Audio Classroom

Designing Your Own Amplifier, Part 1: Voltage Amplifier Stages

This article appeared originally in Audiocraft*, March 1956.*

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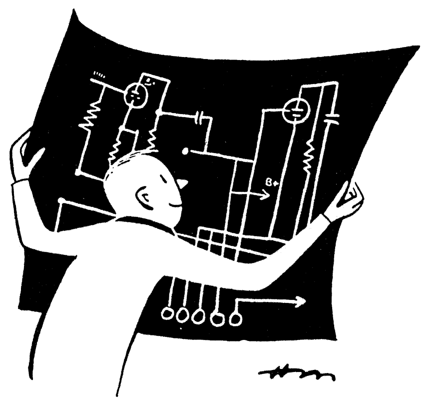

Editor's note: We have left designators for capacitance and frequency as they were in 1956 when this article was written. The cps, cycles per second, are now referred to as Hz (hertz) and µµF today is referenced as pico farads.—Ed.

How do you go about designing an amplifier? Reading the more advanced textbooks on the subject, you may get the impression that it is impossible to design an amplifier without a knowledge of higher mathematics. One book will start by giving a complete analysis of network theory, involving simultaneous equations in a large number of unknowns; another will approach the matter from the viewpoint of tube characteristics and give a general equation for the law relating plate current to plate voltage, applied grid voltage, and so on, in terms of a power series.

The best this can do is tell you how to find the performance of an amplifier using some kind of ideal tube that never exists in practice. There are practical ways to design amplifiers, however, which are quite easy to follow, taken in simple stages; these are what will be discussed in this series.

In this article I shall discuss the design of a simple voltage-amplification stage, using various tube types. In subsequent articles we shall go on to other parts of the amplifier, including the phase splitter, the power-output stage, application of feedback, and so on.

USING LOAD LINES

The best way to examine the gain and operating conditions of a simple resistance-capacitance coupled stage (*Fig. 1*) for a triode tube is to use the plate current-plate voltage characteristics published for the tube type. We can find out fairly easily all we want to know about the operation of the tube.

The characteristics for a triode tube are shown in *Fig. 2. Each curve* represents the variations of plate current as plate voltage is changed, with a fixed value of applied grid voltage. Usually, the curves are plotted for uniform intervals of grid voltage, which makes them convenient to use for our purpose.

Suppose the B+ (power supply) voltage is 250 and we use a plate-load resistor (R_c) of 100k. Then, if the plate is short-circuited to ground, this plate resistor will pass 2.5mA because it will have 250V across it. (The easy way to figure this is to remember that current in mA, multiplied by resistance in kilohms, gives voltage drop in volts.) If the plate potential is 100V, the drop across the resistor will be 150V so the current through it will be 1.5mA. If the plate voltage is 150V the drop across the resistor will be 100V, so the current through the resistor will be just 1mA.

If these plate-voltage and current values, determined by the value of resistors chosen, are joined together on the diagram of *Fig. 2*, we get a straight line passing through the B+ voltage of 250 (at zero current) and the plate current of 2.5mA at zero plate voltage. This is the *load line* for this tube type with a plate-load resistor of 100k and B+ of 250V.

How is the operating point fixed? We must select a suitable grid bias of such value that excursions away from this central point on the grid characteristics will give us suitable amplification. If we use a negative bias of 1V, the operating point will be at 142V on the plate with a current of 1.08mA; this is where the –1V curve crosses the load line. For the moment let us assume that we have chosen this point.

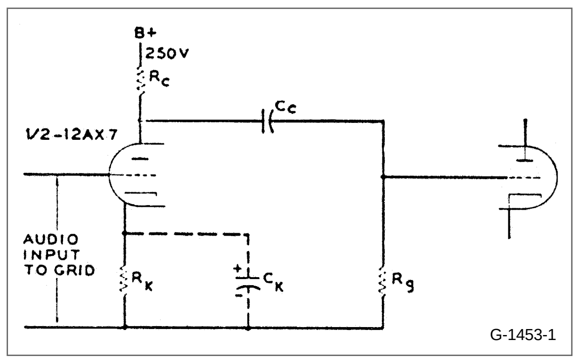

FIGURE 1: Triode voltage-amplifier circuit.

