Some Principles of Radiotelephony

Part III† *— The "How" of Modulator Power*

BY BYRON GOODMAN,* W1DX

Recognizing the need for modulator power in any practical 'phone transmitter, the next step is to examine some of the methods that can be used to generate this power. Part I of this series indicated that a microphone develops an alternating current corresponding to the variations in air pressure that make up "sounds" — the problem is to build up the extremely low power represented by these currents to a power level that can be measured in tens or hundreds of watts. Since vacuum-tube amplifiers will be used for this purpose (although transistors might be substituted at the low-power levels), let's review briefly how a vacuum tube works.

Anyone with a license or studying for a license undoubtedly knows the basic principle of vacuum tube. A heated "cathode," in a vacuum, emits electrons. "Electrons" can get to be rather complicated — ask any physicist — but for our purpose it is sufficient to know that they are the smallest particles whose mass and charge have been determined. The charge is negative and, if any of the electrostatic theory in the introductory paragraphs of many radio textbooks rubbed off on you, you know that *like charges repel* and *unlike charges attract.* Knowing this, the first thing we run into when our vacuum-tube cathode gets up to temperature and starts to emit electrons is "space charge." This formidable term simply means that the first electrons emitted from the cathode hang around the vicinity of the cathode, for want of a better place to go. Being negative charges, they repel other electrons that might have a hankering to be emitted from the cathode. The result is that, with no other charges (or electrostatic fields) near the cathode, we have a cloud of electrons surrounding the cathode, and this cloud prevents further emission from the cathode. The cloud can be pushed out farther by increasing the temperature of the cathode.

Further negative charges near the cathode, from some external source like a battery or charged condenser, only serve to compress the space charge still more. But put a positive charge near the space-charge region, and some of the electrons of the space charge are attracted by this positive charge. (Remember, unlike charges attract.) Moving some of the electrons from the space charge permits other electrons to be emitted from the cathode, to make up the deficit. The higher the magnitude of the positive charge, or potential (it is measured in volts), the greater the number of electrons that are attracted.

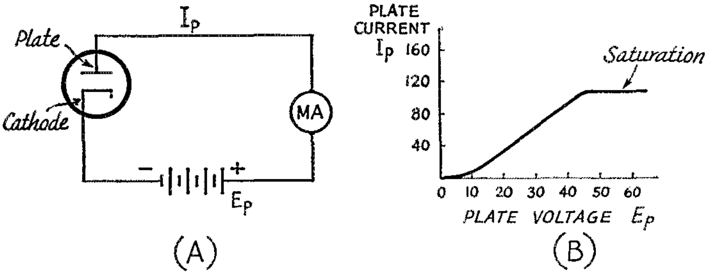

Fig. 10 — When a diode (two-element vacuum tube) is connected in series with a voltage source and meter (A), the current through the tube depends upon the value of the voltage, up to the saturation point (B). Increasing the cathode emission will raise the saturation point to a higher plate voltage.

The Diode

It's easy to prove this to yourself. Take a diode — which is a cathode and a "plate," or "anode," mounted in a vacuum — and connect it as shown in Fig. 10A. The battery, E_p, puts a positive charge on the plate, and the meter *MA* measures the current (electron flow) through the circuit. For a given temperature of the cathode, the higher the value of the plate voltage source, E_p, the greater will be the flow of current. You can tabulate the various values of current that are obtained for different voltages and then plot them on a simple graph, as at Fig. 10B. The plot of these values is practically a straight line from the "0" point up to a point marked "saturation." (Down near the "0" point there will be some slight curvature.) The saturation point indicates that, for the given cathode temperature (and cathode material), we can pass no more current through the diode, regardless of the plate voltage. Why? Because all of the electrons emitted by the cathode are finding their way to the plate. With no more electrons available, we can't increase the current, since the flow of electrons *is* the current. How can the current be increased? By making more electrons available, which means running the cathode at a higher temperature (or using a different cathode material). If we increased the temperature of the cathode and made another series of measurements, we would obtain a curve similar to that of Fig. 10B except that the saturation point would come at a higher plate voltage.

