Audio Classroom

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

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PLATE-TO-PLATE LOAD

The rated value of plate-to-plate load impedance is based on the method usually adopted for transformer design. This may be clarified by considering a true Class-A stage in which both tubes are operating all the time. Such a bias condition is illustrated in *Fig. 4*, for the same 45 tube. Here, for convenience, we have used 60V bias, which gives a quiescent current of a little over 25mA per tube, and the curves for grid voltage of 0, –30, –60, –90, and –120 are drawn in, with composites for each of these combinations. This is to avoid making the picture too confusing.

On the individual curves, two straight lines are drawn, each representing a load resistance of 5,750Ω for each tube separately. Then, on the composite curves (which are drawn straight), a composite load line is plotted that represents a plate-to-plate value of 6,800Ω. From this load line, the dotted curves are drawn, using the original individual curves to represent the load line applied to each tube by this composite load. This is the practical working load for each tube.

The important thing to realize is that the load lines drawn for composite conditions, both in Fig. 2 (part 4a, *GA* 3/00) and *Fig. 4, are referred to current in one half of the output-transformer primary winding.* When the current in each half is equal, the two balance out and produce a resultant magnetization of zero in the transformer, referring to one half of the primary winding. When, say, there is 30mA in one half of the winding, and 5mA in the other half, this is equivalent to having 25mA in the first half and zero in the second. Similarly, the voltages measured at the plate, and charted on the graphs, are referred to one half of the winding, as far as the load is concerned. When the plate voltage in one tube has dropped to 200, and in the other has risen to 350, there is a *change* of 75V *on each half of the winding.*

Therefore, the load lines as drawn represent the working impedance, as measured across one half of the transformer primary winding.

Now, the actual load is connected on the secondary of the transformer. Suppose, for example, that the transformer is a 40-to-1 step-down—that means 20 to 1 from each half of the primary—and that the secondary is loaded with a 2Ω resistor. The impedance ratio from one half of the winding to the secondary is 20^2, or 400 to 1, so the impedance presented to one half of the primary by the secondary load will be 400 × 2 or 800Ω. To refer the

