Loadlines, Power Output and Distortion

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Purpose

To establish a loadline on a triode vacuum tube (valve), determine the power available from this loadline, and the distortion predicted from this loadline. This will allow the reader a step by step way to calculate the parameters for his design. I have chosen to "invent" a tube for illustrative purposes. The characteristic curve below is a hypothetical triode with the following parameters:

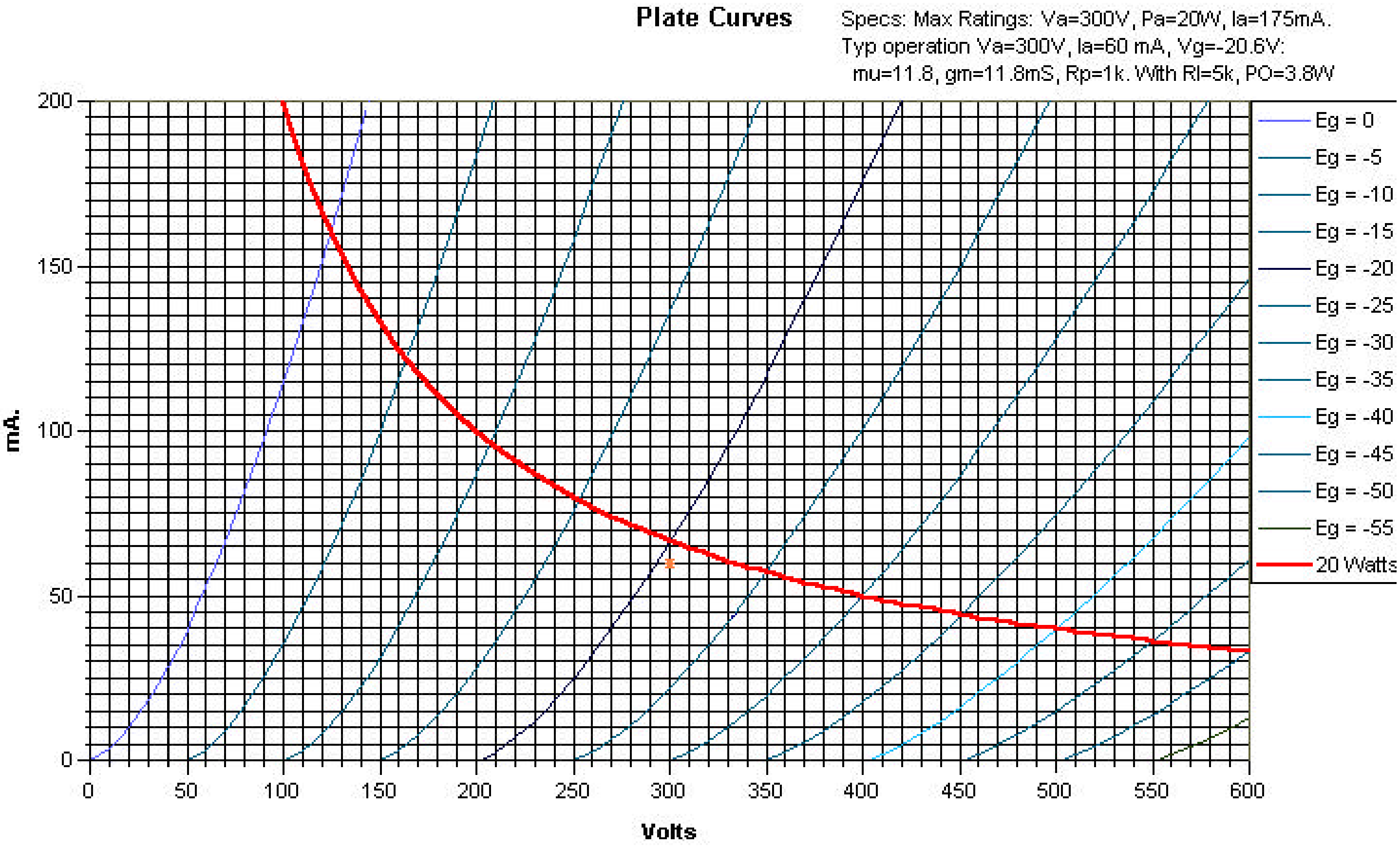


Figure 1: Single ended transformer loaded Class A amplifier

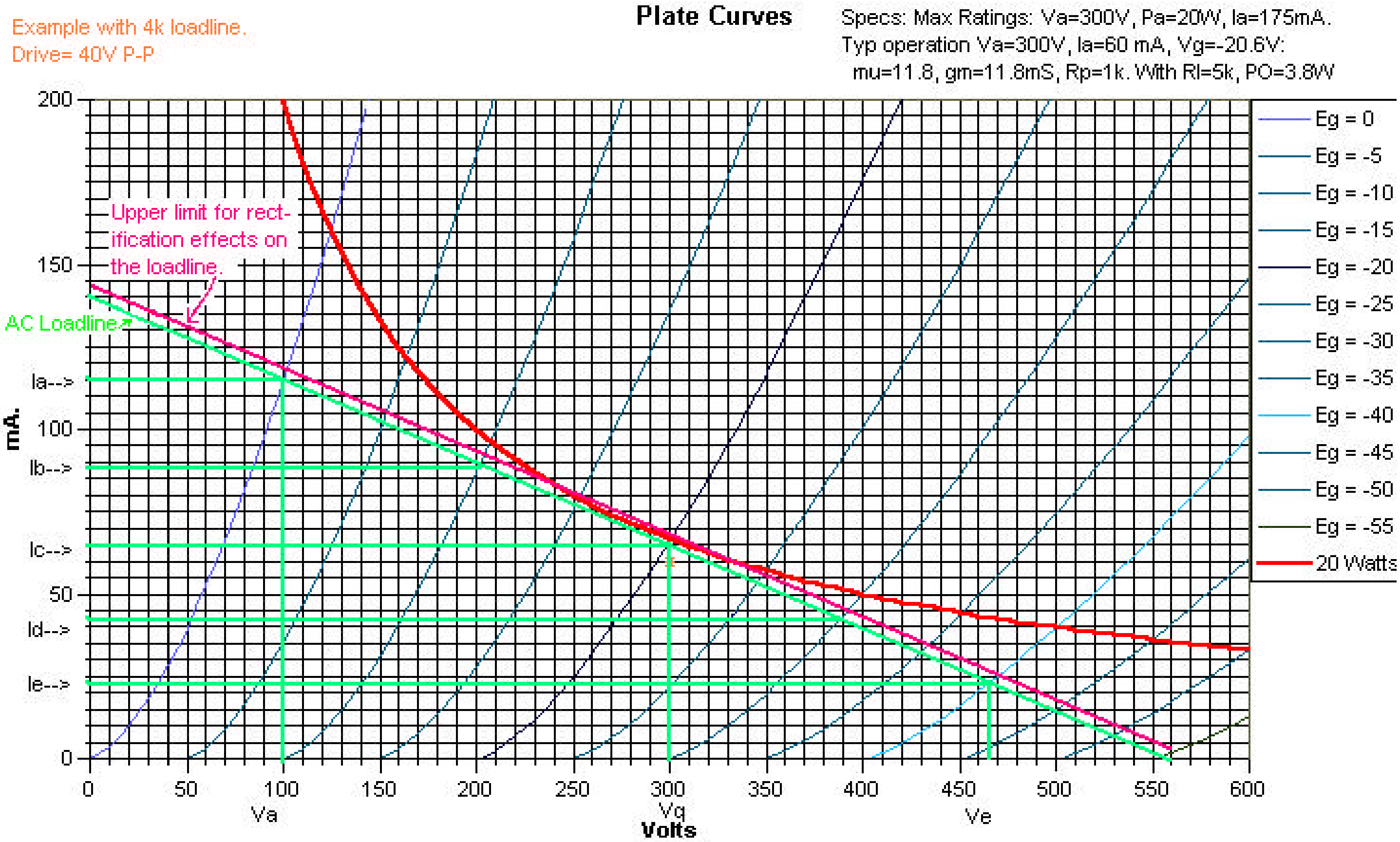
Figure 1 is a single ended transformer loaded Class A amplifier, which is one of the simplest vehicles that can convey the knowledge. Most of the information is appropriate for push-pull operation, once a composite load line is established.

