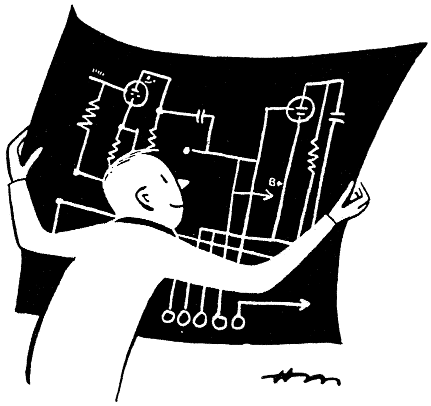
Audio Classroom

Designing Your Own Amplifier, Part 2: The Power Stage

BY NORMAN H. CROWHURST



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In Part 1, where I discussed the design of voltage-amplifying stages, the job was simplified by the fact that you had only to consider the *voltage* swing that a certain load line produced when applied to a tube's characteristic curves. So far, I have not discussed how the maximum ratings impose limits on what we can "get out" of a given tube.

Maximum ratings do limit the performance of voltage-amplifier tubes as well as the power types, but usually it's much easier to stay within the ratings of the former. I have avoided mentioning it because it might have been confusing at that point. But for power tubes, the ratings assume a primary importance. When you come to consider the design of a complete amplifier, you will take all these points into consideration, including the ratings of voltage-amplifier tubes.

TUBE CHARACTERISTICS

There are several ways to go about designing a power stage, depending to some extent on the information available. The tube characteristics—as you have used for voltage amplifiers—provide the most informative approach, but other useful data is published from which it is also possible to make up quite accurate designs.

The tube characteristics on which you draw load lines are the ones that plot plate current against plate voltage for various values of fixed grid voltage. *Figure 1* shows such a set of characteristics for a triode-connected KT66 tube. A pentode tube connected as a triode will give characteristics similar to this. Each of the curves represents all the possible combinations of plate voltage and current that can occur when the particular voltage specified is applied to the grid.

When, in addition to a bias voltage, an audio voltage is applied to the grid, the plate voltage and current must vary in the manner of a line crossing these curves at some angle. The angle of the line will depend upon the value of resistance used as a load for the tube.

Suppose the value of the load is 10,000Ω. Increasing the plate current by 1mA will cause the plate voltage to drop by 10V. Increasing plate current by 2mA will cause the plate voltage to drop by 20V, and so on. A straight line drawn across the curve at an angle representing 10V for each milliampere will be a load line representing 10,000Ω. If you wish to put a load line of 4,000Ω

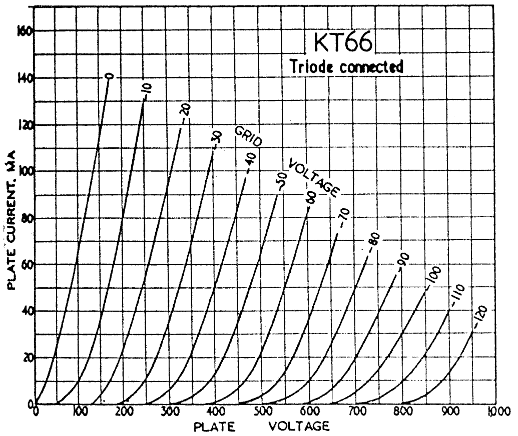

FIGURE 1: Plate-current/plate-voltage characteristics for triode-connected KT66 tube. Each curve represents the variation of plate current with plate voltage when the grid voltage is fixed at the value for which the curve is labeled.

