Audio Classroom

Designing Your Own Amplifier, Part 4a: Push-Pull Power Stages

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The reasons for using tubes in push-pull for the output stage of an amplifier are two: 1) to reduce distortion, and 2) to increase the available power output for a given tube. Push-pull operation was first adopted to get more output from triode tubes. Then, since greater improvement could be achieved with pentodes—they have a higher efficiency to start with—it was applied to them and, still later, to beam tetrode tubes. To this day, however, there are good reasons why some designers prefer triode tubes.

Figure 1 shows the published tube characteristics for a type 45 triode as a single tube. Using its maximum operating plate voltage of 275, you can just get 2W output in Class-A operation. If two such tubes were operated under the same conditions, but in push-pull, you should obviously get twice as much output (4W), but with considerably less distortion, because the second-harmonic components would cancel.

By changing the operating conditions, you can push the 4W up to about 5.5W. Further, by working the tube into the positive-grid region, the same arrangement is capable of giving as much as 18W output, still using only a plate-supply voltage of 275. But when the grids are driven positive, a power drive stage is needed, as you'll see later. Look at the available data to see how this comes about. *Figure 2* shows the same curves drawn twice, with one set inverted so that 275V comes on the same vertical line, right through the combined graphs. First I'll justify and explain this construction.

Since the tubes are operating in push-pull, the coupling provided by the output transformer (*Fig. 3*) acts in such a way that, when the plate voltage on tube No. 1 swings down by, say, 75V, so as to be 200 on this tube, it will swing up on the other tube, represented by the lower half of *Fig. 2*, so as to be 75V above the 275 starting point, or 350V.

Thus you can see the justification for swinging the voltage scale the opposite way around for the second tube. The current scales are back to back for the following reason: the operating point chosen is –70 on each grid. This gives the combination of plate current and voltage represented by the straight dashed lines, about 10mA in each tube at 275V. But because these two currents are in opposite directions in the output transformer, their magnetizing effect in the output transformer neutralizes, and is the same as if no current were flowing.

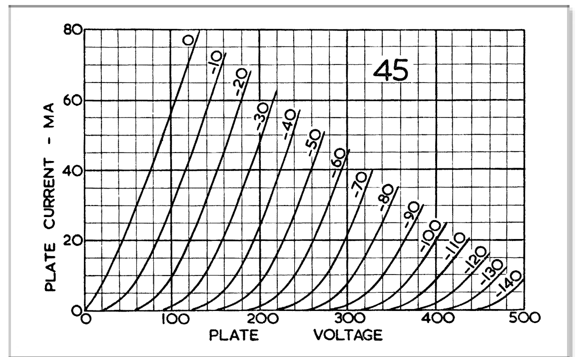

FIGURE 1: Characteristic curves for a 45 tube, which are used as a basis for the discussion of push-pull output stages.

COMPOSITE CURVES

Consider another possibility: while both grids are at the same potential of –70V, suppose there is a momentary reactive voltage from the transformer that makes the first tube plate +25V from the mean value of 275, and the second tube plate –25 volts. Following the respective curves for –70, the first tube's current rises to about 23mA, while the second tube's current drops to about 4mA. The resultant effective current in one half of the primary of the output transformer is the difference, or 19mA.

Plotting a number of such difference values, you obtain, approximately, the straight line joining the two 70V curves. It is here drawn as a straight line, to which it does form a very good approximation in practice. It will probably have a slight curvature, because the two sets of curves do not exactly equalize one another.

In a similar way you can produce resultant curves, which are again approximately straight lines, for other combinations of grid voltages. If the grid input is such as to drive the first grid 10V positive from its bias value, that is, to –60, the same swing will drive the second grid 10V negative to –80, so you can average the currents between these two curves at different combinations of plate voltage and produce another approximation to a straight line for this condition. In this way the whole family of composite curves was produced for *Fig. 2*.

Each line joining pairs of curves represents a composite plate-current/plate-voltage "curve" for a particular combination of grid voltages. The composite represents the magnetizing effect upon one half of the output transformer's primary.

Now look at the picture in a different way, taking a point of view from each individual tube. The straight solid line across the composite tube characteristics represents the load line for both tubes together; it considers only the output transformer and the two tubes as a composite source. But each tube must "see" an individual load line, which is represented by the dotted curves that lead away from the straight load line.

