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The A B C of Amplifier Circuits

By GEORGE CROM

A Paper Delivered Before the The Radio Club of America on Febuary 26, 1928

THE definition of an amplifier can be taken as: A device which produces in its output circuit an enlarged image of whatever is impressed in its input circuit. That is, an applied voltage of any shape passing through the amplifier should give a higher voltage of the same shape.

According to this definition a vacuum tube is not an amplifier. It is a converter as it produces in its plate circuit a *current* that is an image (more or less true) of the *voltage* impressed in its grid circuit.

Now to make an amplifier out of the vacuum tube, circuits must be set up fulfilling certain conditions, and power must be readily available to permit the tube and its circuit to reproduce the large voltage that is desired.

To convert the alternating current in the plate circuit into a voltage, the current must be made to flow through an impedance, which, as direct current must also flow, may take the form of an inductance or a resistance. This plate alternating voltage is applied between the plate of the tube and the filament, the points where the current leaves and returns to the tube, driven by the voltage produced by the grid circuit. The voltage-drop across this plate impedance is then applied to the next tube.

The three power sources that supply the tube, so far as the amplifier is concerned, are only in the way. It is necessary to have them, but if they could be eliminated and the tube would still operate, much better results would be obtained. We are mainly interested in the alternating current circuits and an ideal amplifier would appear as in Fig. 1. The alternating current circuits in this figure are indicated by means of double arrows.

The requirements for the ideal amplifier are:

One: The external grid impedance shall be of the same order as the grid-filament impedance of the tube, so that the voltage thereby applied may be most effective. This is a relatively simple requirement as no appreciable current flows in this circuit.

Two: The external plate impedance must be very much larger than the plate impedance in an interstage amplifier. Only a voltage is applied to the following tubes, no power, and this voltage should be as high as possible. The plate circuit may be regarded as a constant current generator (with constant applied voltage on the grid) and the maximum plate voltage will then be developed by the maximum impedance. The external plate impedance should be as large as it is physically

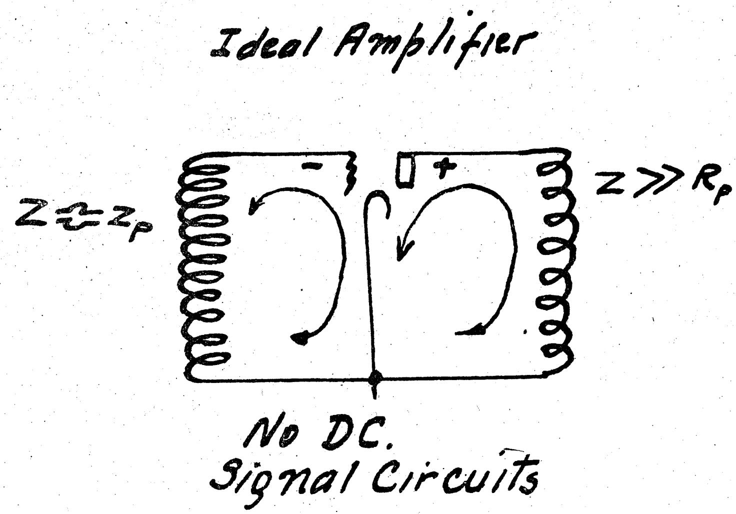

FIG. I

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possible to make, without getting into difficulty with other parts of the circuit, such as d.c. voltage drop, tendency to regeneration, low ratio of transformation, etc., The limits are physical ones and not of design. A discussion of this point can be found in the *Bell System Technical Journal* of July, 1927, and in the *Proceedings I.R.E.* for August, 1927. In an output amplifier (the last stage) power must be applied to the load and the external impedance should, therefore, be of a value that would give the maximum energy transfer. This value will vary with the condition, but should be of the order of $\frac{4}{3}$ to 2 times the plate impedance. Refer to the *Bell System Technical Journal* article noted above.