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* Assistant Technical Editor, *QST*.

† See May and June *QST* for Parts I and II.

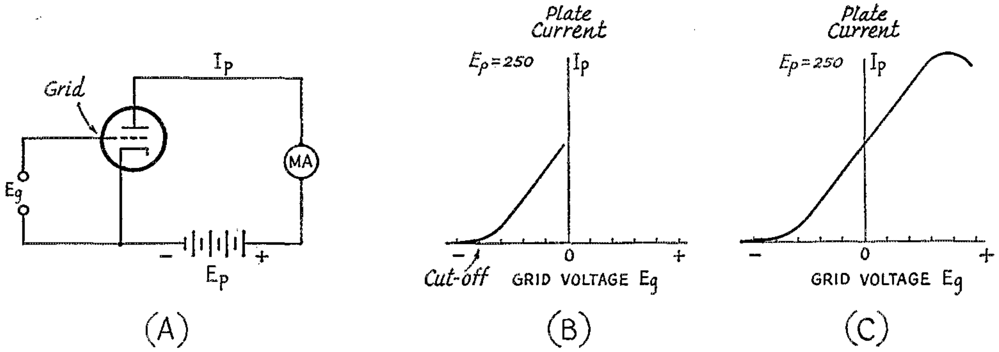

Fig. 11 — A grid introduced between the cathode and plate (A) gives a triode (three-element vacuum tube). For a given plate voltage, the plate current is determined by the grid voltage (B) and (C).

In practice, cathodes are always run hot enough so that "*temperature* saturation" such as this does not take place. "Saturation" is introduced here so that it will not be a stranger later on.

You may wonder why *all* of the electrons are not attracted at low voltages, so that temperature saturation would be reached just as soon as *any positive charge existed in the tube.* The reason ties back to your laws of electrostatics: the lower values of positive charge (voltage) are not sufficient to overcome completely the high value *of negative charge represented by the space* charge. In other words, if the positive charge represents 5 units and the space charge is 25 units, only 5 units will be moving from the space-charge region. Boost the positive charge up to 10 units and you will be moving 10 units away from the vicinity of the cathode, and so on. When you get up to 25 positive units, you're dragging all *you can from the cathode at this temperature.*

From your practical knowledge of such circuits, you know that if you run a diode as in Fig. 10A, the temperature of the plate will increase *with the flow of current through the circuit.* Since this is a series circuit (all parts connected in series, as opposed to parallel) the current in one part of the circuit must be the same as in any *other part of the circuit.* Why, then, does the tube plate heat up, and not the battery or meter? You might say that the "plate has resistance," but you know that it is made of a good conductor like the wires connecting the other parts of the circuit. So, to explain the plate heating, you have to appreciate first that the electrons acquire a velocity in moving from the cathode to plate. This velocity becomes greater as the voltage difference (for any given distance between cathode and plate) is made greater. The electrons have mass, and now velocity, and a moving mass has something called "*kinetic* energy," as anyone who has stopped a baseball barehanded can testify. In the vacuum tube, the fast-moving electrons are brought to a screeching halt at the plate, and the kinetic energy is converted into heat when the electrons strike the plate.

The electrons don't hit the plate and then fall to the bottom of the vacuum tube, the way a lot of baseballs would. Minus their kinetic energy, they replace the electrons that were removed from the plate when it was charged positively by the battery. The electrons that are removed from the plate "nudge" each other back down *the wire the instant the battery is connected,* and others are doing the same thing in the wire from the battery to the cathode. There has to be "equilibrium" (balance) around the circuit at *any instant,* so any tendency for unbalance of charges in any part of the circuit is immediately [1] counteracted through the circuit. The electrons in the tube actually travel the distance from space-charge area to plate to maintain the balance of charges, but the "current" through the wires is only a balancing of charges maintained by movement of electrons from atom to atom, a *relatively short hop.*

The heat developed at the plate can be calculated from the power in watts (volts × amperes) represented by the plate current and the *voltage from cathode to plate. This heat is dissipated* by radiation (and some conduction through the plate connection), and obviously a larger plate will dissipate more power because *its area is larger and it can radiate more heat.*

A diode has no ability to "amplify" signals, of course, and it was only brought in to furnish background for the vacuum tubes that are used as amplifiers. The diode finds use as a *rectifier,* in power supplies and in receivers.