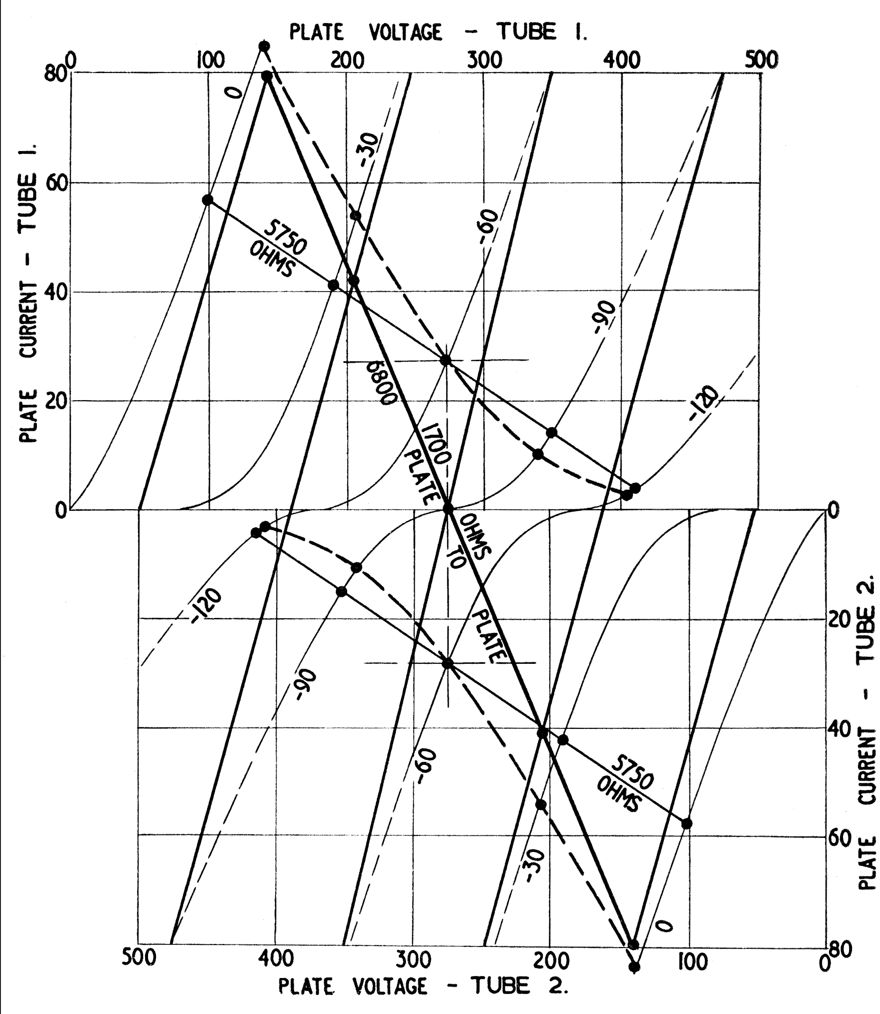

FIGURE 4: Another set of composites drawn from the same originals as Fig. 2, using the same plate voltage but a different bias (–60V) for Class-A operation. This illustrates how to use a lower effective load with a push-pull arrangement than with single-ended tubes.

secondary load to the whole winding, it will be multiplied by an impedance ratio of 40^2, or 1,600 to 1, and will appear as 3,200Ω. The figure quoted as plate-to-plate load would be 3,200Ω, but the load for each tube would be equivalent to 800Ω. This is the load represented by the dashed lines in Fig. 2.

Looking at *Fig. 4* now, we see that the 5,750Ω load lines are at a much more shallow slope than the composite load line. Because of the push-pull operation, it is possible to use a considerably lower effective loading per tube than the 5,750Ω used for only one, so the overall plate-to-plate load is 6,800Ω, which is much less than twice 5,750Ω. But the load for each tube will be only ¼ of 6,800Ω, or 1,700Ω, when drawn against the composite load line.

All this may seem a little confusing at first, but the important point to realize is that the practical circuit makes the two loads appear to be in series, because the windings of the transformer which combine the output are in series. But the magnetizing effect in the transformer is differential, so you subtract the smaller current from the larger.

This means that the current change represented on the curves is double that which occurs in each half-winding, and the voltage difference on the curves is what occurs across one half of the winding (either half). Hence, the effective impedance considered on the composite load line is ¼ of the apparent impedance from plate-to-plate.

OPERATING CLASS

We have used the expressions "Class A" and "Class AB." The method of operation represented in *Fig. 4* is called Class A, because both tubes are contributing to the amplification throughout the entire cycle, even at full amplitude. This is shown by the complete excursion of the individual curved load lines contributing to the composite load line.

In the combination shown in Fig. 2, the individual load lines operate only from –110V bias to zero, while the grid excursion goes on down to the full –140V. During part of a cycle at full output, each tube is biased beyond cutoff. This method of operation is called Class AB.

Class B, from which the idea of AB is derived, is a method of operation where both tubes are biased almost to cutoff, with no signal applied. When any appreciable signal comes along, each tube amplifies precisely half of the wave form, while working with the other tube, which amplifies the other half.

The kind of operation represented in Fig. 2 is called Class AB because for small signals up to approximately ¼ full output—that is, a grid swing of about 35V out of the 70V available, before running into the positive grid region—the amplification is Class A since both tubes are contributing to the output all the time. When the input swings up to full amplitude, each tube operates only part of the time—although it is a bit more than half in each case. For small signals, the tubes act in Class A, but for larger ones, they tend to turn into a Class-B arrangement. This is why the method of working is designated Class AB.

