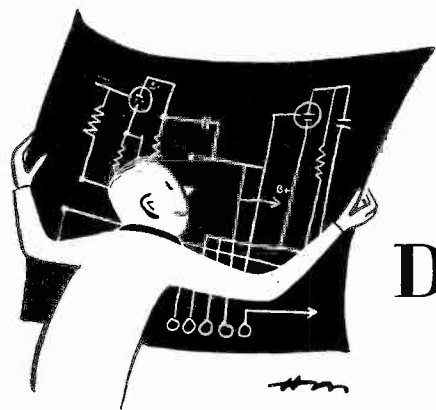




Designing Your Own Amplifier

by Norman H. Crowhurst

Part II: The Power Stage

IN the preceding article, on the design of voltage-amplifying stages, the job was simplified by the fact that we had only to consider the *voltage* swing that a certain load line produced when applied to a tube's characteristic curves. So far, we 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. We avoided mentioning it, because it might have been confusing at that point. But for power tubes, the ratings assume a primary importance. When we come to consider the design of a complete amplifier, we shall take all these points into consideration, including the ratings of voltage-amplifier tubes.

There are several ways to go about designing a power stage, depending to some extent on the information available. The tube characteristics — as we have used for voltage amplifiers — provide the most informative approach, but other useful data are published from

which it is also possible to make up quite accurate designs.

The tube characteristics on which we draw load lines are the ones that plot plate current against plate voltage for various values of fixed grid voltage. Fig. 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 load is 10,000 ohms: increasing the plate current by 1 ma will cause the plate voltage to drop by 10 volts. Increasing plate current by 2 ma will cause the plate voltage to drop by 20 volts, and so on. A straight line drawn across the curve at an angle representing 10 volts for each milliamperere will be a load line representing 10,000 ohms. If we want to put a load line across the curves representing 4,000 ohms we make a change of 1 ma correspond with 4 volts, or 10 ma with 40 volts, and so on. The slope of the line, then, represents the resistance value of the load.

This tells us how to set up the angle of the load line; now, how do we know exactly where to draw it? That will be determined by our operating conditions — what steady-state plate voltage and current we choose, and the DC grid voltage that will have to be used as a bias to obtain this working voltage and current. In a power-output stage we have various limits to our choice.

First, we 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,

we must not exceed the maximum plate voltage specified by the tube manufacturer.

These maximum ratings set a limit on how much we can "push" the tube in our endeavor to get more watts. We have

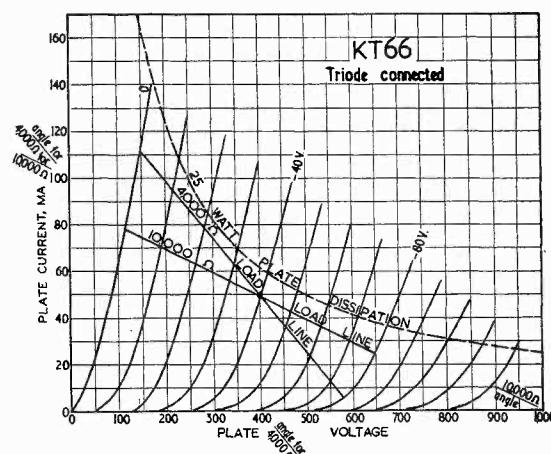


Fig. 2. The curves of Fig. 1, with the maximum dissipation curve drawn in (dotted). Two possible load lines are shown, using operating voltages of 400 on the plate and -40 on the grid. Small construction lines show a convenient way of getting the correct angle for a specific load value: for 4,000 ohms,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

conflicting requirements: getting the most output power, yet allowing the tube a good safety margin so as to ensure long tube life. But whether we want to emphasize the safety aspect or to get as much output power as possible, we want to 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