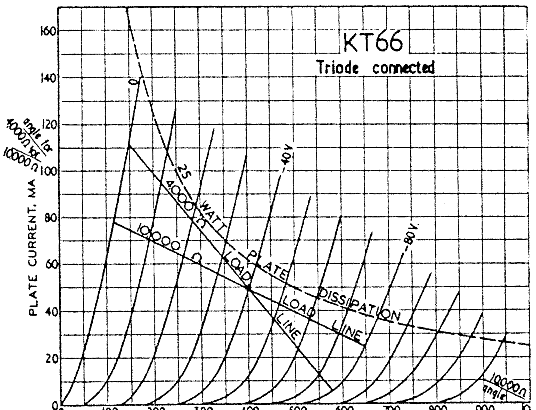

FIGURE 2: The curves of *Fig. 1*, with the maximum dissipation curve drawn in (dotted). Two possible load lines are shown using operating voltages of 400 on the plate and –40 on the grid. Small construction lines show a convenient way of getting the correct angle for a specific load value: for 4,000Ω, 100mA on the current axis is aligned with 400V on the voltage axis. Any values of voltages and current whose ratio corresponds with the required impedance value could be used as easily.

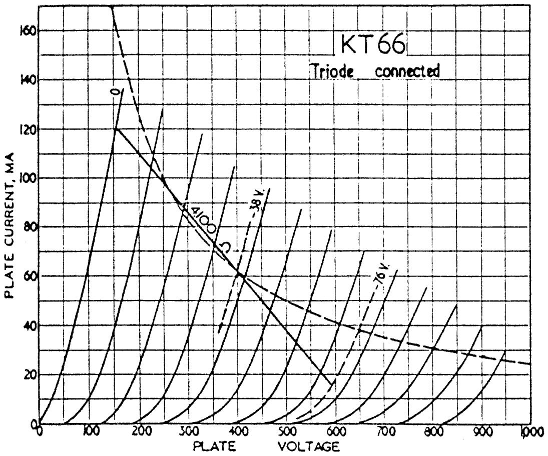

FIGURE 3: Slight adjustment to the operating conditions of *Fig. 2* produces improved results, both in higher power and decreased distortion (see text).

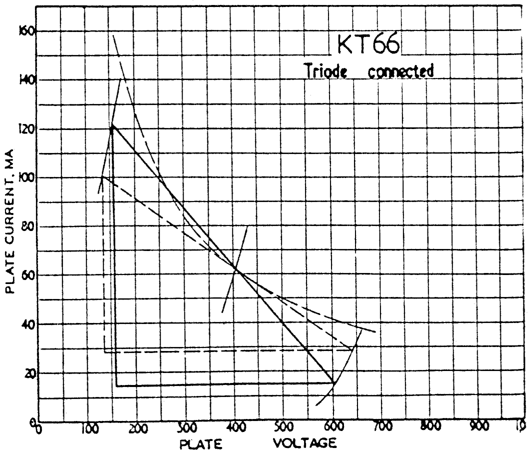

FIGURE 4: Relative power output can be estimated as the load line is changed: the solid-line triangle obviously has a larger area than the dotted-line one, which means increased power output.

across the curves, make a change of 1mA corresponding with 4V, or 10mA with 40V, and so on. The *slope* of the line, then, represents the resistance value of the load.

This tells you how to set up the angle of the load line. Now, how do you know exactly where to draw it? That will be determined by your operating conditions—what steady-state plate voltage and current you choose, and the DC grid voltage that must be used as a bias to obtain this working voltage and current. In a power-output stage there are various limits from which to choose.

First, you must not exceed the plate-dissipation rating of the tube, otherwise the plate will get too hot and the tube will probably become gassy. Second, you must not exceed the maximum plate voltage specified by the tube manufacturer.

These maximum ratings set a limit on how much you can “push” the tube in endeavoring to get more watts. We have conflicting requirements: getting the most output power, yet allowing the tube a good safety margin to ensure long tube life. But whether you wish to emphasize the safety aspect or to get as much output power as possible, you should operate the tube under conditions that will show the cleanest output for the type of tube used. This means that distortion as well as power output must be considered.

PLATE DISSIPATION

When using the tube curves, the first thing to do is set up boundaries or limits within which you can draw a load line. The manufacturer establishes a maximum dissipation rating for the tube. For instance, the KT66 tube, whose triode-connected characteristics are shown in *Fig. 1*, has a maximum plate dissipation rating of 25W. This boundary can be plotted by determining various points on the chart that represent 25W, and then drawing a dotted line across the characteristic curves.