The Triode Vacuum Tube

If we take the diode of Fig. 10A and introduce between its cathode and plate a mesh of wires (called a "grid"), we have a three-element vacuum tube, or "triode." It is shown in Fig. 11A, with the grid drawn "end on" to remind you that it is not a solid sheet like the plate. Let's make the plate voltage some fixed value like 250 volts, and see what the effect of different voltages between cathode and grid will be. If we make this grid voltage, E_g, some high value and connect it so that the negative terminal goes to the grid (and the + to the cathode), we will find that no plate current flows and the meter will

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[1] Actually, the action is not instantaneous — it does take a finite time for electricity to act. The speed in a straight wire is close to the speed of light, however. — Ed.

indicate "0" current. The reason is the basis for all vacuum-tube amplifier action. You will recall that it was the positive electric field of the plate extending over into the space-charge region that made the current flow through the diode. A small negative charge on the grid can neutralize the effect of a higher positive charge on the plate, since the field from a charged body drops off with distance, and the plate is farther from the space-charge region than the grid is. If we reduce the value of the grid voltage (make it lower but still with the negative terminal to the grid), we will reach a point where plate current starts to flow. This point, of course, is where the negative charge of the grid is not sufficient to overcome the positive charge of the plate that can be felt at the space-charge region. As we make the grid voltage still lower, still more plate current will flow.

A plot of the values we have obtained so far might look like Fig. 11B. This is a plot of "grid voltage *vs.* plate current" for a plate voltage of 250. The grid can also be connected to the + terminal of the grid-voltage source, but so far we have no data on what happens and so we can't add it to the graph. You will see that the values do not plot as a straight line — at low values of plate current there is some curvature, but as the plate current increases the graph tends to straighten out. The value of grid voltage that "cuts off" (reduces to 0) the plate current is called the "cut-off" grid voltage for this particular value of plate voltage. It would be lower for lower values of plate voltage and higher for higher plate voltages.

As we continue to make the grid voltage less negative, we will eventually reach a grid-voltage value of 0, and to continue, we must make the grid voltage + with respect to the cathode. As we do this, and plot the results, we will obtain the graph (or "characteristic") of Fig. 11C. The plate current continues to increase as the grid voltage increases, until finally the plate current reaches saturation. This "*plate* saturation" is a different type than the "temperature saturation" mentioned earlier. It takes place when the attraction of the grid voltage is equal to or greater than that of the plate voltage. In other words, if the + field of the grid is stronger at the space-charge region than that of the plate, the electrons will tend to ignore the plate and be attracted to the grid. The plate current first flattens out and then decreases, as indicated. We can get more plate current at this "saturation" value of grid voltage by increasing the plate voltage — that would be "operating on another characteristic" (one drawn for this new and higher value of plate voltage).

Something else happened to the tube when we made the grid positive with respect to the cathode. When the grid was negative with respect to the cathode, no electrons could go to the grid and consequently no current could flow in the grid circuit. But when the grid is positive with respect to the cathode (even by only a fraction of a volt), electrons can find their way to the grid. This represents a current, and thus current flows in the grid circuit. With current flowing, *power* is taken from the grid-voltage source, just as power is taken from the plate-voltage source whenever plate current flows. Consequently, a vacuum tube requires no grid power when the grid voltage is negative, but it does require grid power when the grid is positive.

Before we leave this discussion of simple vacuum-tube operation, let's take a last look at this business of grid power. We will use the circuit of Fig. 11A, except that we will add a large resistor, *R*, in series with the grid. This revised circuit is shown in Fig. 12. The two batteries in the grid circuit have the same voltage — the switch *S* merely changes the polarity at the grid. If the batteries are each 10 volts, for example, we know that switching *S* to the left puts −10 volts on the grid of the tube. What happens when we switch to the right? Your first guess might be that it places + 10 volts on the grid, but you would be wrong. With the grid positive, some current will flow through *R*, and consequently there will be a voltage drop across *R*. Thus, the actual voltage on the grid will be the + volts *minus* the voltage drop across *R*. Obviously, we want a minimum of resistance in series with the grid when the grid is drawing current, or we won't be applying to the grid the voltage we think we are. This isn't just an academic point — it's something to watch out for all the time.