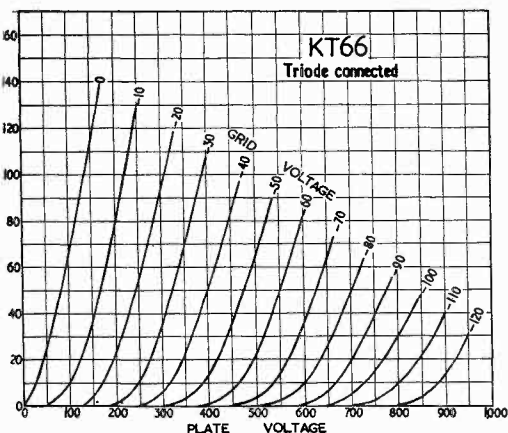


Fig. 1. Plate-current/plate-voltage characteristics for triode-connected KT66 tube. Each curve represents the variation of plate current with plate voltage when the grid voltage is fixed at the value for which the curve is labeled.

limits within which we can draw a load line. The manufacturer establishes a maximum dissipation rating for the tube. For instance, the KT66 tube, whose triode-connected characteristics

Let us assume 400 volts as 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 -40 volts, and the maximum audio swing in the positive direction is taken as being up to 0 grid volts, the corresponding negative swing will be to the -80 -volt characteristic.

Assuming a grid bias of -40 volts as a starting point, we put a ruler across the chart so that it passes through the point where the -40 -volt bias curve crosses the 400-volt 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 -80 -volt 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 -80 -volt end. To achieve the lowest distortion, which means maximum uniformity of spacing between curves along the load line, the line has to be more nearly horizontal, representing a higher impedance.

We shall find, though, when we 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 400-volt maximum plate-voltage requirement, this would require about -38 volts bias. That, in turn, gives approximately 60 ma steady-state current, and the audio swing is now limited from 0 to -76 volts on the grid. Refer to Fig. 3. Moving up in this way has resulted in 2 gains, compared with the -40 -volt point.

It has enabled us 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 us 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, as shown in 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 580 volts and 160 volts, and 14 ma and 120 ma. These represent changes of 420 volts and 106 ma. Multiplying them and dividing by 8,000 gives just over 5.5 watts, 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 400-volt midpoint to the 580-volt maximum is 180 volts; the negative excursion goes down to 160 volts, which is a drop of 240 volts. For symmetry the midpoint between 160 and 580 volts should be $\frac{160 + 580}{2}$ or 370 volts. The actual

400-volt operating point is 30 volts from the middle of the wave form. So the peak-to-peak ratio of second-harmonic distortion to the fundamental frequency, at 5.5 watts, 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 which will be explained 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. This too will be explained.

Notice that the load line we have drawn cuts across the 25-watt 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

Fig. 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.

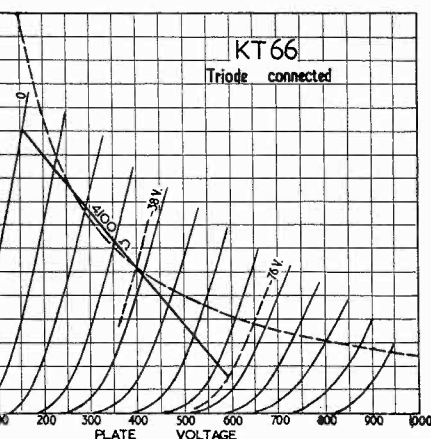
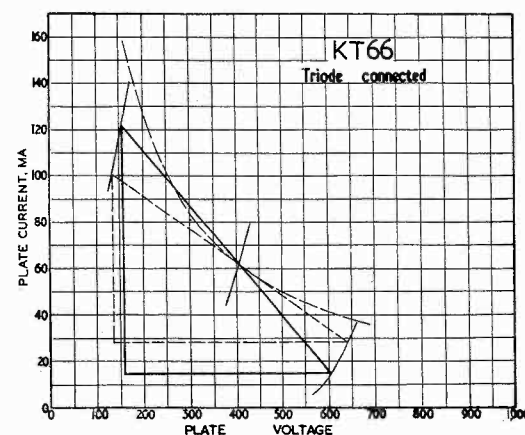


Fig. 3. Slight adjustment to the operating conditions of Fig. 2 produces improved results, both in higher power and decreased distortion (see text).

are shown in Fig. 1, has a maximum plate dissipation rating of 25 watts. This boundary can be plotted by determining various points on the chart that represent 25 watts, and then drawing a dotted line across the characteristic curves.