Three: There shall be no feed-back from the plate circuit into the grid circuit. The grid circuit is sensitive to small voltages while large voltages are developed in the plate circuit. The input and output impedances should not couple magnetically. The wires from the grid and filament to the input impedance should be close together in order to reduce the area of the single-turn loop they form. If these leads are of appreciable length they should be twisted together to reduce the field set up. This is especially true in high-frequency amplifiers where a loop of 6″ on a side will have large inductance and may be enough to make an oscillator circuit.

The plate and filament leads to the plate impedance should likewise be kept together and twisted, if necessary. As the current in these leads is relatively large, the field set up may be extensive and is a common cause of regeneration. Twisting these input and output leads does no great harm. Most radio-frequency circuits where the capacity introduced will have the greatest effect already have condensers as part of these impedances and these condensers can, therefore, be reduced slightly to compensate the capacity of the leads.

Four: Neutralization should be used if there is sufficient signal voltage in the plate circuit to transfer enough energy back to the grid circuit to cause regeneration, through the capacity of the tube itself.

THE PRACTICAL AMPLIFIER

IN FIG. 2 is shown a general amplifier as it actually is. The big change from the ideal amplifier is caused by the necessary addition of the power sources. These power sources or source are represented by an impedance, usually a resistance, having a direct current drop through it, so that one end is positive and the other negative. The filament circuit, usually, takes no part in the operation of the amplifier and should be neglected, except where it does enter. The various B and C voltages are taken off as shown. Usually, more than one stage is used at a time and all the B