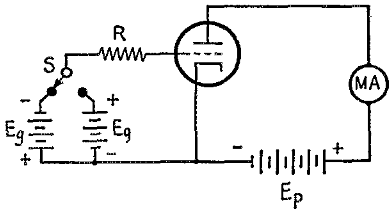

Fig. 12 — **If there is resistance in series with the grid of a vacuum tube, an applied voltage will appear at full value on the grid if the voltage is negative with respect to cathode, but it will be reduced by the voltage drop through the resistance *R* if the applied voltage is positive.**

There are, of course, tetrode (four-element) and pentode (five-element) type tubes that are used for audio amplifier and modulator work, but we can save a discussion of their operation and merits for some other time. They use a control grid that behaves much the same way the grid works in a triode, and they use a cathode and a plate. Extra grids make up the additional elements.

Tube Ratings

Earlier, it was mentioned that practically all vacuum tubes are run at a cathode temperature sufficient to deliver more electrons than will normally be required, and consequently we never run into "temperature saturation" with a properly-operated vacuum tube. Now let's look at some of the limiting factors of vacuum-tube operation and how they are determined.

Handbooks and tube manuals furnish information on the proper operation of vacuum tubes.

The correct filament (or heater) voltage is listed. If the filament (or heater) voltage is maintained at this value (or within ±5 per cent, usually) the cathode will be at a temperature sufficient for all normal uses of the tube. The manufacturer has determined this value by experiment and design, and one has a right to expect good tube life when this value is maintained — and other ratings are not exceeded.

Another important factor in determining what a tube can or cannot do in the way of power output is the "plate dissipation." You will recall that this depends upon the area (and construction) of the plate — the book rating is one that the manufacturer believes can be maintained without injury to the tube. Vacuum tubes are built with plate dissipations ranging from a watt or so — small receiving tubes — to large transmitting tubes capable of dissipating hundreds or thousands of watts. As we will see later, the plate-dissipation figure is not the maximum input that can be run to a tube — it is the power that can be safely dissipated by the plate. We can run more power than this to the tube if we use up the additional power in some other way, such as converting it into audio or r.f. power and delivering it to a load.

Tubes also have grid-dissipation ratings, for control and screen grids, and these must also be respected if the tube is to give reasonable service.

The factor that determines how much of the d.c. input power supplied to the plate circuit of a tube is recovered as useful audio or r.f. power, and not wasted as plate dissipation, is the *efficiency* of the tube. The efficiency depends upon how the tube is operated, as will be explained later. Suffice to say, a tube operated at 70 per cent efficiency delivers .7 of the plate circuit d.c. input as power out of the tube and dissipates the remainder (30 per cent) at the plate.

How a Vacuum Tube Amplifies

So far we have merely looked at how the grid voltage of a vacuum tube controls the plate current. If the tube is to be used as an amplifier, how do we go about it? To illustrate, take the circuit of Fig. 13A. It is somewhat similar to Fig. 11A, except that we have added a resistor *R* in series in the plate circuit, and a transformer is used in the grid circuit. The alternating-voltage signal, E_g, to be amplified is introduced through this transformer and, to simplify any arithmetic, we will make the turns ratio of the transformer 1:1, so that there will be no "step up" or "step down" through the transformer. The voltage of the "bias" battery, E_g, will be selected as that value equal to about one-half the cut-off voltage, as indicated in Fig. 13B. At this grid voltage, the value of plate current will be I_p, found by moving vertically from this grid voltage up to the characteristic and then horizontally across to the plate-current scale. This value of plate current is called the "static plate current" — "static" in this sense means "with no signal" — and the value of E_g, the "grid bias," determines it.