For illustration: 500 volts at 50 ma is one pair of values that represents 25 watts; 625 volts at 40 ma, 400 volts at 62.5 ma, 250 volts at 100 ma, and 1,000 volts at 25 ma are some other values that can be used to plot the maximum-dissipation line shown in Fig. 2.

The other maximum limit specified for triode tubes is the plate voltage. This is specified in one of 2 ways: the real limitation is the maximum positive excursion, because the danger is that of flash-over 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.

operating point. Therefore, at all signal levels, the average dissipation throughout a cycle will always be within the 25-watt 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 10 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: we only get $5\frac{1}{2}$ watts output with about 7% distortion, for a plate dissipation of 25 watts. To get 50 watts output at this rate, we should need a tube or tubes with plate dissipation of 250 watts.

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 250 volts. Fig. 6 shows curves for the same tube taken with a screen voltage of 325 volts, 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; one has to look at the numbers to see the differences. We find that the plate currents are successively higher as the screen voltage is raised. A high-

er 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, 6, and 7 to indicate the rated maximum plate dissipation of 25 watts. Screen dissipation is not shown, but is limited to 6 watts for this tube.

Sometimes screen current is indicated on the same diagram as the plate-current curves, as shown at Fig. 8. These curves do not help as much as one 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 wave-form cycle is always kept within the specified limit. It does not matter if one peak of the screen-current wave form does exceed 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, 6, and 7 is 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 out at the other. In the case

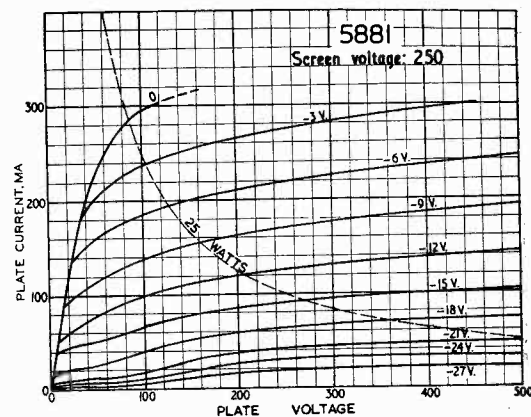


Fig. 5. Plate-current/plate-voltage characteristics for type 5881 tube working as a pentode, with 250 volts on the screen. Numbers on the curves represent grid voltage at which they were taken.

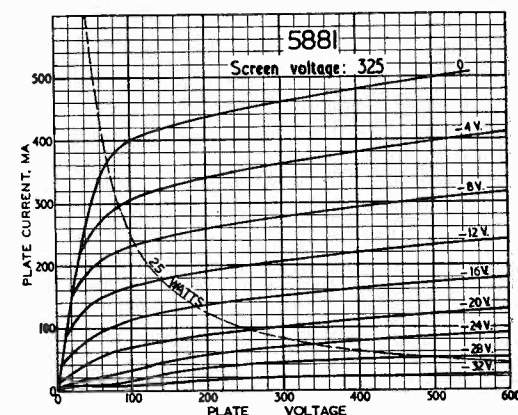


Fig. 6. Characteristics similar to those of Fig. 5, but with the screen voltage at 325. Notice the increased scales; the raised screen voltage produces larger plate currents for same plate voltages.