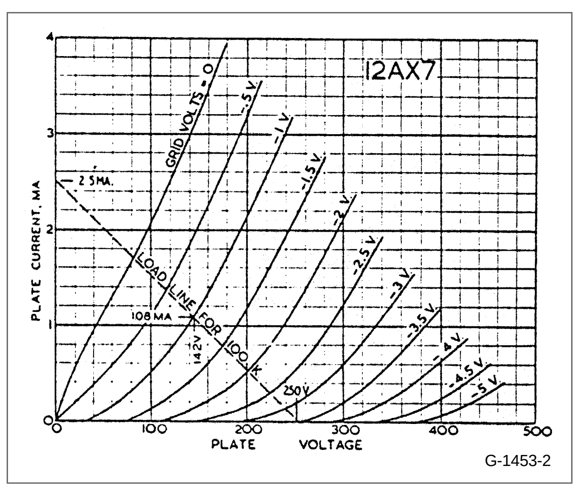

FIGURE 2: Plate current-plate voltage characteristic curves for 12AX7 tube, used to evaluate circuit elements in *Fig. 1*.

Now, to get a suitable grid bias we must select a cathode resistor R_k of such value that with 1.08mA passing through it the bias is 1V. With a 1k resistor (assuming the value to be precise, which it is unlikely to be using 10% resistors) 1.08mA will produce 1.08V for bias. This will get us as near to the operating point we have chosen as is practical. We could go right on to calculate the output of the stage for a given input, and then obtain a figure for stage gain, except that we have not yet taken into account the effect of the grid resistor (R_g) in the following stage.

Assume R_g to be 470k. Then, so far as the audio signal is concerned, 470k will be coupled in parallel with the 100k plate load resistor. This is because the coupling capacitor is large enough that it does not allow the charge across it to change during the audio fluctuation, and accordingly the audio signal voltage at the top end of the grid resistor swings with the voltage at the plate of the stage we are considering.

So the effective plate load, for AC signals, is 100k in parallel with 470k, which works out to about 82k. The 100k resistor fixes the operating point, because the DC plate feed to the tube passes only through this resistor. But the dynamic load line, as it is called, representing the condition of the tube when an audio signal is being amplified, must be obtained by using a value of 82k.

As a result we must draw a load line whose *slope* represents 82k, passing through the operating point we have chosen at –1V grid bias and a plate voltage of 142. We use the same means of finding the new slope as for the old. A conveniently close approximation would be taken by assuming 3mA passing through 82k (with the plate grounded). This will produce a voltage of 246V. We draw a couple of light markers at the 3mA point on the plate-current scale and the 246V point on the voltage scale. These determine the new slope; with a parallel rule we draw a line with the same slope through the old operating point (*Fig. 3*).

LOAD-LINE CONCLUSIONS

Now, let's see what this load line can tell us.

Gain. For a swing of grid voltage 1V either side of the bias point, which means from 0 to –2, the plate voltage will swing (from its central point of 142) down to 85 and up to 195. This means that for 2V change on the grid there is a 110V change at the plate, or a gain of 55.

Distortion. The excursion of plate voltage for 1V positive on the grid—that is, from –1 to 0—is from 142V down to 85, a change of 57V. For an opposite grid swing of 1V, the plate voltage changes from 142 to 195, or 53V. We assume that the cathode resistor is bypassed by C_k (*Fig. 1*) so that cathode voltage is constant.

