What is a Load Line

An explanation of the static and dynamic characteristics of triodes and pentodes

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RECENT correspondence from readers shows that many are hazy about the significance of a load line. I still remember when I first saw a senior engineer take a set of tube characteristics, lay a ruler across them and draw a line with a pencil on the curves. From this he produced some mystifying data about the gain of the tube, its distortion, etc. At that time it all seemed rather wonderful but mystifying. Since then I have met many who have studied the subject in their technical courses but who remain rather vague on the true significance of a load line.

The first thing to understand is the different ways in which tube characteristics can be presented. Taking first the simple triode, there are three quantities that can vary: grid–cathode potential, plate–cathode potential and plate current. The tube characteristics are usually shown in one of two ways: by taking fixed plate–cathode potentials, curves are plotted showing the way plate current varies with grid voltage (Fig. 1-a); by fixing the grid–cathode voltage at various values and plotting curves of plate current against plate voltage (Fig. 1-b). In the triode the curves produced by both methods are similar, probably one reason for the confusion that often exists about them.

The best method of proving to yourself the difference between the two kinds of curves is to use one set of curves to produce the other (Fig. 2). Here the curves of Fig. 1 are repeated but corresponding points on the two sets of curves are indicated by corresponding numbers. In Fig. 2-a a particular grid voltage is represented by a vertical line while in Fig. 2-b it is represented by a curve. Thus the points numbered 1, 2, 3 are all at a grid voltage of zero on both diagrams; the points numbered 8, 9, 10, 11, 12 are all at a grid voltage of −2. In Fig. 2-b a plate voltage is represented by a vertical line, while in Fig. 2-a it is represented by a curve. Thus the points numbered 7, 11, 15, 18, 20 are all at a plate voltage of 200 on both diagrams. You can trace out the correspondence of other points on both graphs for yourself.

The grid-voltage plate-current curves are not very helpful in showing the characteristics of a tube when operated with a plate load, because each curve represents the change in plate current *for constant plate voltage* as the grid voltage is changed. If the tube is operated without any resistance in the plate circuit, so that only the current fluctuates and not the plate voltage, these curves can be very useful. The waveform of the plate current for a sinusoidal grid voltage can be plotted using one of these curves by the method illustrated in Fig. 3.

A sine wave is drawn edgewise, underneath one of the curves, and the graph lines extended to provide reference points on the sine-wave input voltage. For clarity, only a few points are shown. To get a nice accurate curve a greater number of points should be used. At the right side of the diagram, corresponding reference points are projected out and the same baseline points along the curves are identified. In this way, if the plate-voltage curve were a straight line, as represented by the dotted line, a sine wave would be repeated, due to the proportional spacings. However, because of the curvature of the tube characteristic, the plate-current variation is distorted from sinusoidal as shown by comparing the solid plate-current curve with the dotted curve.

The load line

Now we are introduced to the load line. A practical amplifier circuit in its simplest form is shown at Fig. 4. The addition of a plate coupling resistor means that when grid voltage is changed, plate voltage and plate current also *both* change. This is when the load line comes into use to plot the exact nature of plate-voltage and plate-current change with applied grid voltage.

At the top end of the plate resistor a fixed B plus voltage is applied. If the tube does not pass any current, there will be no current flow through this

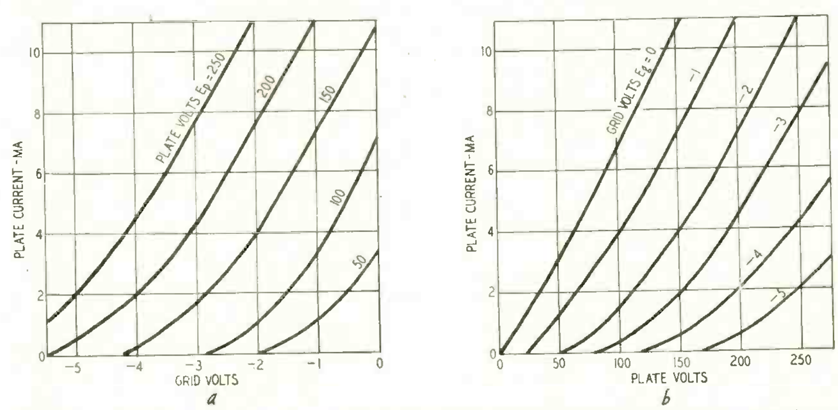


Fig. 1—Two ways of representing the characteristics of an electron tube.