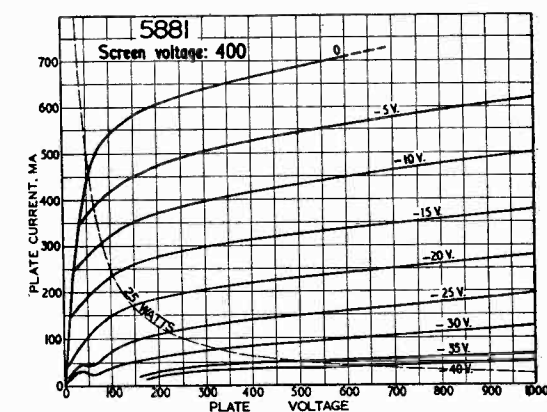


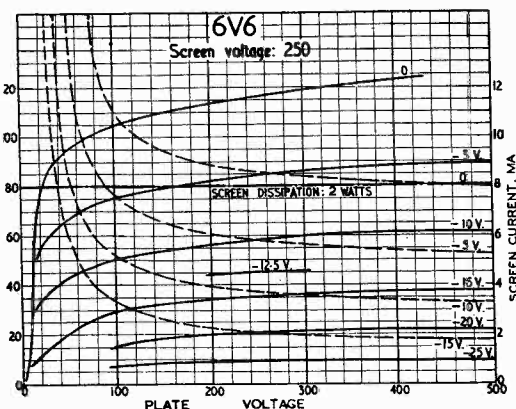
Fig. 7. Raising the screen voltage to the limit of 400 volts. Most of the curves are now above the specified maximum dissipation curve. This is because the tube is designed for push-pull operation.

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 (see Fig. 9).

If the tendency to close up is greater

Continued on page 41

Fig. 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 effects screen current markedly. Maximum screen dissipation of 2 watts is a horizontal straight line on the chart.



covered AC lines or, if it is desired to run a wire under a rug, a section of flat 4-conductor cable of the type used for antenna rotators. When only one amplifier is used the wires can be paired; if 2 amplifiers are employed, all 4 wires will be used. It is recommended that this system be driven by a single amplifier of at least 20 watts output, or by two 10-watt amplifiers.

AMPLIFIER DESIGN

Continued from page 27

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

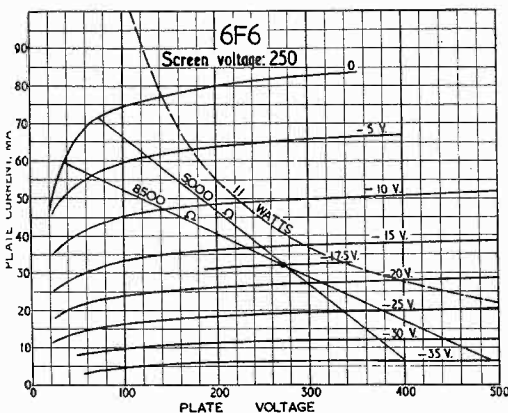


Fig. 9. How changing the value of a load affects output when applied to pentode curves. The 5,000-ohm line manifests mostly second-harmonic distortion, indicated by wider spacing toward the top end, and closer spacing toward the bottom. The 8,500-ohm line manifests mostly third-harmonic distortion, indicated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

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 *vs.* load impedance for the same amount of drive, the result appears as at 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 over-all 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

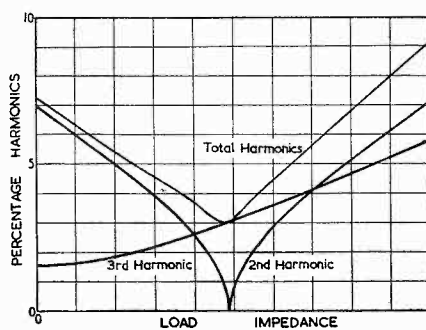


Fig. 10. Typical variation of harmonic content in a pentode output stage as load value is varied. Curves are for constant grid swing and plate voltage.

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.

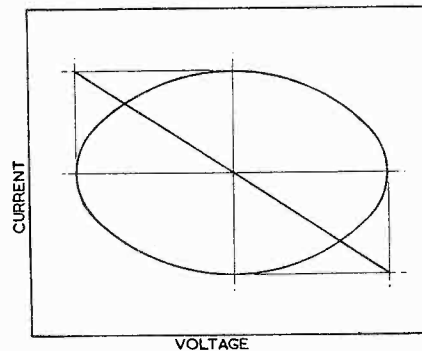
The relation between voltage and current in reactance, when plotted on graph paper or presented on an oscillo-

scope 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.