These two curves add to produce the solid straight line. Note that the dotted curves intersect the individual tube-characteristic curves at the same values

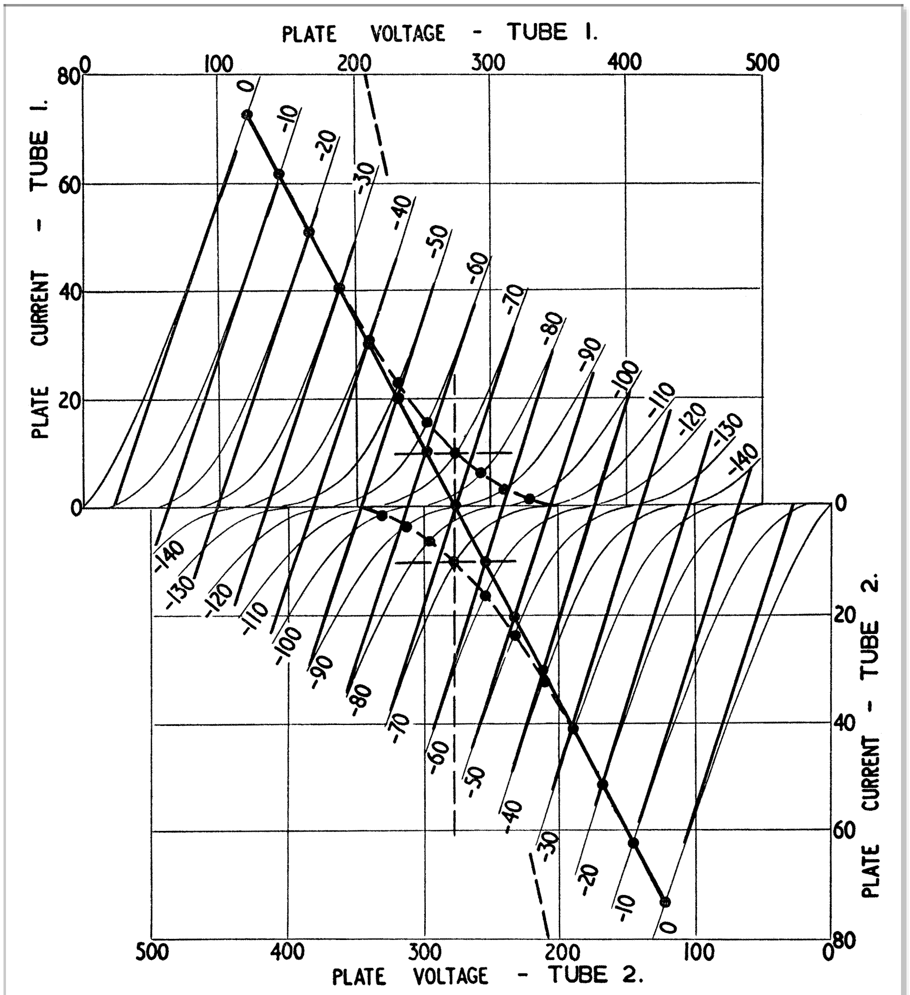

FIGURE 2: How two copies of the curves in *Fig. 1* are put together to make composite characteristics. Dashed lines near the center indicate the operating points for the two tubes, with 70V grid bias. Light curves are those of individual tubes, and straight lines joining them are the composite characteristics. Solid line crossing these composites is the composite load line, while the dashed curves show the components of this load presented to each tube. Short pieces of dashed line at the top and bottom indicate the optimum load (not drawn in full, to avoid confusion).

of voltage (represented by being in the same vertical line) that the solid load line intersects the composite straight line.

Notice also that the curvatures, both of the individual load lines and the individual tube-characteristic curves, when added together in this manner, offset one another and produce a close approximation to an ideal set of characteristic curves—both the load line and the individual composite characteristics are straight lines. The great advantage of this condition is that when the load becomes reactive, so as to open out into an ellipse, as studied in my previous article in this series, no appreciable increase in distortion occurs, even if the reactance effect becomes considerable.

The load line drawn in *Fig. 2* is not actually the optimum load for these characteristics. It was drawn at an angle that was convenient to show how the composite characteristics work. In practice the optimum load, as given in the tube data, is that represented by the portions of dashed line at the top and bottom of the chart. To avoid confusion, these are not joined at the center, and the full length of this optimum load line, out to the zero-grid characteristic curves, would go off the chart to a plate current of approximately 125mA. This is going up to a much higher plate current than allowed for in the characteristic plotted in *Fig. 1*.