For illustration, 500V at 50mA is one pair of values that represents 25W; 625V at 40mA, 400V at 62.5mA, 250V at 100mA, and 1,000V at 25mA are some other values that can be used to plot the maximum-dissipation line (*Fig. 2*).

The other maximum limit specified for triode tubes is the plate voltage. This is specified in one of two ways: the real limitation is the maximum positive excursion, because the danger is that of flashover from a high potential difference between the plate and grid; but most circuit designers prefer to have a maximum working-voltage figure, which is the highest supply voltage that can be connected to the plate circuit.

In any output stage the plate-supply voltage is connected to the end or the center tap of the output-transformer primary, the plate being connected to the other end. In the quiescent or no-signal condition the plate voltage is almost equal to the supply voltage, being reduced only by the small DC drop in the winding.

When the plate voltage changes because of an applied audio signal, the fluctuations will go positive as well as negative from this supply voltage. If the figure given by the tube manufacturer for any particular tube is the maximum supply voltage, this should be limited to the value stated. Then there is no need to bother about the positive-excursion limit because the specification given takes care of this. Assume that 400V is the maximum.

POWER OUTPUT

The next step in figuring out the optimal position of a load line is to realize that the grid-voltage excursions, positive and negative, from the working point will be equal. Thus, if the bias is chosen as –40V, and the maximum audio swing in the positive direction is taken as being up to zero grid volts, the corresponding negative swing will be to the –80V characteristic.

Assuming a grid bias of –40V as a starting point, we put a ruler across the chart so that it passes through the point where the –40V bias curve crosses the 400V plate-voltage line. Then the ruler can be rocked about this point, and the way it crosses the other curves examined. Notice how the linearity of the output varies, represented by the evenness of spacing of the bias curves between the 0 and –80V lines. If the load line is made too steep, representing too low a load impedance, the spacing between the grid-voltage curves toward the 0 end of the line will be wider than it is toward the –80V end. To achieve the lowest distortion, which means maximum uniformity

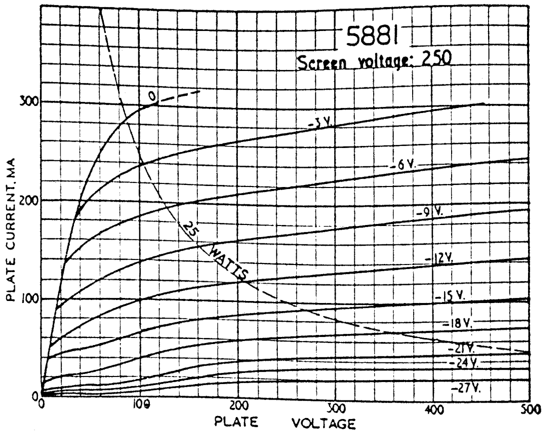

FIGURE 5: Plate-current/plate-voltage characteristics for type 5881 tube working as a pentode, with 250V on the screen. Numbers on the curves represent grid voltages at which they were taken.

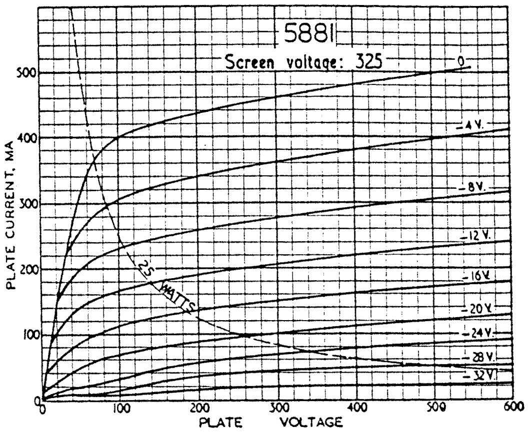

FIGURE 6: Characteristics similar to those of *Fig. 5*, but with the screen voltage at 325. Notice the increased scales; the raised screen voltage produces larger plate currents for same plate voltages.

of spacing between curves along the load line, the line must be more nearly horizontal, representing a higher impedance.