When a signal is applied through the transformer — e.g., 3 cycles of a sine wave — this varying voltage adds to or subtracts from the bias voltage. When the instantaneous grid voltage becomes more negative, the plate current is decreased, and when the grid voltage becomes less negative, the plate current is increased. The plate current, therefore, follows the changes in the grid voltage, as shown by the portion marked "output current" in Fig. 13B. The voltage drop across *R*, which is being measured by *V* (a fast-moving voltmeter like an oscilloscope), changes in the same manner. If *R* is large, a small change in the plate current develops a large voltage across *R*. Thus a small signal voltage at the input becomes a large signal voltage at the output, and the tube "amplifies" the signal.

There are several things to remember about this type of amplifier. The grid circuit took no power, except what little might be dissipated in the resistance of the primary of the transformer. The plate current, I_p, if read with a *d.c.* meter, would show no change from the static value, with or without signal, because the d.c. meter can't follow the rapid changes in current, and the *average* change is 0. If we were to increase the value of E_g, we might swing the grid far enough to get on the curved portion of the characteristic, or into the grid-current region, or both. In such a case, the plate current indicated by a d.c. meter would not be the same with or without signal. Swinging on to the curved portion of the characteristic would result in *distortion* of the negative half-cycles of plate current. Swinging into the positive grid region might distort on the positive

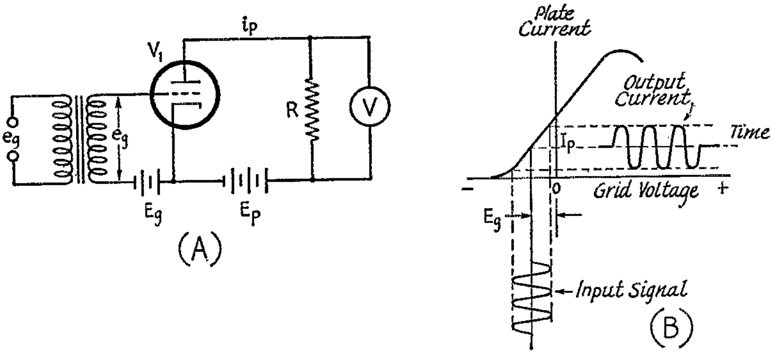

Fig. 13 — (A) A vacuum tube will "amplify" a signal if the signal is applied to the grid and a suitable "load" (*R* in this case) is provided in the plate circuit. (B) The action can be traced through by applying the signal to the "characteristic" of the tube.

half-cycles of plate current because the grid would take power. The grid voltage might not be maintained, through the inability of the signal source to furnish the necessary power.

An amplifier of this type, when working within the distortion limits, is called a "Class A amplifier." A Class A amplifier is one in which the output voltage waveform is a faithful reproduction of the input voltage waveform and there is no change in plate current as measured by a d.c. meter. Commonly, there is no grid power required, although this is not a qualification.

Class B Amplifiers

A Class A amplifier can, of course, be designed to furnish considerable audio power, but it is not a very efficient way to obtain large amounts of audio power. Class A amplifiers usually run about 20 or 25 per cent efficient with tolerable distortion, and so we must cast around for a more efficient means for generating audio power, unless we want to spend all of our money for modulator tubes and power supplies. An amplifier running Class A and using a tube with a plate dissipation of 40 watts would deliver only 10 to 13 watts, with a power supply furnishing 50 to 53 watts. Most of the power goes to heat the tube plate.

Of course, we can operate more tubes in a Class A amplifier by connecting two or more in *parallel* (grids tied together, plates tied together, and cathodes tied together). Connected this way, two tubes would give twice as much output as one tube, but with twice as much d.c. power input supplied to them. In other words, the efficiency would remain the same.

Or we can operate the two tubes in push-pull, as shown in Fig. 14. Here you will see that a transformer has been substituted for the plate load resistance, R, of Fig. 13A, but aside from this change, the connections to V_1 are the same in Fig. 14 as they are in Fig. 13A. But in Fig. 14, V_2 is connected to other parts of the grid- and plate-circuit transformers. The net result is that when the plate current in V_1 is increasing, because the grid voltage is going less negative at that instant, the plate current in V_2 is decreasing because the grid voltage to that tube is going more negative. At another part of the signal cycle, the conditions would be reversed, and the plate current would be decreasing in V_1 and increasing in V_2. The term "push-pull" is quite descriptive of the action.