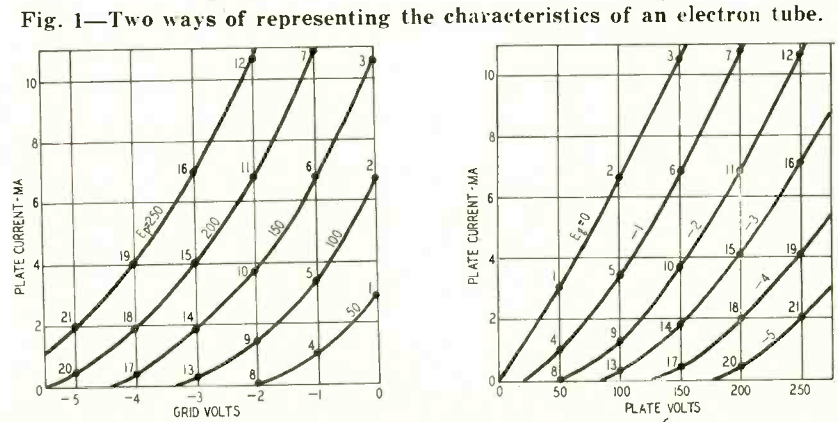
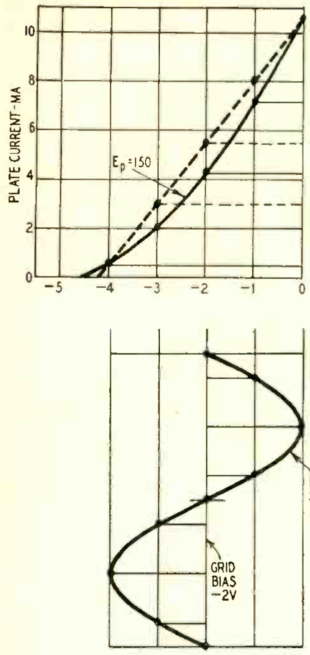


Fig. 2—Points on curves show correspondence between the sets of curves.



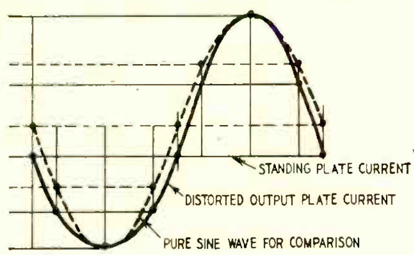


Fig. 3—E_g-I_p curve shows distortion in stage with constant plate voltage.

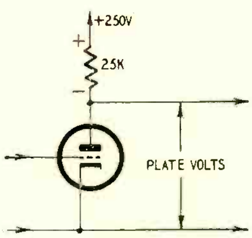
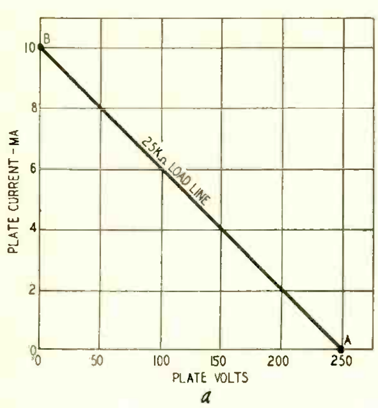


Fig. 4—A basic amplifier circuit.



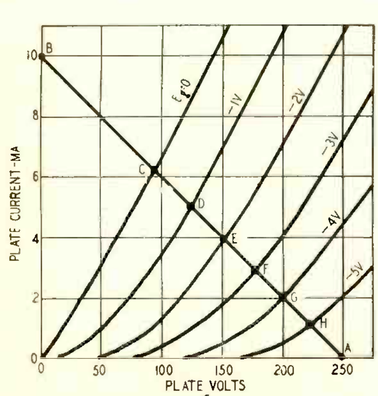


Fig. 5—Showing load line principle.

resistor, and the plate voltage will be the same as B plus, 250 volts in this case. But if the tube draws 10 ma, there will be a drop of 250 volts across the 25,000-ohm resistor—which means that the plate voltage will have dropped to zero. If the tube draws say 6 ma, there will be a drop of 150 volts across the resistor, leaving the plate at 250 − 150 = 100 volts positive. A lot more points could be taken, representing different plate voltages according to the current drawn by the tube, but they will all be found to fall in the straight line AB of Fig. 5-a.

Whatever happens in the grid circuit the plate current and voltage must be given at some point along this line because of the voltage drop across the 25,000-ohm resistor. For this reason such a line is called a "25,000-ohm load line." In Fig. 5-b the curves of Figs. 1-b, 2-b are redrawn and the 25,000-ohm load line drawn through them.

Suppose that the grid voltage is −1: The combination of plate current and plate voltage must be somewhere along the curve marked "grid volts −1." It must also be somewhere along the load line AB which represents the only possible plate voltage and current combinations in the circuit of Fig. 4.

The values when the grid voltage (E_g) is −1 are given by point D in Fig. 5-b—about 120 volts and 5 ma. Similarly other points C, E, F, G, H, along the load line, where the grid voltage curves cross it, give the plate voltage and current for the value of grid voltage represented by each curve.