You will find, though, when you come to calculate the power, that this reduces the available watts output. A better output can be obtained by working nearer the maximum dissipation curve. To keep within the 400V maximum plate-voltage requirement, this would require about –38V bias. That, in turn, gives approximately 60mA steady-state current, and the audio swing is now limited from 0 to –76V on the grid (*Fig. 3*). Moving up in this way has resulted in two gains, compared with the –40V point.

It has enabled you to work with a lesser audio grid-voltage swing which, apart from the slight increase in stage gain this represents, makes it easier to keep the distortion down. It has also enabled you to use a steeper angle for the load line, representing a lower resistance, which probably means that a greater output power will be available.

The only way to be *sure* whether a change increases available power or not is to calculate it. It can be estimated roughly by gauging the relative area of the triangle formed by the load line, between the extremes of grid voltage used, with the horizontal and vertical lines making a right-angle triangle (*Fig. 4*). The load line that gives the triangle of greatest area will produce the greatest power output.

Maximum power represented by a load line, with a sinusoidal audio wave form, can be calculated by subtracting the lower plate voltage from the higher value, and the lower current from the higher value, then multiplying these quantities together and dividing by 8,000 to get the answer in watts. In *Fig. 3* the values are 580V and 160V, and 14mA and 120mA. These represent changes of 420V and 106mA. Multiplying them and dividing by 8,000 gives just over 5.5W, which is about the power output this tube will furnish working single-ended as a triode.

DISTORTION

Now to check distortion. The maximum positive excursion from the 400V midpoint to the 580V maximum is 180V; the negative excursion goes down to 160V, which is a drop of 240V. For symmetry the midpoint between 160 and 580V

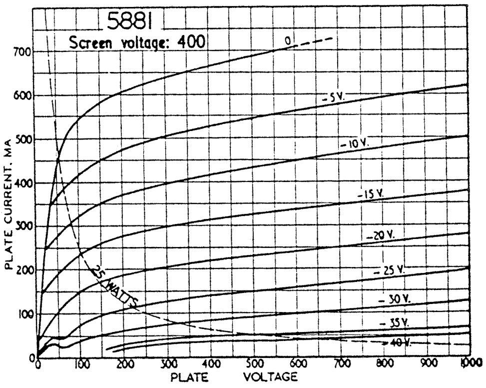

FIGURE 7: Raising the screen voltage to the limit of 400V. Most of the curves are now above the specified maximum dissipation curve because the tube is designed for push-pull operation.

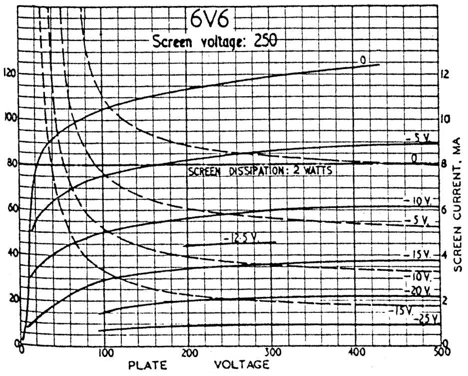

FIGURE 8: A pentode characteristic chart with screen currents as well as plate currents plotted. Solid-line curves are for plate current and voltage. The dashed curves are for screen current, the screen being fixed at a voltage of 250 for all these curves. Obviously, plate voltage affects screen current markedly. Maximum screen dissipation of 2W is a horizontal straight line on the chart.

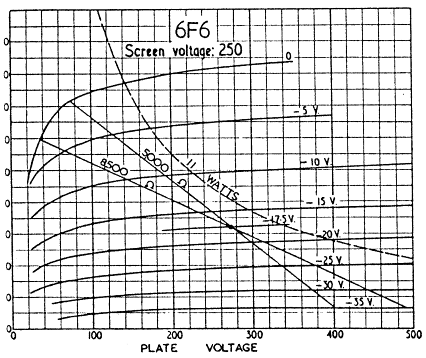

FIGURE 9: How changing the value of a load affects output when applied to pentode curves. The 5,000Ω line manifests mostly second-harmonic distortion, indicated by wider spacing toward the top end, and closer spacing toward the bottom. The 8,500Ω line manifests mostly third-harmonic distortion indicated by closing up of the spacing toward both ends of the line.

should be (160 + 580)/2, or 370V. The actual 400V operating point is 30V from the middle of the waveform. So the peak-to-peak ratio of second-harmonic distortion to the fundamental frequency, at 5.5W, is 30 to 420, or about 7.1%.