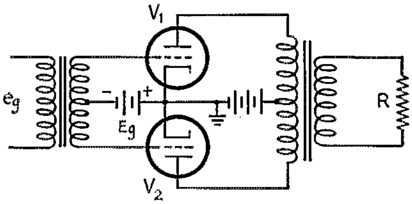

Fig. 14 — For greater output, two tubes can be connected in "push-pull."

In the plate circuit, the net effect of the varying currents through the halves of the transformer primary is to induce in the secondary a signal that corresponds to the grid-circuit signal.

Now suppose that we increase the value of E_g to the point where very little plate current is drawn by the tubes when there is no signal. Then when signal is applied, first one tube conducts, because its grid is driven less negative with respect to cathode, and then the other tube conducts. The tube whose grid is driven more negative of course draws no plate current during this time. Under these conditions, we have an amplifier where first one tube contributes to the output and then the other tube contributes while the first one idles. You can visualize this by placing two tube characteristics "back-to-back," as in Fig. 15. Here you can see that V_1 contributes half of the time and V_2 contributes during the remainder of the time. Since there is some curvature to any practical tube characteristic, the two characteristics are aligned so that at low signal levels both tubes are drawing a little plate current all of the time.

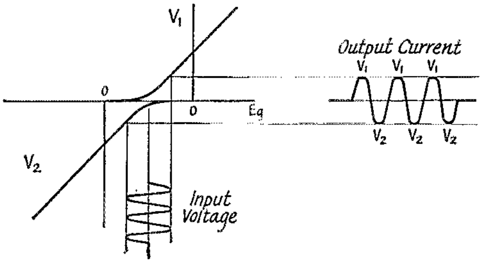

Fig. 15 — **The characteristics of two tubes connected in push-pull and biased near cut-off. The tubes "take turns" supplying the output current, and consequently have time to cool off between half-cycles.**

Tubes operated like this work at a higher efficiency than they do in a Class A amplifier, because the tube is not conducting during all of the signal cycle, and the tube plate can "cool off" between half-cycles. Furthermore, the static plate current is lower than in Class A operation, so the tube heating under no-signal conditions may be less. Amplifiers of this type are called "Class B," and their theoretical efficiency can run up to 78 per cent. In practice, it may run as high as 60 per cent, since there are no tubes built with an "ideal" characteristic, and the necessary output transformer will dissipate some of the power output from the tube. In all instances where maximum power is sought from the tubes, it is necessary to drive the grids into grid current over part or all of a half-cycle, and this can be done provided one remembers that it is important to maintain the grid-voltage waveform while the grid is taking power.

By definition, a Class B amplifier is one in which the tube conducts (has plate current flowing) over only half of the signal cycle and in which the output power varies as the square of the grid voltage. Obviously, the tubes in Fig. 15 are not quite adhering to this definition, because the curvature of the characteristics required that

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inch. Spacing between all coil terminals is 5/16 inch. C_1 and C_3 are grounded to a lug fastened to the case midway between L_1 and L_2. C_6 and C_8 are similarly grounded to a lug between L_4 and L_5. L_3 is grounded to a lug near the base of its form. The filter looks very much like the 300-ohm model, except for the ground connections, the coaxial terminals and the four less capacitors. Adjustment is carried out in the same way.

Adjustment Procedure and Installation

It will be noted that the filter diagrams give tune-up frequencies for each section. The dotted lines indicate short heavy busses to be installed after the assembling of the filter is completed. The turn spacings of the coils are adjusted to give resonant frequencies as shown, with all four busses in place. Next, cement the windings in place, allow to dry, and then remove the busses. The filter is now ready for use.

The frequencies indicated for the two coils either side of the center one must be held within very close limits if the desired characteristics are to be attained. Check the accuracy of your grid-dip meter in a well-calibrated 50-Mc. receiver before making these adjustments. The frequencies indicated for the other sections will be close enough if the average grid-dip meter calibration accuracy is used.