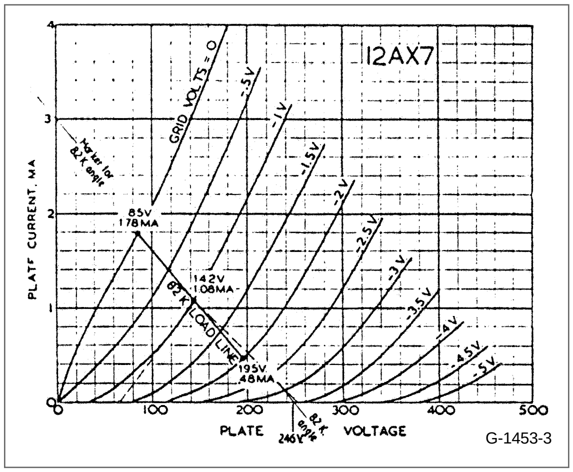

FIGURE 3: Curves for 12AX7 with addition of a dynamic load line, showing change in slope caused by following stage grid resistor. Markers indicate the new slope.

This difference between plate swings on opposite grid swings shows there will be some second-harmonic distortion in the output waveform. We can work out approximately how much by seeing how much the center of the waveform is offset. The midpoint between 85V and 195V is

$$\frac{85+195}{2},$$

or 140V. This is 2V off center. The ratio of pk-pk amplitude of second-harmonic to pk-pk amplitude of fundamental is

$$\frac{2}{195-85},$$

or 1.8%.

Effect of Cathode Bypass. If we do *not* bypass the 1k cathode-bias resistor it will help to reduce harmonic distortion, but it will also reduce the calculated gain of 55. This can also be determined with the curves. At the quiescent operating point, the 1.08mA normal current will produce a bias voltage drop of 1.08V across the 1k cathode resistor.

When the grid is made 2V negative with respect to the cathode, the plate current drops to 0.48mA, which means that the voltage drop across the bias resistor decreases to 0.48V. This, in turn, means that the grid signal required to obtain –2V from grid to cathode will have to be 1.6V. In the opposite direction, the 1V grid-to-cathode swing changes the current from 1.08mA to 1.78mA, so the grid voltage swing must be 1.7V in this direction.

Now see what this does to the amplification. The negative-going grid excursion of 1.6V gets amplified to a plate excursion of 53V, a gain of 33.1. In the positive-going excursion the applied grid voltage swing of 1.7V gets amplified to 57V, a gain on this half of the applied waveform of 33.5. The *average* amplification throughout the whole applied waveform is now 33.3 in place of the original 55.

But we have an off-center effect of 0.2 part in 33.1 + 33.5, or 66.6, which means the second-harmonic distortion has now been reduced to about

$$\frac{0.2}{66.6},$$

or 0.3%.

Applying a nice large capacitor, like 50µF, across the 1k bias resistor will bring the gain up to the 55 figure by making the 1V swing either way from the bias point give the full plate swing. This happens since the cathode voltage does not have time to change by the values just calculated, because of the large charge stored in the capacitor.

Maximum Level. The voltage swing we have given is in each case that of the peak value. Ordinarily the instruments we use measure RMS values, which are 0.707 times the peak values. This means that the 1V peak input voltage, assuming the cathode to be bypassed, will be 0.707V RMS, while the RMS plate output voltage will be 55×0.707, or 39V.

CHANGING CIRCUIT VALUES

Any variety of load lines can be drawn to represent different values of the plate coupling resistor and the following stage grid resistor. Following this method appropriate values of the cathode resistor can be evaluated, together with the available gain and voltage output, and an estimate of distortion. In general, with the 12AX7 curves we have just used, if a larger output swing or slightly greater gain is required, it can be obtained by using higher values of resistance all around.

For example, if you care to try the scheme yourself: Using a plate resistor R_c of 470k, a grid resistor R_g of 1MΩ for the

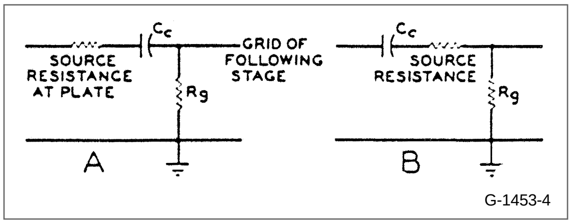

FIGURE 4: Total resistances on both sides of the coupling capacitor determine the low-frequency attenuation characteristics.