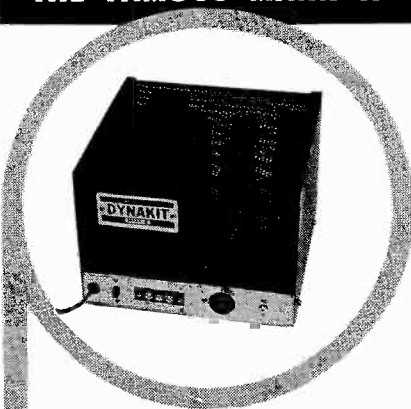
If the reactance is pure — that is, with no resistance included — the major and minor axes of the ellipse will be horizontal and vertical, as shown in Fig. 11. In practice, of course, there

Continued on next page

Fig. 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.



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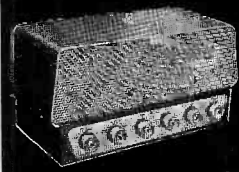
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AMPLIFIER DESIGN

Continued from preceding page

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

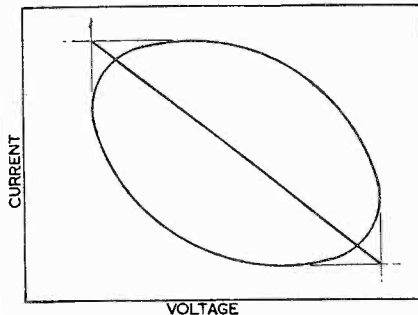


Fig. 12. Comparison between load lines representing pure resistance (straight line) and combination of resistance and reactance as impedance (ellipse) having the same magnitude and at the same values of plate voltage and current.

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. This we shall go into in detail in a subsequent article. There are other special circuits, such as the ultra-linear, unity coupling, and several more, that we shall discuss later on as well.

THE DB IN HI-FI

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the output transformer of the amplifier, to represent the impedance of the loudspeaker. This load must be the one which the manufacturer of the amplifier or output transformer specifies as the correct value for proper output impedance matching under the conditions used.

2) Feed a sine-wave audio signal into the input of the amplifier.

3) Turn up the gain of the amplifier and signal source until the maximum undistorted signal is reached. This can be observed on a 'scope which is connected across the output load resistor.

4) Measure the voltage across the load resistor.

5) Compute the power from the formula V^2/R .

To check the hum, remove the signal and measure the voltage using the voltmeter across the same load resistor. The power-output voltage is known (step 4 above) from previous measurement. Multiplying by 20 the log of the ratio of the power-output voltage to the hum-output voltage will indicate the hum in db inherent in this amplifier. An alternate way of computing the hum in db is the use of the voltage ratio table above.

If, for example, the voltage output due to the power delivered were 16 volts across the load resistor, and the hum voltage were 1 volt, the voltage ratio would be 16:1. (Note the use of voltage ratio here since the measurements are both made across one load resistor). Thus the amplifier would have $16:1 = 8:1 \times 2:1 = 18 \text{ db} + 6 \text{ db} = 24 \text{ db}$ hum below full power output.

Frequency response is also measured with respect to the voltage across a load resistor. This is done by varying the input frequency to the amplifier (keeping this input voltage constant) and noting the voltage output variation with frequency. From these voltage changes, the db variation with frequency can be calculated as above.

The frequency response of an amplifier with various tone-control settings can be checked in a like manner. The tone controls are set at any desired position. The input frequency to the amplifier is varied while the input voltage is kept constant. Variations observed on the VTVM can again be calculated in terms of db.

To avoid much of this calculation, many voltmeters are calibrated in terms of db as well as in volts. When such a meter is connected across a load resistor, and all db measurements are

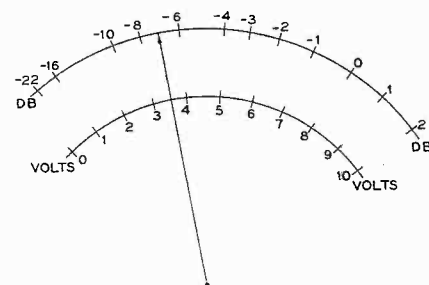


Fig. 1. Meter with voltage and db scales.

made only across this one resistor, the meter's reading in db has meaning.

These meters are based on the formula previously noted,

$$\text{db} = 20 \log V_o/V_i$$

A voltage ratio of 2:1 would be indicated on the meter directly as a 6-db difference.

If in the tone-control test, for example, 1,000 cycles read 9 db on the meter, and 10,000 cycles indicated 3