If the capacitors are within the tolerances specified, and the filter is adjusted carefully as described above, it should show no noticeable loss on any TV channel. For best results, the filter should be grounded to the TV receiver chassis and mounted close to the tuner. Where the receiver has an appreciable lead length between the input to the tuner and the antenna connections at the back of the receiver cabinet, installing the filter at the latter point will reduce its effectiveness considerably. A small sheet-metal bracket can be used to ground the filter case to the receiver chassis, often using existing holes in the chassis.

These filters are capable of ending a lot of TVI woes. Installed on your own TV set, one should permit you to receive all channels, including 2, without TVI due to fundamental overload while you operate your ham rig on any amateur frequency up to at least 51 Mc. The 300-ohm filter has enabled me to operate as high as 52.6 Mc., with an effective radiated power of 480 watts, without a trace of TVI on Channel 2. I live in a semifringe area. Need I say more?

Radiotelephony

(Continued from page 38)

some static plate current be drawn. As a result, the tubes will conduct during slightly more than half of a signal cycle.

Although the preceding definition is the strictly-accurate one, a Class B amplifier is more likely to be thought of as one with acceptable distortion in which the plate current (as read by a d.c. meter) varies with the signal. In other

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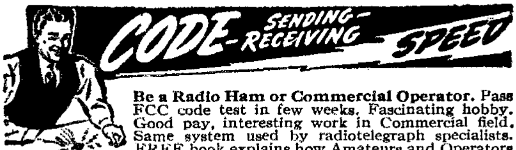

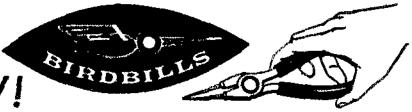

words, the meter indicates more current on louder passages than on weak ones. And there are intermediate designations between A and B. An AB_1 amplifier is one that operates Class A at low signal levels, but the d.c. plate current varies at high levels. No grid current flows at any time. An AB_2 amplifier is much the same: it operates Class A at low signal levels, the d.c. plate current varies at high signal levels, but grid current flows on signal peaks. The so-called Class B amplifiers you will run into are actually AB_2 amplifiers, although Class B operation is approached fairly closely with a few special tubes designed for the purpose.

It is impossible to make use of two triodes' full capability in Class AB_1 operation, and they are always run Class AB_2 when full output is required. (They can't be made to draw enough plate current unless the grid is driven positive.) On the other hand, one tetrode type (the 6146) will deliver almost as much in Class AB_1 as it will in AB_2, because the screen voltage helps to make the tube draw high plate current even when the control grid is negative. However, most tetrodes will give from 20 to 100 per cent more output in AB_2 than they will in AB_1. The Class AB_1 amplifier, which requires no grid driving power, is easier to drive, and this may be a consideration in some instances.

The Driver Stage

The stage that supplies the signal to the audio power amplifier is called the "driver stage." As mentioned above, it usually poses no problem in Class AB_1 operation, and it may be a resistance- or transformer-coupled stage of low power capability. It is not always possible to use resistance coupling, however, because some tubes are restricted in the permissible resistance in the grid circuit, and it will be found difficult to get sufficient grid swing. However, transformer coupling can be used in such cases. When resistance coupling is used, it is necessary to use a "phase inverter" stage somewhere in the audio amplifier, to get the necessary push-pull excitation for the power stage.

In Class AB_2 operation it is important to maintain the grid-voltage waveform when the grid is drawing current. This is usually done by selecting for the driver stage a tube, or tubes, with low plate resistance, since a low plate-resistance tube can maintain a signal into a variable load — the grid circuit of the modulator stage — better than a high plate-resistance tube. The variable load is presented as the grid voltage swings from negative (no grid current) to positive (grid current).For best economy it is desirable to utilize as much as possible of the available power of the driver stage, and for this reason some care must be exercised in selecting the proper transformer for coupling the driver stage to the modulator. The selection of transformers for modulator stages will be the subject of a future article in this series.

[*Part IV of this article will appear in a subsequent issue.* — Ed.]