A further class distinction comes between operation with and without positive grid swings. A small subscript 1 after the letter designating the class indicates that the grid is never driven positive with respect to the cathode; a subscript 2 indicates that it is driven positive, and accordingly that power drive is required in the grid circuit.

Thus the operation in Fig. 2, with a 3,200Ω plate-to-plate load, gives 5.5W maximum output in Class AB_1 and 18W in Class AB_2.

PENTODES IN PUSH-PULL

How about working pentodes in push-pull? These can provide an even more efficient output stage, although the distortion situation is not as good, and the operating conditions are more critical than with triodes. However, with modern feedback amplifiers, it is possible—for specification purposes at least—to achieve a very good output.

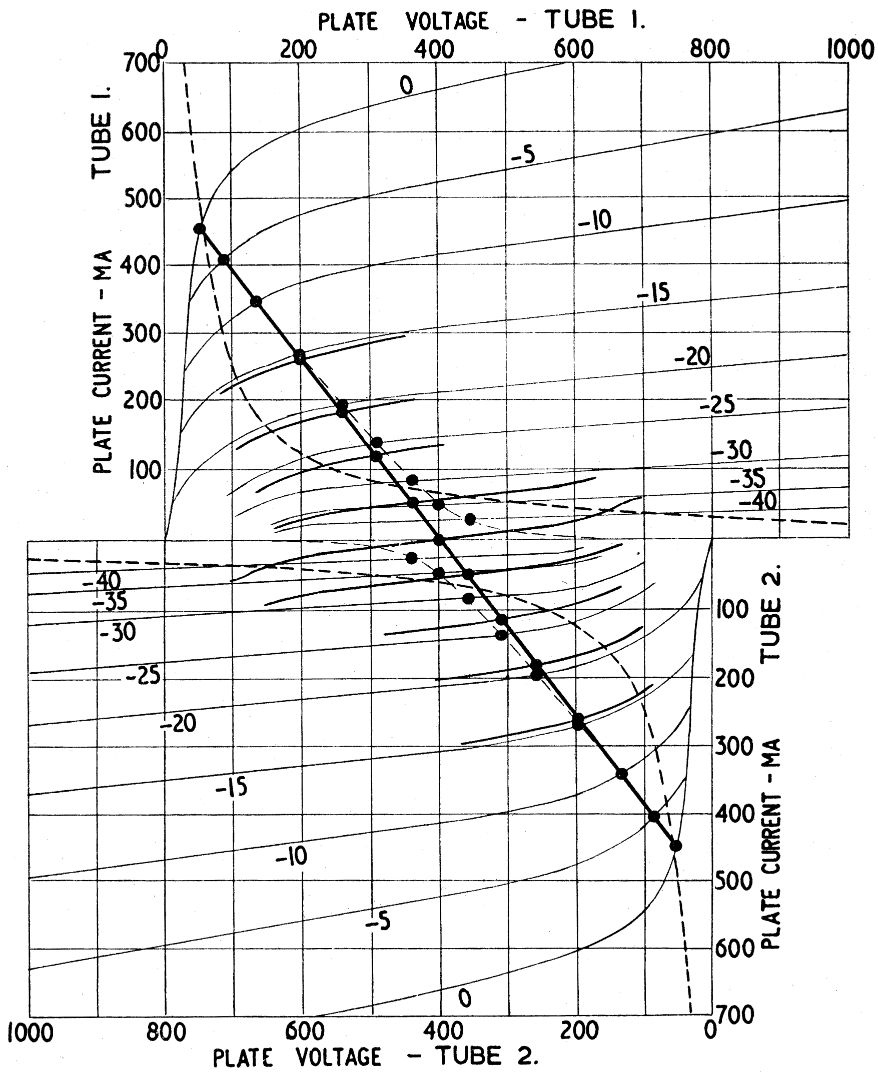

FIGURE 5: Two sets of curves for the 5881 tube, with 400V on plates and screens, put together for composite characteristics. This method of operation can be used to work the tubes harder without exceeding their ratings. However, pentodes and tetrodes operated this way are still much more critical of loading than are triode-type tubes.