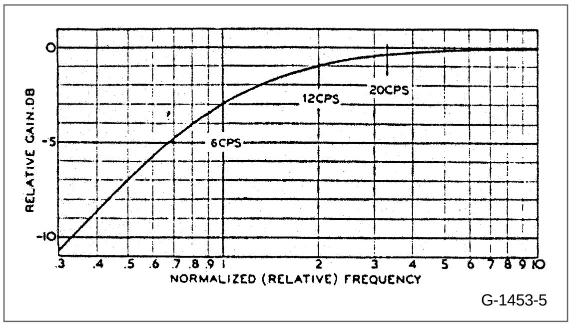

FIGURE 5: Normalized low-frequency rolloff curve for one RC circuit. Point at which response is down 3dB is labeled "I," and attenuation in dB can be determined for multiple and submultiple frequencies.

following stage, and a cathode resistor of 5.2k, the grid bias is 1.5V, the voltage gain 61, and the pk-pk output voltage about 182, representing an RMS value of about 64V. The static plate voltage is 120, and the negative and positive voltage swings go to 20 and 202V, respectively. This means that the 120 is approximately 9V off center, which, for 182V excursion, represents a distortion of about 5%.

It will be realized from these few figures that this tube is a fairly good voltage-amplifier triode because it is not very critical of the values with which it works, and 5% second-harmonic distortion for a tube with that large an output swing is quite good. A stage requiring an output voltage that large will usually be operated in push-pull, so as to minimize the distortion.

But there is something further we want to find out about this stage before we pass on to other types of circuits. This is its frequency response.

FREQUENCY RESPONSE

A typical resistance-coupled amplifying stage is maximally effective over a certain range of applied frequencies. At both ends of this range the stage gain decreases progressively for higher and lower frequencies.

The low-frequency rolloff is determined by the relation of the coupling capacitor reactance to the resistances in the circuit, which are the source resistance apparent at the plate of the stage we are considering, and the following stage grid resistor R_g (*Fig. 4*). It will be realized that transposing the series elements, consisting of the source resistance and the coupling capacitor, will not affect the response of the arrangement in any way. When we arrange it as in *Fig. 4B*, it is quite evident that the frequency characteristics of the voltage appearing at the junction between the source resistance and R_g will be the same as the frequency characteristics at the top end of the source resistance, because this is merely a straightforward resistance potentiometer and cannot have any influence on frequency response.

Now we must calculate the source resistance at the plate. This involves the AC plate resistance of the tube, which we shall discuss further in a minute, but for the moment we consider it as an AC resistance between the plate of the tube and ground. If we use a very high B+ voltage and an extremely high plate-load resistor to go with it, of many megohms, the source resistance would simply be the plate resistance of the tube. Taking the tube manual value of 62.5k for the 12AX7, if we put a load on the output of 62.5k we should halve the available voltage swing.

In point of fact, the 100k plate-load resistor that we used here also reduces the available voltage swing, because the tube has an amplification factor of 100 and we have only managed to get a gain of 55 from it. We have already shunted down the plate resistance with 100k to B+, so any further loading effects applied to the plate, through the coupling capacitor, will be applied across the parallel combination consisting of the plate resistance and the 100k plate load shunting it. The source resistance we consider in *Fig. 4*, then, is the parallel combination of the effective plate resistance with the plate-load resistor.

PLATE RESISTANCE

The value for plate resistance given in the tube manual, 62.5k, is not taken for the operating conditions that we have assumed. To get an accurate result we should take the value of plate resistance at the chosen operating point. This, it will be recalled, was a bias of 1V, 142V on the plate, and 1.08mA plate current. The plate resistance at this operating point is the controlling factor in frequency response. Actually, the response will change slightly throughout the waveform because the plate resistance varies up and down the load line, but we cannot take this into account too readily.

