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Making Use of Load Lines

by Norman H. Crowhurst

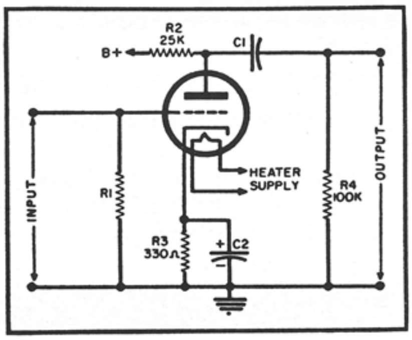
The gap between "theory" and "practice" can be bridged by using graphic tube characteristics and load lines.

Ever since the days when electronics went under the name of radio there has been a controversy between the "theory" and "practice" boys. The proponents of "theory" like to start by calculating a circuit in all its detail. After building it, they hand it over to a practical man to make it work. The practical man naturally argues that practice is of greater value because the theorists never arrange to arrive at the right answer the first time.

Often the designer who relies on theory does not take all of the factors into account. In "theory" a tube has simple characteristics which are listed in a neat little table and by using a convenient formula with algebraic symbols the gain of that tube in a certain circuit can be calculated. An amplifier designed on this basis often misses its objective in one of two ways: either it has less gain than was anticipated; or, if a margin of gain was allowed to take care of this contingency, it turns out to have considerably more gain than was required. It may also be deficient in that although it has the correct gain it will not handle the full output for which it was intended.

This sort of thing happens because the neat little table of tube characteristics

Fig. 1. A simple resistance-capitance coupled stage for voltage amplification.



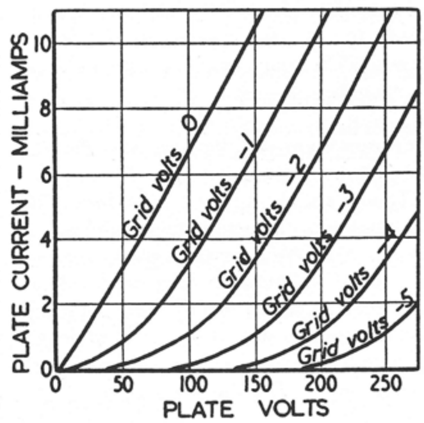


Fig. 2. Tube characteristics for use in the circuit of Fig. 1. Refer to article.

does not tell the whole story. The best link between theory and practice, which enables the prospective designer of an amplifier to come fairly close to the right answer the first time, is the use of graphic tube characteristics and the drawing of load lines. To illustrate this we will take a simple voltage amplification stage, the purpose of which is to receive a specified input voltage on the grid of a tube and amplify it as much as possible at the plate, in order to drive the next stage.

Assume that the circuit is the simple one shown in Fig. 1 and that the tube we have chosen has characteristics shown in Fig. 2. The first thing to do is to draw a load line (Fig. 3) from the "B+" voltage to be used across the tube characteristics at an angle representing the plate resistor R2.

This is done by taking the "B+" supply voltage of 250, in this case, and dividing it by the value of R2 (25,000 ohms). Thus, 250 volts divided by 25,000 ohms will give a plate current of 10 ma. The load line is then drawn between 250 volts and 10 ma.

Next we want to find what value cathode resistor (R3) is required to provide the right operating bias. This really is quite simple: we have to find a point along the load line that will be a suitable operating point to give the required degree of grid voltage swing without running into distortion and then find out what resistance in the cathode will give us the bias value corresponding to this operating point.

Suppose we know that the maximum voltage swing applied at the grid of this tube will be 1 volt, then from the tube characteristics, we will find that the best operating position is about 1 volt negative so that the swing of 1 volt alternately positive and negative from this position goes from zero to -2 volts. That this will give the minimum distortion can be seen by examining the spacing between the various curves representing different grid voltages. The spacing between the curves for zero, -1, and -2 grid volts is nearer equal along the line than any other pair of adjacent grid voltage curves. The spacing should be equal so that all of the waveform is amplified uniformly. To allow a slight margin to avoid the positive grid region which causes grid current flow, in case the voltage swings a little more than 1 volt, we will choose a bias voltage of -1.5 volts. This gives us the point B on the load line shown in Fig. 3.

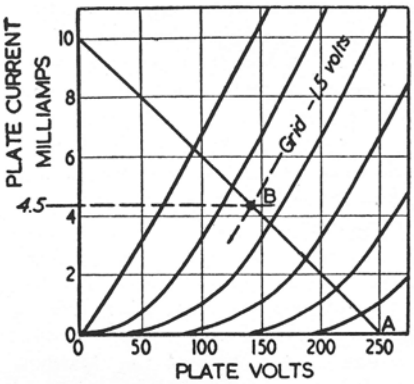


Fig. 3. First step in calculating values. The load line represents an R_2 of 25,000 ohms. The cathode bias resistor is calculated from plate current and the bias voltage operating at point B. Refer to text.