Because it is *second* harmonic, however, it can be considerably reduced by using a push-pull output arrangement. This neutralizes second- and even-order harmonics in a way I will explain subsequently. Push-pull operation also permits the output to be more than doubled by utilizing a greater length of the load line for each tube during its negative excursion. I will explain this as well.

Notice that the load line you have drawn cuts across the 25W dissipation curve slightly. Is this permissible? The operating point is on the edge of the curve, and any plate excursions occur equally on either side of the center operating point. Therefore, at all signal levels, the average dissipation throughout a cycle will always be within the 25W rating of the tube.

The important matter in dissipation ratings of tubes is that the *average* dissipation over the cycle must be within the rated value. Practically all heated-cathode tubes will take considerably more than their maximum plate dissipation for short intervals. This is the principle exploited to an extreme in pulse-amplifier technique; a tube may be operated up to ten times its maximum average dissipation during the pulse. So the load line shown in *Fig. 3* is quite legitimate.

Although the KT66 is not designed as a triode, it is fairly representative, when so connected, of good triode tubes. This tube is not particularly efficient as a single-ended output stage: you get only 5½W output with about 7% distortion, for a plate dissipation of 25W. To get 50W output at this rate, you need a tube or tubes with plate dissipation of 250W.

TETRODES AND PENTODES

It was the desire for bigger outputs at less power expenditure that led to the development of pentode and tetrode output tubes. These have characteristics similar to those shown in *Fig. 5*, which are for the 5881 with a fixed screen voltage of 250V. *Figure 6* shows curves for the same tube taken with a screen voltage of 325V, and the curves in *Fig. 7* are for the same tube with a screen voltage of 400.

These sets of curves are all quite similar; you must look at the numbers to see the differences. Notice that the plate currents are successively higher as the screen voltage is raised. A higher screen voltage makes it possible to get a greater output from the tube, because a larger plate-current swing can be obtained with the same plate-voltage swing. Limitations to consider in selecting the operating characteristics for a tetrode or pentode tube are plate dissipation, screen dissipation, and maximum operating voltages.

A curve for maximum plate dissipation can be drawn on these charts by the method already shown for triodes; a dotted line is drawn on each of the sets in *Figs. 5–7* to indicate the rated maximum plate dissipation of 25W. Screen dissipation is not shown, but is limited to 6W for this tube.

Sometimes screen current is indicated on the same diagram as the plate-current curves (*Fig. 8*). These curves do not help as much as you might expect, and for this reason they are usually omitted. The voltage applied to the screen as these curves are plotted is constant. It is the plate voltage that is varied for different values of grid voltage, and the screen is held to the same constant voltage value for the whole family of curves. The maximum screen dissipation is, accordingly, represented by a horizontal line across the curves (*Fig. 8*).

As in the case of plate dissipation, the screen dissipation condition is satisfied provided the average dissipation throughout the audio waveform cycle is always kept within the specified limit. It does not matter if one peak of the screen-current waveform exceeds the maximum dissipation momentarily.

This being the case, the more direct method of determining that the screen dissipation is kept within bounds is to take the tube manufacturer's recommended operating voltage. If this is used, the dissipation will not be exceeded. A lower voltage may be used if desired, with consequent economy in both screen and plate dissipations.