As far as the load line is concerned, it is unimportant that the characteristics are curved in the regions on either side of it. The only part of interest is the slope of the section immediately adjacent to it. So, drawing a tangent to the –1V grid curve where the load line crosses it, we get an ideal version of the tube characteristic.

And using the same method we employed to construct the load line, we can calculate the value of the resistance. This tangent line passes through 0mA at 65V on the plate-current scale, and 1mA at 140V, on the plate-current scale, a change of 75V for 1mA. The effective plate resistance is 75k. The parallel combination of the 100k plate load with a 75k plate resistance gives a 43k source resistance. In this case our careful calculation of plate resistance hasn't affected very much the

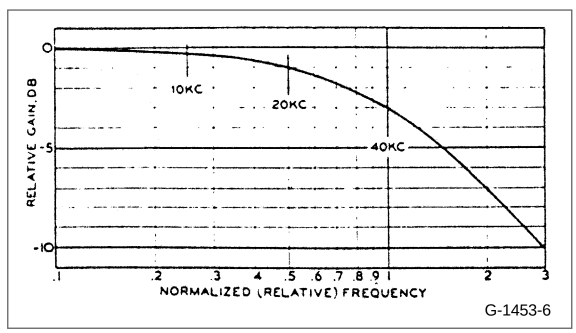

FIGURE 6: Normalized high-frequency rolloff curve. It is used in same way as *Fig. 5*.

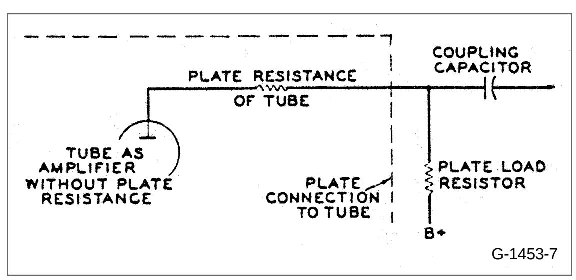

FIGURE 7: Equivalent circuit used as basis for calculation of stage gain from plate resistance and the amplification factor.

total circuit resistance (*Fig. 4*) because 43k has to be added to 470k, which adds up to 513k.

Use of a reactance chart shows that .05µF gives a reactance of about 500k at a frequency of 6cps. This means that the response would be 3dB down at 6cps, about 1dB down at 12cps, and 0.4dB down at 20cps. These figures can be obtained from the normalized response curve (*Fig. 5*). Response at the low-frequency end seems to be adequate.

At the other end of the response curve the loss is due to stray capacitance shunting the total *parallel* impedance of the circuit. This is made up again of the plate resistance of the tube, the plate-load resistor, and the grid resistor. We have already calculated the effect of 100k in parallel with 470k—about 82k. The combination of the 75k plate resistance in parallel with the 82k effective plate-load resistance is approximately 39k.

If the following stage is another half of a 12AX7, which has a grid-to-cathode capacitance (C_{gk}) of 1.6µµF and a grid-to-plate capacitance (C_{gp}) of 1.7µµF, and if it is also working at a gain of 55, the Miller effect will raise the *effective* grid-to-ground capacitance markedly. Effective tube capacitance from grid to ground is $C_{gk} + C_{gp}\ (1 + A)$, where A is stage gain. In this case it is 1.6 + 1.7 (1 + 55), or approximately 97µµF. If we allow 7µµF for various stray effects owing to the wiring, this makes a total of 104µµF. From a reactance chart 100µµF has a reactance of about 40k at 40kc [kHz—Ed.], which means the gain of this stage will be 3dB down at 40kc and about 1dB down at 20kc. Loss of gain can be determined from the normalized response curve (*Fig. 6*).

Now it is obvious why we need to know the plate resistance more accurately. It is the lowest resistance value of those that determine high-frequency rolloff, so that variation of the plate resistance will effect the resultant more than small variations of either of the other values in the circuit.