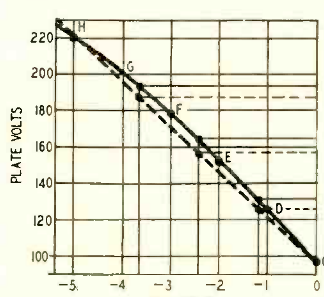
Load line shows distortion

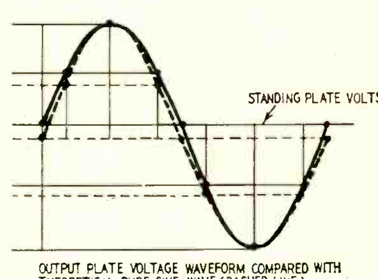
Using a method similar to that used to show distortion of the plate current without any plate load in Fig. 3, a curve is plotted using the plate-volts–grid-volts points of Fig. 5-b. This is shown in Fig. 6. The dotted line represents a truly linear result while the slightly curved line is obtained by plotting the values obtained from the actual points C, D, E, F, G, H.

From Fig. 6 the reference lines are again extended downward and to the right so that a sine wave can be drawn as the input to the grid and a corresponding output waveform can be drawn by reference to the curve. The dotted and solid curves on the right side of Fig. 6 show the plate-voltage output waveform as compared with a pure sine wave. The difference between the dotted and solid curves here is much less than in Fig. 3, which indicates much less distortion from true sinusoidal.

The simple circuit of Fig. 4 can represent part of a direct-coupled amplifier. The method just described may be used to find the best value of coupling resistor to use. To do this, a number of different load lines can be drawn across the same set of plate-current–plate-voltage curves for the particular tube being used.

Fig. 7 shows how the slope of the load line depends upon the resistance value it represents. Three values of resistance are shown drawn through the same B plus voltage of 250. A simple way of drawing each load line consists of determining what current will flow if the plate is short-circuited to ground and then marking off this current value on the current scale at the left, where voltage is zero. This point is then joined to the B plus voltage point along the voltage scale, which





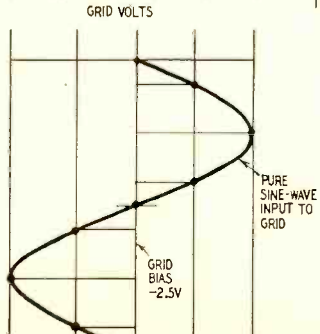


Fig. 6—Using load line information to determine amount of distortion.

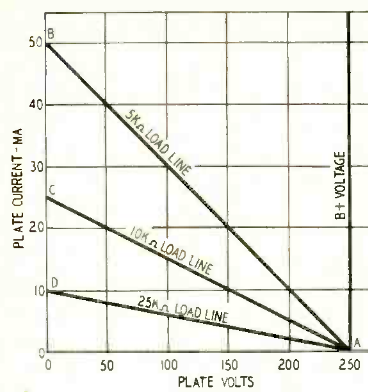


Fig. 7—Comparing load line slopes.

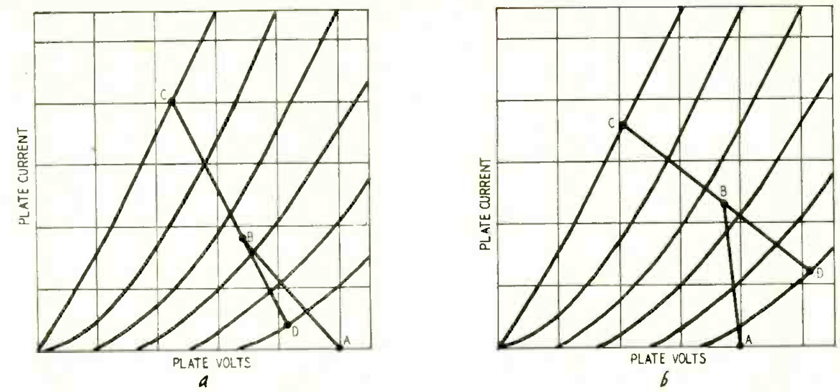


Fig. 8—Practical dynamic load lines for various type coupling circuits.

corresponds with the plate current being zero, as was explained in reference to Fig. 4. When no current is flowing, the plate voltage is equal to B plus. When the plate voltage is at zero, the whole B plus voltage is dropped across the load resistor.

An examination of Fig. 7 shows that lower resistance values are represented by steeper sloped lines, while higher resistance values correspond with lines nearer the horizontal.