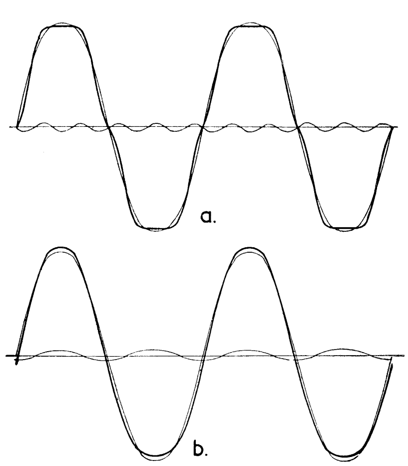

FIGURE 6: To illustrate how pentode distortion is more serious than its specification figures suggest, "a" shows the effect of 5% fifth harmonic on a wave form; from this, the load line of *Fig. 5* will give less than 5% distortion, although it looks bad. At "b" for comparison, the effect of 5% second harmonic is shown. In each case, the thin lines represent the component frequencies, fundamental and harmonic, while the heavy line is the composite distorted wave form.

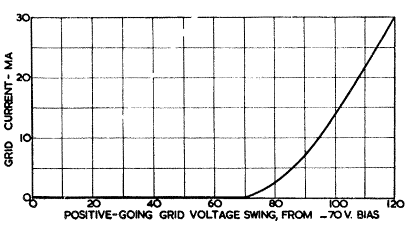

FIGURE 7: The grid-current curve of an output tube. Bias is –70V, and the positive swing is 120V from this.

Figure 5 shows two sets of 5881 characteristics placed back to back to produce composite load lines. Here again, the operation is Class AB, so that toward each end of the load line only one tube is conducting. In the region near zero plate current on each, the resultant plate current is contributed in part by each tube, so a difference value is taken to produce composite load lines.

These characteristics illustrate how it is possible to increase the output rating of pentode tubes (or beam tetrodes) by this method of operation. The heavy dashed lines represent the maximum rated plate dissipation of 25W. The fine dashed curves represent the load presented to each tube, while the solid load line is the composite value. The bias is –35V, and 400V are applied to both plates and screens. This gives 50mA for each tube at the quiescent point. The composite load line is for an impedance of 800Ω; by the relationship already discussed, this represents a plate-to-plate working impedance of 3,200Ω.

About 70W output can be obtained from these two tubes, rated at 25W plate dissipation, with distortion a little less than 5%. This is possible because the individual load lines go through points representing about 50W dissipation at about –15V on the grid, but dissipation during the whole negative-going excursion from the –35V bias point is far below 25W. The average over a complete cycle of the applied signal is within 25W.

From the high-quality point of view, however, this output rating should be examined more closely. At a first glance, the composite curves would suggest that the distortion must be considerably more than 5%, because the spacing between consecutive curves along the composite load line deviates quite markedly. But notice how the deviation occurs: closing up occurs both at the extremities, between the zero and –5V curves, and also between the composite curve for –35V on each grid and the curves representing –30V on one and –40V on the other. The extent of closing is almost equal in all three regions. This signifies that there will be a flattening of the tops of the wave form, and also a kinking near the zero line, as shown in *Fig. 6*.

This is equivalent to almost pure fifth-harmonic distortion. Now, 5% fifth harmonic will produce a deviation from a true sine wave that is about as noticeable as a 10% third or 20% second harmonic. This is caused by a much more rapid deviation from the true wave form. Second-harmonic distortion causes one area of closing up and one area of widening out per cycle. Third-harmonic causes two areas of closing up and two areas of widening out per cycle. Fifth-harmonic causes four areas of closing up and four areas of widening out in every cycle. The amplitude of any harmonic is measured in terms of the variation from the mean value of true sine-wave fundamental.