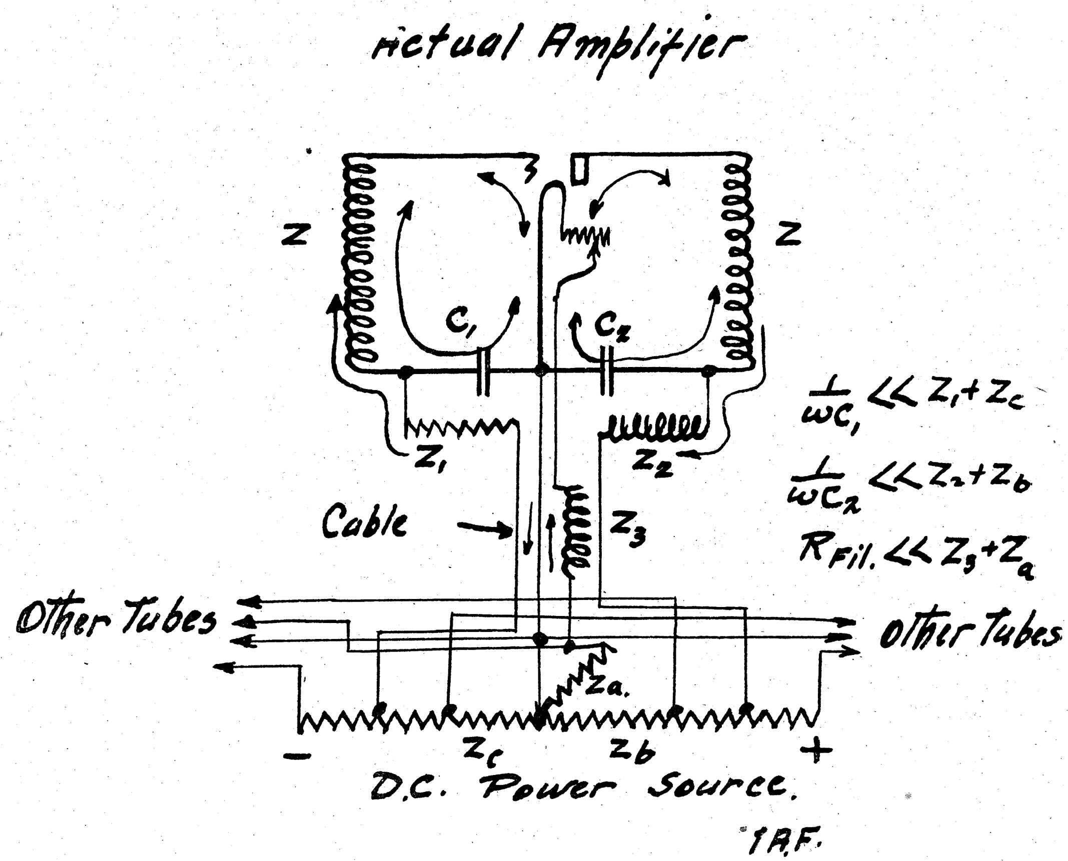

FIG. 2

and C voltages are taken off at various points of this common impedance, with d.c. flowing through it.

If the alternating current in the input or output circuits of one stage flows through the impedance of the power source, it will cause a voltage drop in it, which will be applied to the circuits of the other stages and regeneration, or even oscillation, will take place. This is the cause of "motor-boating," low frequency distortion, paralyzed tubes, howls, and similar symptoms of regeneration.

In order to keep the signal current out of the sources of power, it is necessary that condensers be placed between the filament of the tube and the lower ends of the input and output circuits. The conditions to make these condensers (by-passes) effective are: (1) In the grid circuit $\frac{1}{wc_1}$ shall be very much less than the impedance of the external circuit. And, likewise, $\frac{1}{wc_2}$ shall be very much less than the impedance of the external plate circuit.

If we examine these conditions we find that we can make C large or we can make the external impedance large. In the grid circuit, only a very small direct current flows from the power source to the grid so that Z_1 can be a large resistance of small size, or a large coil on a small iron core. In the plate circuit, appreciable direct current may flow so that the value of Z_2 as a resistance must be low, unless the d.c. voltage is raised to compensate its drop, or a choke on a proper iron core may be used. The direct current flowing in the filament circuit is so large that it is difficult to increase the external impedance. Another fact also causes trouble here. The impedance of the average source of filament power is very much less than 20 ohms, which is the resistance of the average filament, so that it is almost impossible to get a big enough condenser to have sufficient low impedance at 60 cycles for an audio amplifier. In such cases, it is better to omit the filament condenser and to introduce a choke coil of low d.c. resistance in the positive filament line. In precise measurement circuits, such a choke is necessary, although in ordinary amplifiers it is not needed. In radio-frequency amplifiers, by-pass condensers can be used that will have low impedance and when placed across the filament circuits will assist in removing coupling.

At 60 cycles, a 1.0-mfd. condenser has an impedance of about 2650 ohms. This is the lowest value condenser that should be used in an audio amplifier. A 50,000-ohm leak if used in the Minus C lead will pass less than $\frac{1}{20}$th of the grid signal current at 60 cycles when a 1.0-mfd. by-pass is used. The secondaries of the cheaper forms of audio transformers have an inductance of around 125 henrys with d.c. of 1 mil, and a corresponding impedance of 45,000 ohms, which again will pass about $\frac{1}{20}$ of the plate signal current in a detector circuit. Fortunately, as the plate voltage is raised, and the plate current at different stages, the value of the impedance in the power source rises so that the amount of inserted impedance may be less. The choke coils may have a smaller impedance and in consequence, saturation difficulties due to the larger ampere turns can be avoided by reducing the number of turns on the choke coils for the later stages.

In a radio- or high-frequency amplifier, the condensers may be smaller and the inserted impedance, also, physically smaller. It is interesting to point out here that some of the past failures with radio-frequency by-passing were due to the fact that the condensers used (of paper), had considerable inductance so that their effective impedance was high. Tests made on some of the earlier paper by-pass condensers showed that near 200 meters, 1.0-mfd. condensers had as much inductive reactance as they had capacitative reactance, and acted as if they were not in circuit. Most of the by-pass condensers now made are non-inductive.

At very high frequencies, the two filament leads can be wound in a coil with or without an iron core and signal current kept out of the A-potental source. At these frequencies, input and output leads have high inductance and should be made part of the coil or part of the condenser.