With a plate-load resistor of 470k and a grid resistor of 1MΩ, the plate resistance is 85k. The total parallel resistance works out to be about 67k, which means that the 3dB down point will move from about 40 to 23kc.

Just how important these figures will turn out to be depends on the rest of the circuit and how we are designing the amplifier, which we shall come back to later in the series. We may be using feedback, in which case we can allow rolloff at frequencies within the audible range and straighten the whole thing up to some degree by feedback. Or we may be designing a stage which doesn't have feedback, or which is required to have an extremely good response in spite of the fact that feedback is being used. But before these factors can be discussed it is necessary to know more about the rest of the problem.

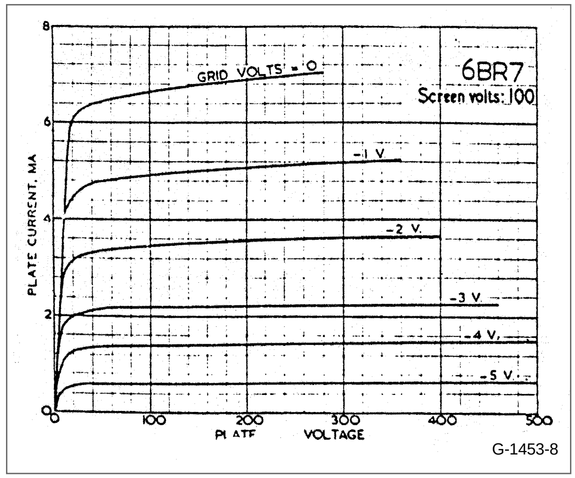

FIGURE 8: Plate current-plate voltage characteristic curves for the 6BR7 pentode.

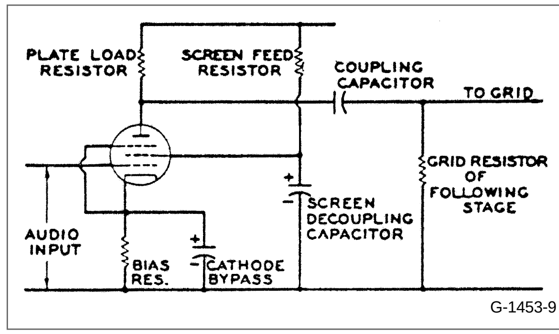

FIGURE 9: Pentode voltage-amplifier stage.

TUBE MANUAL TABLES

An alternative method of design, if it is not convenient to use the curves available, is to follow the tables published in tube manuals which give information similar to that shown in *Table 1* for the 12AX7. Such tables give a limited number of suitable operating conditions, but usually no information is given about distortion. Neither is it possible to see what effect different bias values have on the total available swing, or on distortion.

In general, if the tube is being used for maximum gain, but is not required to have maximum voltage-handling capacity, a lower value of bias can be used to achieve better linearity and lower distortion by keeping well away from the curvature of the characteristic.

If not as much information as this is available, then you must be content with the tube parameters issued and the simple gain formula. The tube parameters given for the 12AX7 operating at 250V on the plate are: amplification factor, 100; plate resistance, 62.5k; plate current, 1.2mA for a bias of –2V. This is rather limited information. Moreover, the plate voltage here does not have the same meaning as the B+ voltage we have been working with.

Here it means voltage *on the plate*; it does not allow for the drop in the plate-load resistor. The only way we can obtain a figure for a bias resistor is to divide the plate current into the bias voltage given, which in this case is 1.2mA with a bias of 2V. This would require about 1,660Ω. We shall need less than 2V, because the working plate voltage will be less than 250, so that we must guess that 1,200 or 1,500Ω would be all right.