If the variation must occur four times a cycle instead of only once, then it will need to be only a quarter as great to produce an equally noticeable effect both on listening—in audible harmonic distortion—and on the visual presentation of the wave on a scope. A similar principle holds true with regard to the corresponding intermodulation (IM) distortion, but the figures will be modified to some extent by the relative audibility of the respective tones. At low frequencies, the harmonics and higher-frequency components are much more audible than the fundamental, so the magnification will be even greater. At high frequencies, the reduction in aural sensitivity to the higher harmonics will tend to offset the otherwise increased noticeability.

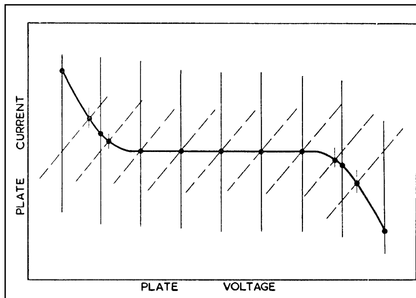

FIGURE 8: Applying the form of load line produced by push-pull grids, with the characteristics of *Fig. 7*, to idealized tube characteristics. The parallel vertical lines, representing a theoretical tube with zero AC resistance, would be ideal. The parallel dotted lines show how the presence of AC resistance, represented by the slope, causes distortion where the grid current occurs; along the straight central section, the spacing is the same, but closing up occurs at ends.

As regards IM distortion, in theory the values measured will depend upon the deviation from normal, and so should be proportional to the percentage harmonic reading, regardless of the order of the harmonic. In practice, however, the audibility of the IM rises in proportion to the order of curvature producing it.

The net result of this general principle is that, although pentodes appear to give harmonic-distortion values competitive with triodes, and very much more output, the figures given are somewhat deceptive because the order of harmonics pentodes produce is much higher than those of the triodes.

There is another factor that the push-pull operation does not remove from the pentode tube: notice how little the load line of *Fig. 5* would need to rotate or tilt about its central point before much more distortion becomes evident. Rotated in a clockwise direction, indicating an impedance lower than the optimum value, the spacing between the zero and –5V curves will open out, representing the introduction of a larger proportion of third harmonic than the original value of the fifth. Going in the opposite direction, the spacing between the zero and –5V grid characteristic closes up with a similar rapid increase in both the third and the fifth.

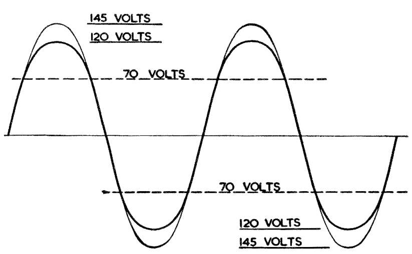

FIGURE 9: The forms of distortion that will occur by using 1:1 coupling from a push-pull 6SN7 to get the drive discussed as necessary for type 45 tubes.

This low value of distortion has been obtained by what is in effect *a critical adjustment of load value*. Not only this, but the load line used represents a pure resistance. Because the characteristic curves it intersects are all very definitely curved, any opening out into an ellipse, due to reactances being present, will also introduce distortion quite rapidly. This is a good reason why a great many high-fidelity enthusiasts still prefer to use triodes, although they do not give such large power outputs as pentodes for the same plate-dissipation rating.

Of course, pentodes connected as triodes behave exactly the same as triodes and can be considered in the same group.

POWER DRIVE STAGES

We have mentioned the use of power drive—that is, providing current for driving the output-tube grids positive with respect to their cathodes—so we must consider how to achieve this drive effectively without distortion.

Consider first the kind of load the output-stage grids will provide for the preceding stage. Assume, for example, that we are using 70V negative bias. Then, for the first positive 70V of a signal swing, there will be practically no load on the previous stage; the impedance looking into the grid will be very nearly that of the grid resistor. Then, as the grid starts to go positive with respect to the cathode, it will start to conduct.