As shown before, the leads to the input or output impedances should not embrace much area in order to prevent coupling from their loops to other loops or coils in the same or other stages. The by-pass condenser leads are part of these important leads and the by-pass condensers should be placed so that the loop areas are small. It is common practice in the electrical trade to twist wires of one circuit to reduce the external field, such as twisted pair of telephone lines, transpositions of telephone wires and power lines, putting wires of a power circuit in conduit, etc. The signal circuits of an amplifier differ only in degree from these examples and are subject to the same law. The elimination of external fields is even more necessary here as there is present the vacuum tube which is susceptible to regeneration. The wires of any signal circuit or part of a circuit must be kept together and may have to be twisted if they are of appreciable length.

If the by-pass condensers of a stage are not placed close to the tube, each pair of leads to a condenser should be twisted together. As small part of the signal in each circuit flows in the external power circuit, it is best to keep all the power supply leads together by making them into a cable.

EXTREME CASES

FIG. 3 shows some extreme cases which may be met in actual practice. Twisting the grid and filament leads of the input circuit where they are long, only increases the capacity across the detector grid coil. This may move the dial of the tuning condenser a division or so for a given wavelength, but it removes the field due to these leads. The radio-frequency current in the detector plate circuit passes through the 0.001-mfd. condenser to the filament. This condenser should *not* be placed across the primary of the audio transformer, as it may introduce serious regeneration. The r.f. choke assists in keeping the r.f. current where it is wanted. This choke should not couple to any coils or loops in the receiver.

If shielding is used, the two wires of a signal circuit must go through the same hole in the shield, or current will be set up in the part of the shield between these wires. It has been common practice, even with some of the larger radio companies, who should know better, to connect the detector to the audio amplifier, when the two are separated, by only the plate wire. A circuit cannot consist of one wire and the audio current must, in this case, return through the ground or the filament leads, thus forming a large loop which couples to various coils, transformers, outside fields, loops, etc., and introduces serious regeneration. Two signal wires twisted together must be used to connect separated parts of any amplifier. Numerous cases of bad distortion, motor-boating, howling, etc., have been found to be caused by this one fault in the detector circuit.

The capacity added by a long input cord to an audio amplifier is not serious and can be compensated by making the r.f. by-pass condenser smaller, if its effect on the audio characteristic is noticeable. The d.c. plate voltage can be connected at any point to the right of the plate by-pass condenser through a choke which may be the secondary of an old audio transformer that has departed its useful life.

In an audio amplifier, transformers should be shielded to help eliminate magnetic and capacity coupling, though the latter is almost negligible. Magnetic coupling between transformers is most serious with silicon steel cores. Transformers made of high permeability cores, usually, have negligible fields, and the transformers of adjacent stages may be placed as close as desired without signs of coupling. These types of transformers are, however, very susceptible to external fields on account of their highly permeable cores and should be kept away from external magnetic fields or placed in a neutral position with respect to them. In a radio amplifier, it is almost impossible to prevent magnetic coupling between coils, unless very good shielding is used. Poor shielding is worse than none at all, as it usually distorts the field so that a neutral point cannot be found. Radio-frequency shielding should be of heavy copper with all joints well soldered or should make good electrical contact along each joint which cannot be soldered. If the shielding is not complete, currents will be set up in it, which will induce fields on the outside of the shield and thus couple to circuits on the outside.

One element of an amplifier should be completely enclosed in one compartment, which compartment should be connected to the amplifier circuit at only one point. If connections are made at more than one point, current will flow through the shield and thus defeat its purpose. In other words, the shield must not be used as a conductor. Good shields are expensive and if in a given receiver only so much can be allowed for shields, it should be put into one good shield for one stage and let the other stages remain unshielded.

In the above discussion, little has been said about feed-back through the tube. It is becoming more evident that regeneration due to feed-back through the tube itself is not as serious as some would have us think it. The majority of regeneration in average amplifiers is due to magnetic and circuit coupling, and if these two are removed, as suggested above, that due to the tube itself is almost negligible.