Referring to the current scale at the left-hand side of the tube characteristics, we find that point B represents a plate current of 4.5 milliamps. We now have the information necessary to calculate the value of the bias resistor R3; it must drop 1.5 volts with a plate current of 4.5 milliamps; this means its resistance value must be 1.5/.0045 = 330 ohms.

Now, to work out the rest of the circuit, in order to provide a voltage for driving the next stage grid, we need a coupling capacitor C1 and a grid resistor R4. To calculate the effect of these components on the amplification of the tube we have to recognize two things that may not be obvious at first sight: first, that the coupling capacitor C1 blocks any DC potential from the grid of the next stage and, second that at audio frequencies the reactance of capacitor C1 is negligible.

This means that, as far as audio frequencies are concerned, R2 and R4 are effectively connected in parallel because at one end the reactance of C1 has negligible effect, and at the other end "B+" is connected to ground through a low reactance decoupling or smoothing capacitor. So we have to draw another load line to represent R2 and R4 in parallel.

We can easily calculate the value of this load line from the formula R = (R2 + R4)/(R2 X R4). Assume for example that we choose 100,000 ohms as the value for R4. R2 has already been set at 25,000 ohms so the value of R works out to be 20,000 ohms

If R2 is actually 20,000 ohms instead of 25,000 ohms, the load line would be as shown dotted at line AD in Fig. 4. But because the DC feed to the plate of the tube is only through the 25,000 ohm resistor, the "direct current" load line is truly represented by the line AB, and the operating point has been set by choice of resistor R3 at point B. So the "dynamic load line", as it is called, or the load line for amplifying purposes is represented by drawing a line having the same slope as AD, but passing through point B. This is very simple to construct, by drawing a line parallel to AD through the point B. This line is shown as EF.

EF is shown connected between the grid voltage curves for zero and 3 volts, because the actual swing which will be employed for amplification purposes will not be greater than this -- actually a little less.

Now we can see how much amplification the stage will give. Point E on the zero grid voltage curve represents a plate voltage of about 98 volts. Point F, on the -3

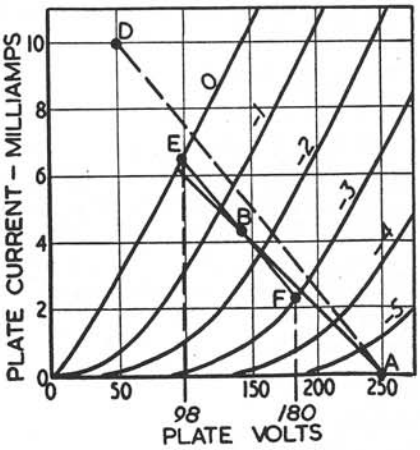


Fig. 4. Remaining steps in calculating performance of stage. AB is the direct-current load line, obtained as shown in Fig. 3. EF is the dynamic load line, taking into account the effect of R_4 through C_1.

grid voltage curve, represents a plate voltage of about 180 volts. So the grid voltage variation of three volts between zero and -3 will give a plate voltage variation of 82 volts -- from 98 to 180. These are convenient values to read on the graph but other voltages will run proportionally, so dividing one by the other, this means that a grid voltage swing of 1 volt will give a plate voltage swing of 82 divided by 3 = 27.3 volts. Otherwise expressed, this stage will show a gain of about 27.

This method of working out the performance of a tube comes a lot nearer to the practical results than calculation using the algebra given in textbooks and the tabulated tube constants given in a tube manual. It will also show without any doubt whether the tube is capable of handling the volume level intended at the particular point in the amplifier without overloading, a point which use of the tabulated data in a tube manual may overlook.

All that is left in completing the stage is to determine the value of the cathode bypass capacitor C2. By good engineering standards the reactance of C2 at the lowest frequency to be amplified by the stage should be 10% or less of the cathode resistor R3. In this case, the reactance of C2 at, say 50 cycles, should be 33 ohms at most. This would work out as 100 mfd.

Pursuing the case we have just considered a little further, we know that full volume will represent 1 volt on the grid of this tube and that this 1 volt on the grid will produce about 27 volts on the plate. From there we can consider the next stage with the characteristics of a suitable tube, knowing that we will get up to 27 volts swing on its grid.

In this discussion, we have been working forward, i.e. we started with 1 volt input and worked our levels forward toward the output. In practice, it is often better to work backward from output to input. We know first what voltage we need at the grid of the output tubes. From there we work backwards to find what tube and what resistance values we can use to get this voltage to drive the output tubes. We then find what voltage this tube needs to swing its grid to give the required plate swing. Then we move back to an earlier stage to find how we can get enough gain from the available input voltage.

Irrespective of whether we work backwards or forwards, this discussion has shown how valuable a load line can be in determining a circuit for a simple tube. We have kept the discussion to a consideration of voltages, because the kind of stage we have talked about has been the one known as a *voltage amplifier.*

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