This principle enables us to visualize the effect of other kinds of circuit in producing a *working* load line, including the effect of other circuit components. Actual values can be calculated quite simply and a load line drawn in to represent any particular kind of circuit. Fig. 8 shows practical load lines for (a) resistance–capacitance coupling and (b) choke or transformer coupling. In each case the line AB represents the d.c. drop from B plus to the plate under the condition of normal static bias, while the load line CD passing through the point B represents the dynamic load line when an alternating signal is applied to the grid.

In the case of Fig. 8-a—due to a further resistor (R_g of Fig. 9-a) coupled a.c.-wise in parallel with the plate load resistor by the coupling capacitor—the effective resistance in the plate circuit is reduced. Its value can be calculated by the simple parallel-resistance formula. Hence the load line AB, as determined by the value of load resistor R_L in Fig. 9-a, determines the operating position B, according to the grid bias applied to the tube.

If the scales for current and voltage are the same as in Fig. 5, AB would represent 22,000 ohms. When alternating signal is applied, the load line CD (a resistance equal to R_L and R_g of Fig. 9-a in parallel) represents the "dynamic" behavior of the tube as signal voltages are applied. The slope of CD, according to scale, is 12,000 ohms, which means R_g must be 27,000 ohms. Points along load line CD can be used after the manner of Fig. 6 to determine the degree of distortion and also to determine the effective amplification of the tube.

When choke or transformer coupling is used, the resistance from B plus to the plate is small, being merely the winding resistance of the choke or transformer primary. This is represented by the section AB in Fig. 8-b. The position B is determined again by the static value of bias applied to the grid of the tube. In this case however, the effective a.c. resistance of Fig. 9-b is considerably higher than the d.c. resistance of the choke winding. Thus it is represented by a load line less steep, such as CD in Fig. 8-b.

Using the same scales AB represents a resistance of about 3,500 ohms, while that of CD represents about 32,000 ohms.

A similar construction applies for the direct-coupled transformer coupling of Fig. 9-c. In the case of transformer coupling the actual value of resistance applied across the secondary of the transformer must be "referred" by multiplying it by the square of the turns ratio to get the effective a.c. resistance presented by the primary of the transformer in the plate circuit of the tube.

Figs. 10 and 11 show a whole family of characteristics for typical triode and pentode tubes. In each, a series of load lines has been drawn through the same static bias operating point. In the case of triodes (Fig. 10) the spacing of points where the grid-voltage curves intersect the individual load lines, lines nearer the horizontal, representing higher resistance values, produce the more even spacing, representing lower distortion. Load lines approaching the vertical and representing lower values of load resistance result in unevenness of spacing, stretching out toward the top end and second-harmonic distortion similar to that present in the plate-current curve shown in Fig. 3.

For pentodes (Fig. 11), the effect of variation of load resistance is reverse. A low value of resistance, represented by a load line that crosses the curves almost vertically, results in comparatively low distortion, while a high value of resistance, represented by a line that crosses the curves almost horizontally, produces a high degree of distortion. This is because all the grid-voltage curves converge together to the left of the "knee" of these curves and the spacing to the right spreads out.

Another useful feature of load lines, as shown in the article "What Is Optimum Load?" (March, 1954), enables the correct operating conditions to be chosen from the viewpoint of staying within various boundaries of tube operating characteristics. END

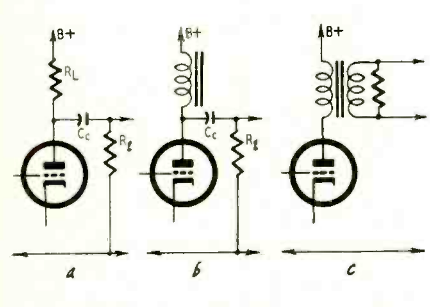


Fig. 9—Typical coupling circuits.

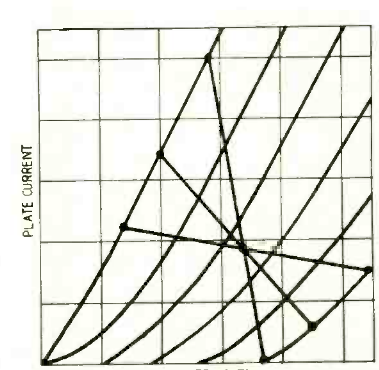


Fig. 10—Typical triode characteristics.

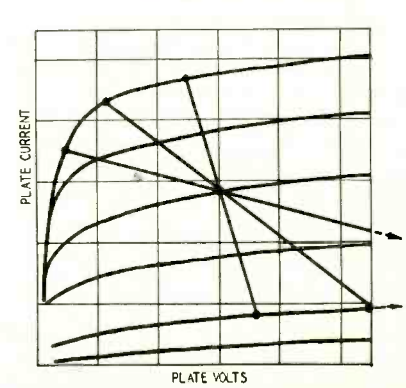


Fig. 11—Pentode characteristic curves.