily in practice, with 201A tubes, is about 10,000 ohms.

We may try to increase the amplification by making the value of the grid-leak resistance high; but when we do this we make it more difficult for the grid charge to leak off the grid. This is the very reason why we were forced to introduce the grid-leak resistance into the circuit, so we must be very careful about its value. If it is too high, the tube "chokes up"; there are likely to be grid "clicks" or even "howling" of the amplifier.

But even without considering the blocking of the grid, there is a practical limit to the resistance, beyond which it does not pay to go. It is shown in the paper previously referred to that, when using a tube having a plate resistance of about 10,000 ohms, and a resistance r1 of 10,000 ohms, little is gained in amplification by making the grid leak resistance higher than about a half a megohm.

Let us suppose then that we are going to adopt these values for our resistance-coupled amplifier. The next question is "How large should the condenser be so that the amplification will not drop more than 3.4 per cent. per stage at a cut-off frequency of 50 cycles?"

DESIGNING THE AMPLIFIER

It will not be possible to explain in this popular journal how this question is answered. For the technical details the reader is referred to the more technical paper. Let it be sufficient to say that when the circuit of Fig. 2B is analyzed, an equation can be derived from which the chart of Fig. 5 was plotted. This chart shows the relation between the grid-leak resistance and the capacity required in the resistance-coupled amplifier, in order that the amplification may not drop more than 10% in the *entire* amplifier, from the high frequencies to the cut-off.

To show how this chart is applied, take the present example, where rp is 10,000 ohms (which may stand roughly for a 201A tube) and rg is half a megohm. Also suppose there are three stages to the amplifier. By following the broken line upward from the point representing a half-megohm for rg, to the line marked "Three Stages," and then over horizontally, we find the capacity required in the condenser C.

It will be noted that this value is very much greater than that ordinarily used. It will also be noted that, if we wish to use a smaller condenser we may do so, provided we increase the value of the grid-leak resistance. But we may run into trouble by doing this as we have seen before, and the amplifier may start to "howl." The tendency to "howl" depends upon many things; and certain values of resistances and condenser which may cause one amplifier to howl may not cause such trouble in another. The condenser to be used should not become too large, either, as there are other difficulties involved, such as the "time lag" in the combination of condenser and grid leak. It may take too long for the condenser to charge up and pass the current through to the resistance; so that distortion may arise from this cause.

The main point of this whole discussion is that larger condensers must be used to make resistance-coupled amplifiers all that many believe or claim them to be; and that under no circumstances can "perfect" reproduction be obtained with them. They can, however, be made so "perfect" that the human ear cannot detect the departure from perfection, but this can be done only by the sacrifice of amplification, and use of additional stages. "All is not gold that glitters" and "All resistance-coupled amplifiers are not distortionless amplifiers."