If the tube was operated from a *very* high B+ voltage, and fed through a large load resistor so as to give 250V on the plate, an amplification of 100 would be approached. But, since we are using a practical load of 82k, we are effectively picking off a fraction of this 100 amplification factor across the 82k, which is in series with the plate resistance quoted as

TABLE 1

12AX7, PLATE SUPPLY 100V						
Plate-load resistor:	0.10		0.22		0.47MΩ	
Grid resistor, next stage:	0.22	0.47	0.22	0.47	0.47	1MΩ
Cathode resistor:	4,700	4,800	7,000	7,400	12,000	13,000Ω
Max. output voltage:	6	8	6	9	9	11 RMS
Voltage gain:	35	41	39	45	48	52
12AX7, PLATE SUPPLY 250V						
Plate-load resistor:	0.10		0.22		0.47MΩ	
Grid resistor, next stage:	0.22	0.47	0.22	0.47	0.47	1MΩ
Cathode resistor:	1,500	1,700	2,200	2,800	4,300	5,200Ω
Max. output voltage:	47	55	45	57	51	64 RMS
Voltage gain:	43	47	49	54	57	61

62.5k (*Fig. 7*). We obtain an actual amplification of

$$\frac{100 \times 82}{82 + 62.5} = 57,$$

which is a little optimistic compared to the figure we determined more accurately a while ago.

But it will be seen to give a figure which is pretty close, provided not much other information is needed. We cannot tell how much grid swing we can use, nor what plate swing we can get out of the stage, nor how much distortion to expect. But for some circumstances this much information could be very useful; it would enable us to compute, within limits, the gain of a stage.

So much for designing a voltage-gain amplifier around a triode. What about using a pentode, which gives considerably more gain?

PENTODE VOLTAGE AMPLIFIERS

Figure 8 shows the plate current-plate voltage characteristics for a 6BR7, a comparatively new, low-microphony pentode for audio work. It is possible to use these characteristics to set up the conditions and calculate the gain of the tube under any given operating conditions *provided the screen voltage is 100*. But the usual practice in this type of stage is to series-feed the screen (*Fig. 9*), rather than apply to it a stabilized 100V. This type of circuit gives a more stable gain figure and more consistent performance than one with a fixed screen voltage and automatic cathode bias, because the grid bias and the screen voltages tend to adjust to compensate one another.

But, since it is much more difficult to compute distortion figures from pentode characteristics for the reason that they do not produce primarily second harmonics, like triodes, there is not too much to be gained by going through the full procedure. The best way to design a simple pentode amplifier stage is to use tabular information given in tube manuals. *Table 2* gives the published operating conditions for a 6BR7.

Selecting the middle condition, for 200V plate and screen supply, we will get a voltage gain of 120 with a peak output (an RMS figure) of 70V. The thing we don't know about this is how much distortion is produced, but if we want an output well inside 70V we can be assured that this tube will give a reasonable waveform compared with other tubes.

In this case the plate resistance is quoted as 2.3MΩ for 250V on the plate, or 1.5MΩ for 100V on the plate. We shall be fairly safe in taking an intermediate figure of 2MΩ. In calculating response we have to use the effective resistance of the plate-load resistor, given as 250k, in parallel with the plate resistance of 2MΩ, which comes out to about 230k. If we use a compromise of 220k for the plate load, which is a preferred resistor value, the resultant works out to 200k for the parallel combination, and we can expect the gain to be about 105 with the 220k load instead of the quoted 120.

In this case, however, the data does not include the value of the following grid resistor, as in some tables. It is to be assumed that the grid resistor will also shunt down the gain proportionately because, as with the triode, it is effectively in parallel with the plate load for AC signals. Thus, the gain with a 220k load would be reduced to about 90 in practice.

It may be better to use a plate-load resistor of 270k in this case, with a 1MΩ resistor in the following grid. That way, for calculating frequency response, the parallel combination of the plate resistance with the 270k resistor works out to about 240k, while the effective AC load for the tube is 1MΩ in parallel with 270k, which is about 210k and which should give a gain of just about 100.