The curvature of the conduction characteristic when it runs positive will be somewhat like that of a diode: this is not exactly a straight line, but a curve of about 1½ power law. *Figure 7* shows the current in the drive circuit. The current will naturally be in the same direction as the voltage. On the opposite swing, the current will be negative from the point of view of the first circuit, though it will be positive grid current in its own circuit.

Thus, the current loading on the preceding stage occurs only at the tips of the drive-signal wave form. It is rather like trying to place a heavy article on a top shelf that you can reach only on tiptoe. The article is fairly easy to lift until you get it to head height; then it becomes harder. When you get on tiptoe, it requires all your effort to lift it the last little distance. If someone gives you a push at the critical moment, you simply won't make it! In providing power for a grid drive, the highest current drain occurs at the very extreme tip of the voltage swing.

If we apply the composite load line representing the grid-current load to some theoretical tube characteristics as in *Fig. 8*, we can see that the ideal tube characteristics will be vertical straight lines, representing zero AC resistance. It is immediately evident that triode tubes present the best initial possibility of approaching this.

A useful drive tube is the 6SN7 that was discussed under "Phase Inverters" (Part 3). Using the 8V grid-bias operating condition with transformer coupling, a single tube would give a swing of 340V, pk-pk. If two such tubes were operated in push-pull, an available pk-pk voltage of 680 would exist on the primary. The AC resistance of each tube at zero grid voltage is about 6.5k.

Suppose the peak drive voltage required is 120V on each grid, and that the peak grid current is 30mA. When 30mA is drawn from a source with an AC resistance of 6,500Ω, a voltage drop of about 20V is obtained. If the drive circuit gave a 120V open circuit, the drive would be reduced to 100V because of grid current. We should need to provide an input swing that would give about 145V without grid current, which would be loaded down to the 120V required.

The wave form will be as shown in *Fig. 9*. Without bothering to calculate how much distortion this represents, it can be seen to be quite large. Remember, though, that this stage has available a pk-pk swing of 680V (that's not allowing for grid-current loading), whereas we require only 240V (120 for each grid of the output stage).

Let's assume that we will throw away about 40V of available swing because of the loading of the extreme tips, and to allow a safety margin. We need to use a step-down transformer that will change the 640V we have to the 240 required. This is a step-down ratio of 8:3, or 2.67:1. The loading effect of the grid current will then be reduced from 30mA to $\frac{3}{8} \times 30$, or 11.25mA. This current in the AC resistance of 6,500Ω represents just under a 7.5V drop in the available swing per tube of 344V. That drop will be stepped down on the secondary side by a ratio of 8 to 3, resulting in less than 3V in the 120V grid swing required. An open-circuit swing of 123V will be ample to give a loaded swing of 120, an obvious improvement over the 1:1 coupling ratio. Distortion will be less than 1.5%. The complete circuit is shown in *Fig. 10*.

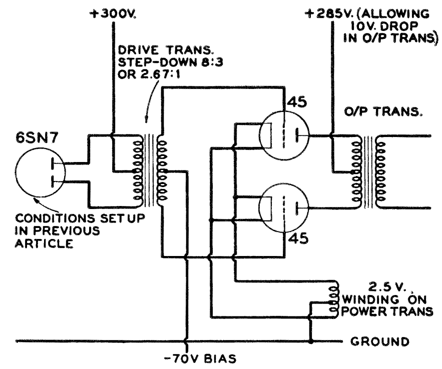

FIGURE 10: Using a step-down transformer of ratio 8:3, or 2.67:1, the distortion which is so prominent in *Fig. 9* can be reduced to less than 1.5%. See text.

In this article we have so far not considered questions such as frequency response, the stability of the amplifier, or other things you must account for in practice. We intended to present a picture of what push-pull amplification can do. Before we can really design a complete, up-to-date, push-pull output amplifier, we need to go over some other details connected in one way or another with the use of feedback, so Part 5 will deal with feedback in amplifier design. This will provide the basis for completing a whole amplifier, using the procedures already discussed. ❖