This method of operation is rendered possible by the fact that the high currents occur only for a part of the time represented by the full excursion of the load line. During almost half of the signal period, when the load line runs out to these extremities, one tube is completely inoperative. This means that the plate dissipation, on an instantaneous basis, can go up to at least twice the nominal maximum rated continuous value.

This tube can be pushed even harder by using positive grid drive. Then the plate current goes up to about 212mA on positive-going peaks, giving a rated output of 18W. Even with this large excursion, the maximum-signal plate current, measured as the average for the two tubes, is only 138mA.

The efficiency of such a stage is obviously quite high compared with single-ended operation. For 18W output, the plate supply must be 275V at 138mA, which is about 38W. This represents a much higher efficiency than you can achieve with single-ended tubes.

With some of the larger triode output tubes, it is even possible to get an output equal to or greater than the combined dissipation rating of the tubes. There is a British transmitting-type triode capable of using a 1,000V plate supply and rated at 100W plate dissipation. By operating this in Class-AB push-pull with grid current drive, it is possible to get as much as 250W audio from the two tubes without exceeding the average dissipation of 100W each. This means that the plate-circuit efficiency is better than 50%.

Another question in the operation of push-pull output stages is how to provide the grid bias. If you are not running into the positive grid-drive region, it is possible to use a method of plate-to-grid coupling similar to that used for other stages. It is not particularly necessary to use a low-resistance source, but cathode bias has a serious limitation in this kind of circuit, for reasons which will appear in a moment.

The conditions shown in *Fig. 2* are based on the use of a fixed bias of 70V. In this example, the combined plate current changes from about 20mA for the two tubes when there is no signal to about 90mA for the 5.5W output achieved without the grids going positive, or 138mA for the 18W output achieved by using positive grid drive.

If you had used a bias resistor to give 70V bias at 20mA, you would need a cathode resistor of 3,500Ω. But when the plate current rises to 90mA, the same resistor will give a bias of over 300V. Of course, this assumes that you get your 275V plate-to-cathode in each case, which is obviously impossible.

If, in the quiescent condition, you had a plate-supply voltage made up of 275 plate-to-cathode, plus 70 cathode to ground, this would mean a B+ supply voltage of 345. Obviously, when the drive is applied, the 345V supply will need to divide itself between plate-to-cathode and cathode-to-ground. This would probably be about fifty-fifty, meaning there will be about 170V from plate-to-cathode and 170V bias.

It is evident that the operating points on the curves are modified from zero to maximum signal for this type of operation, but it *is* possible to use cathode bias with considerably reduced output.

An example is given in the tube-data manual, using 275V maximum plate voltage and a bias resistor of 775Ω. The zero-signal plate current is quoted as 36mA. This will give a cathode-to-ground voltage of about 28V, so the overall supply voltage should be a little over 300V. If you now consider maximum-signal operation, at 90mA you will have a bias voltage of 70, which is 42V more than you had at zero-signal output. If you had 275V from plate to cathode at zero signal, you will get only 233V plate-to-cathode under maximum-signal conditions.

This means that the curves for producing the composite characteristics *at maximum signal* must be moved along so that the 233V points coincide, instead of the 275V points as in *Fig. 2*. Obviously this will reduce the maximum available output. It also changes the optimum load for achieving maximum output. For fixed-bias condition, the recommended plate-to-plate load is 3,200Ω, while for cathode bias it is 5,060Ω. ❖

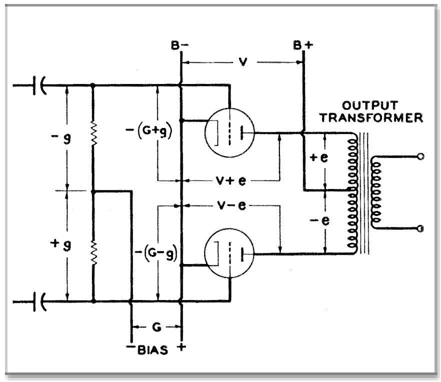

FIGURE 3: This schematic of a push-pull output stage shows the justification for the method of construction employed in *Fig. 2*. When one grid swings positive of the bias (G) by an excursion (g), the other swings negative by the same amount. Similarly in the plate circuit, when one plate is negative of the mean value (V) by a swing (e), the other swings positive by the same amount.