In most pentode-type tubes, there is a plate-voltage limit because of the high impedance or plate resistance of the tube. Too high a load impedance would result in excessively high positive plate-voltage swings, corresponding to negative grid swings, that might cause flashover damage to the tube. The particular tube represented in *Figs. 5–7* is

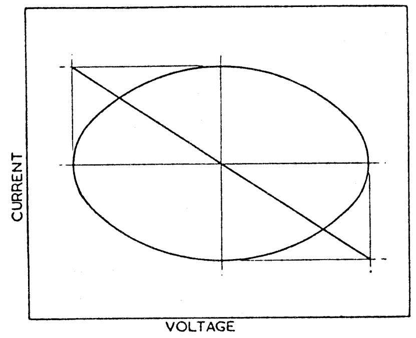

FIGURE 11: Comparison between load lines representing pure resistance (straight line) and pure reactance (ellipse) of same magnitude and at the same values of plate voltage and plate current.

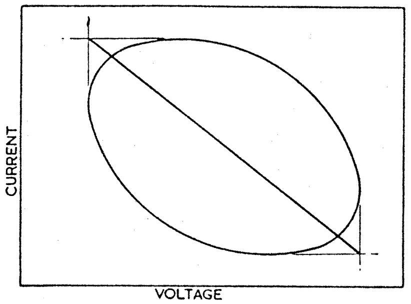

FIGURE 12: Comparison between load lines representing pure resistance (straight line) and combination of resistance and reactance as impedance (ellipse) having the same magnitude and at the same values of plate voltage and current.

designed for push-pull operation, so the dissipation in each tube only occupies about half the time for a full-length load line.

With the pentode-type tube, minimizing distortion is a little more difficult than with the triode arrangement, because the triode tends to introduce primarily *second*-harmonic distortion, indicated by closing up of the intersections between the load line and the different grid-voltage curves toward one end and opening them out at the other. In the case of a pentode, use of a load line representing too high a value results in closing up the points of intersection toward both ends of the load line (*Fig. 9*).

If the tendency to close up is greater at the top end of the line than at the bottom, then there will be a combination of third-harmonic and second-harmonic distortion, the second harmonic being in opposite phase to that produced by the triode tube. Use of some lower value of load will result in practically uniform closing up at both ends, while a still lower value causes more pronounced closing up at the bottom end of the line.

When these results are analyzed in terms of distortion versus load impedance for the same amount of drive, the result appears as in *Fig. 10*. Third-harmonic distortion becomes progressively less as the load value is reduced. Second-harmonic distortion, on the other hand, passes through a null point, at which the closing-up effect at both ends of the load line is balanced. In practice, minimum overall distortion is achieved by using a value of load slightly lower than that which gives minimum second harmonic.

Determination of operating bias point from the working plate current and plate voltage, together with the amount of grid swing necessary to give full output, is calculated in just the same way as was described for the triode tube. Choice of load line for maximum output and minimum distortion is assessed in much the same way too.

IMPEDANCE LOADS

This way of using a load line, while very convenient for making calculations, overlooks one thing in the practical performance of the amplifier. This is the fact that the load line represents a *pure resistance* load. Most amplifiers are used to feed loudspeaker loads, which have considerable reactance at various frequencies.

The relation between voltage and current in reactance, when plotted on graph paper or presented on an oscilloscope screen, is an ellipse. This means that the load line applied to tube-characteristic curves for a reactive load, or for a load that is a combination of reactance and resistance (an impedance) will be an ellipse, the horizontal and vertical dimensions of which will be in a proportion representing the impedance value.

If the reactance is pure—that is, with no resistance included—the major and minor axes of the ellipse will be horizontal and vertical (*Fig. 11*). In practice, of course, there is always some resistance present, otherwise there would be no power output. So the practical form of ellipse, representing impedance, is shown in *Fig. 12*.

It may be possible to get a very nice, large output and low distortion using a straight load line, but is the uniformity of the characteristic curves good enough to allow the load line to spread out into an ellipse? This will depend upon the type of tube and the operating conditions chosen. Triode and pentode tubes both introduce distortion when reactance is added, but under different conditions and degrees as the combination of resistance and reactance is varied.

These problems are the reasons push-pull operation has become used almost universally. I will detail this in a subsequent article. There are other special circuits, such as the ultralinear, unity coupling, and several more, that I will also discuss later. ❖