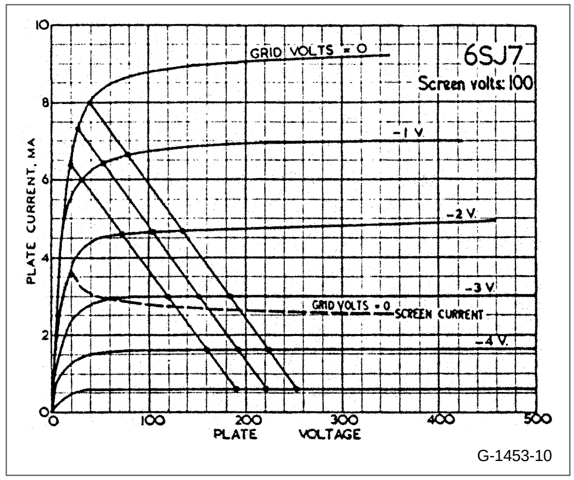

FIGURE 10: Characteristic curves for 6SJ7 pentode. Position of the load line is critical for pentodes. Each load line is for resistance of 30k; displacement is caused by variation of other parameters, and affects distortion. Center load line closes equally at ends, indicating mostly third-harmonic distortion. Other two lines indicate second-harmonics of opposite phase.

Now for the frequency response. The value we must use with the coupling capacitor to determine low-frequency rolloff is the total series resistance, or 1MΩ in series with 240k, a total of 1.24MΩ. For the high-frequency end the reactance of the stray capacitance has to be compared with the total parallel circuit resistance: 1MΩ in parallel with 270k in parallel with 2MΩ plate resistance, which works out to be about 200k.

If the following stage has an effective input capacitance of 100µµF the stage gain will be about down 3dB at 8kc, which is not too good. It may be better to reduce the value of the plate-load resistor so as to improve the high-frequency response.

Alternatively, if we are considering an input stage, there are reasons why it would be better to keep a high plate-load resistor, with a fairly high value of cathode-bias resistor, and shunt the stage down by using a lower value of resistor in the grid of the following stage. Both procedures will, of course, reduce the gain too. These conditions we shall discuss later in the series.

There is not much problem at the low-frequency end. A .01µF coupling capacitor will have a reactance of 1.25MΩ at about 13cps—and we certainly don't need to use as small a value as .01µF.

TRIODE OR PENTODE?

We can see right away why triode tubes are preferred for most applications in audio amplifiers, except the output stage, which I will discuss in later articles. The

TABLE 2

6BR7 OPERATING CHARACTERISTICS

Plate voltage:	100	250	V
Plate current:	2.0	2.1	mA
Screen voltage:	100	100	V
Screen current:	0.7	0.6	mA
Grid voltage:	–3	–3	V
Plate resistance:	1.5	2.3	MΩ
Mutual conductance:	1,100	1,250	µmhos [mho is an obsolete term for siemens—Ed.]

AS RESISTANCE-COUPLED AMPLIFIER

Plate & screen supply:	100	200	300	V
Plate-load resistor:	0.25	0.25	0.25	MΩ
Screen series resistor:	1.0	1.0	1.2	MΩ
Cathode bias resistor:	2,500	1,500	1,200	Ω
Peak output voltage:	35	70	100	RMS
Voltage gain:	90	120	140	

operating conditions are easier to calculate; the tubes have more stable gain and more consistent distortion figures. If you try fitting load lines to the characteristics of the 6BR7 or any other pentode, you will find that a relatively small movement of the load line on the curves, representing slight changes in operating conditions (which can easily occur), will alter the proportioning of the spaces along the load line quite considerably (*Fig. 10*).

If the load line gets far toward the "knee" of the zero grid voltage curve, the grid curves close up toward the top end as well as the bottom end of the line. If the closing up is approximately similar at both ends of the load line, the resulting distortion produced is mostly third harmonic. But if the load line is moved further away the distortion contains second harmonics in opposite phase to those produced when the load line is too near the knee, so that the closing up is more toward the top end.

In short, without going into a lot of detailed work, pentode characteristics are fairly critical as to operating conditions for obtaining minimum harmonic distortion. Because in audio work it is important to achieve very low distortion, it is generally better to keep away from pentodes unless there is a good reason for using them. ❖