As amplifiers are made better, the signal voltage on the plate goes up and the effects of grid plate feed-back increase so that neutralization in any of the common forms may become necessary.

One firm in New York last year made some two-stage r.f. receivers and by careful attention to the above principles—good shielding, by-passing, avoiding loops, and cabling of leads—was able to operate the receivers over the usual tuning range without neutralizing condensers and without appreciable regeneration, although the standard form of this receiver had neutralization. The average radio-frequency amplifier with three or four turns in its primary does not amplify, and so does not have a signal voltage on its plate sufficient to feedback enough energy to the grid. But they are usually chock full of regeneration, due to magnetic coupling, common impedance, loops in wiring, etc., and really operate as regenerators.

POWER IN INTERMEDIATE STAGES

ANOTHER common delusion regarding amplifiers is in the amount of power necessary for the intermediate stages. In every stage, except the last, the amount of power handled is low. The general considerations which fix the operation of an amplifier with regard to power were first stated in an article by this writer in RADIO BROADCAST for November 1925 and many times since then. They are as follows: *First:* the filament shall be maintained at a sufficient temperature to allow the maximum electron flow. *Second:* the grid must remain negative at all times. *Third:* sufficient voltage shall be available in the plate circuit so that at the most negative grid voltage the plate current does not drop below a limiting value. *Fourth:* sufficient impedance

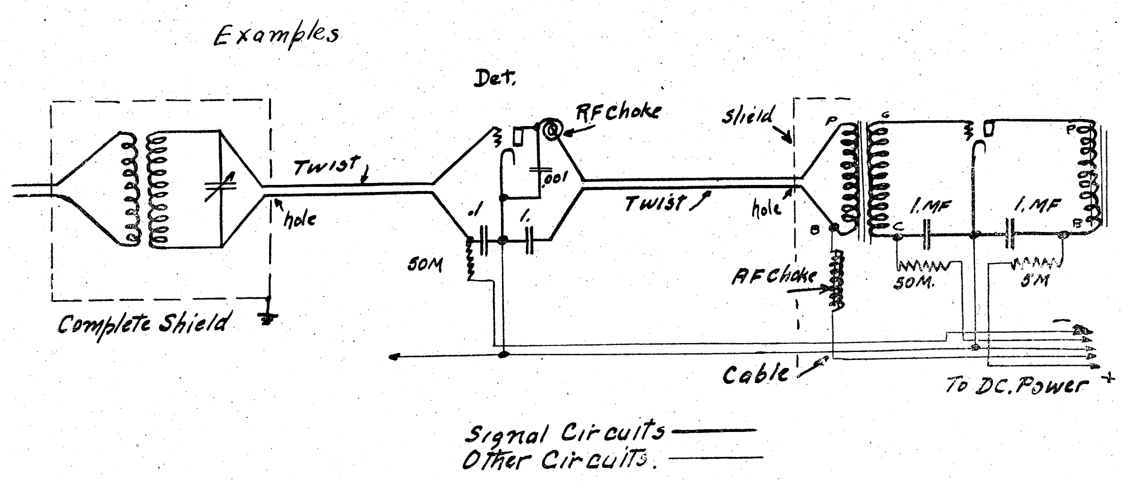

FIG. 3

shall be in the plate circuit to flatten out the operating characteristics of the tube.

These principles show that a 201-A tube with 6-volt bias and 100-volt plate can carry a maximum signal of about 4 volts (RMS) on the grid. If a 3:1 transformer of good design is used after the tube, the full amplification of the tube and transformer will be obtained, which will give 84 volts on the grid of the succeeding tube. This tube would then have to have a bias voltage of 120 volts in order to keep its grid negative. Such a grid bias would require a 250-watt tube with 2000 volts on the plate as the output tube. In actual operation of amplifiers we do not get such voltages on the first or second audio tube, because, the detector tube will overload long before this signal is reached and the bad distortion caused thereby will make us cut it down. From these figures it is readily seen that there is no excuse for operating the first audio tube at plate voltages higher than 90 volts, as it is not possible to overload this tube before other tubes overload. It is, also, clearly evident that the last tube must have a high grid and plate voltage in order to prevent it from overloading. When high grid and plate voltages are used on the last tube, it is economical to design the tube for these voltages and to use a tube with a low output impedance in order to get a good transfer of the signal energy to the output device which is usually of low impedance.

Most loud speakers are very inefficient and require considerable power to operate them, especially at the low frequencies and this power must, of course, come from the output tube. At 60 cycles the few loud speakers which will pass that frequency will stand an input of 6 watts with no signs of rattling, blasting, or other supposed loud speaker faults. Even higher inputs have been used with some types of loud speakers. The 210 tube has a maximum power output of $1\frac{1}{2}$ watts when certain assumptions as to distortion are made (see *Bell System Technical Journal* for July 1927). Such a tube cannot operate good loud speakers up to their maximum load and higher power tubes will be necessary if the loud speaker is to be operated up to its maximum. The weak point in the chain is evidently not the loud speaker, although considerable improvement can be made in their characteristics.

For a sound level slightly above normal and a good loud speaker, from one to one and a half watts is required as input power. This means that a 210 tube will be worked right up to its limit and will have considerable distortion due to the curvature of its characteristic which is not straightened out as the impedance of the plate circuit is low.

One way to remedy this condition is to use two 210 tubes in push-pull in the last stage. Push-pull operation straightens out the characteristics of the tube and eliminates most of the second harmonics. It also will eliminate the hum due to operating these filaments on a.c. as the filaments are not in the signal circuit. Another advantage is that an output transformer having good audio characteristics can be readily built for push-pull circuits due to the elimination of the direct current saturation upon its core. Such a transformer can be designed to have the proper impedance ratio to transfer the maximum power from the tube to the load. Increased power is thus made available for the speaker and better quality results, in addition to that caused by lessened distortion in the tubes themselves.

In the operation of a push-pull amplifier using 210 tubes, larger power must be available and so a higher voltage rectifier must be used than has been customary. In a push-pull circuit, as long as there is no overload on the push-pull tubes, the filaments of the two tubes are not in the signal circuit and no signal current will flow from the center tap of the input and output impedances to the filament. But if overloads occur, signal currents will flow through the center taps and so by-pass condensers should be used if there is any possibility of the push-pull stage being overloaded. A series resistance in the minus C lead will also help prevent overloading and is of great value in preventing oscillations due to lack of symmetry of the push-pull circuit. A push-pull circuit can be self-neutralized, if desired, by small capacities connected between the grid and plate of opposite tubes.

In conclusion, attention is directed to the fact that radio amplifiers are built upon exactly the same principles which other electrical apparatus is built and good results cannot be expected unless these common electrical principles are followed. While the effects of radio may be mysterious, the causes are not, though they are not always recognized, and each detail can be worked out according to well-known laws.

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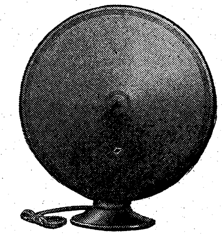

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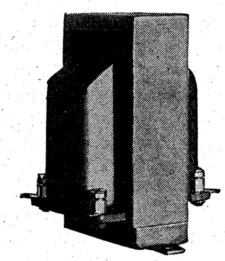

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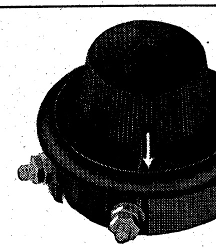

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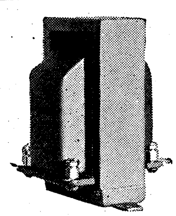

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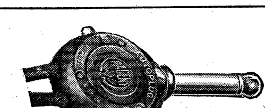

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