Establishing a Load Line

1. Get the tube characteristics from the datasheet for your design (shown above for my example). If not already on the characteristics, plot the maximum power dissipation curve (voltage x current = power).
2. Select a reasonable quiescent current operating point for your design. Often this is described in the manufacturers typical operation. For instance, a reasonable starting point for my example would be 300 volts and 60 mA. (This is the orange "dot" on the characteristics above.) Whatever you pick MUST BE within the tube's ratings. For this example, I'll choose to ignore the manufacturers recommendation, and use 300 volts and 65 mA. Put a dot on the tube characteristics at this point. (I am expecting that the "recommended point" is somewhere near optimum, but I want to run the tube a little "hotter", perhaps gaining more power output, lower distortion, or both.)
3. Now start drawing a potential load line. This is a straight line whose "slope" is the primary "impedance" of the transformer. How do you do this? Pick a point somewhere about DOUBLE the quiescent voltage and zero plate (anode) current. Draw a line (called "loadline" in the curve below) through these 2 points extending to the 0 plate volt axis. Did your loadline go above the max power curve you drew? Not good. Go back, pick a different zero current point. Is the voltage at no current more than twice the "rated" voltage? Not good. Go back and pick another point. Within specfcations? Good. Now determine the impedance. Z=(maximum voltage - quiescent voltage)/quiescent current. Alternately, you can pick an impedance to suit available plate transformers. In this case, if you go outside the safe boundaries, you must choose a new quiescent point. The curve below chooses a 4k load line.
4. Having now chosen a tentative loadline, we need the following information from it.
    1. The required grid bias (you'll need to supply the grid with this value of DC voltage).
    2. The quiescent voltage (called Vq)

3. Voltage where the grid bias voltage is zero (called Va).
4. Voltage where the grid bias is double the quiescent value (called Ve). Note... if the plate current reaches zero before you get to this bias, you've got a bad operating point, go back to step 3 and try again.
5. Current at 0 volt grid bias (called Ia). If this current is above the maximum rated tube current, go back to step 3 and try again. Hint: If its off the scale, chances are the current is too high.
6. Current at half the quiescent bias voltage. (Called Ib.)
7. Quiescent Current (Called Ic.)
8. Current at 1.5 times the quiescent bias voltage (Called Id).
9. Current at twice quiescent bias voltage. (Called Ie).

Note that these are all plotted out on the following set of tube curves for our example.



For our example, the data is as follows:

Va = 99V, Vq = 300V, Ve = 465V, Ia = 115mA, Ib = 89mA, Ic = 65mA, Id = 42mA, Ie = 23mA. In addition, 40V p-p are required from the driver stage, and a 4k plate transformer is required.

Rectification Effects

In any device with even order distortion (not just second harmonic as sometimes stated), the average current of a Class A stage will change depending on the signal level. If the distortion is relatively low, the effect is relatively unimportant, if the distortion is high, this effect becomes increasingly important. (It is also more important for self bias than fixed bias, as the bias voltage is a function of the average current).

This effect modifies all tube operating characteristics. The degree can be seen by comparing the quiescent current (65 mA in our example) with the average current as taken from the "extremes": that is, (Ia+Ie)/2. In our example that value calculates to 69mA (note that is not substantially different). The effect requires an iterative plot of the load line on the tube characteristics. The "worst case" is shown in "pink" in the constructed load lines above. The real case will be between the two extremes. Notice that the "curve" includes some portion above the maximum dissipation. In this case, the power dissipated in the tube is (300*0.069 - power output), or in this case 16.5 watts. This is still LOWER than the 20 watt max dissipation case, so there's no problem. Note the quiescent dissipation is still 300*0.65, or in this case 19.5 watts.

The remainder of this document ignores this effect: it is important in high distortion cases only, but high distortion cases are not of much interest.

Power Output

Po = (Ve - Va) x (Ve-Va) / (8 x load Impedance).

In our example this is (465 - 99) x (465 - 99) / (8 x 4000) = 4.18 watts. This number is an approximation in that it assumes low distortion.

Second Harmonic Distortion

HD2(%) = 75 x (Ia + Ie – 2 x Ic) / (Ia + Ib - Id - Ie)

In our example this is 75 x (115 + 23 – 2 x 65) / (115 + 89 - 42 - 23) = 4.3%

Third Harmonic Distortion

HD3(%) = 50 x (Ia - (2 x Ib) + (2 x Id) - Ie) / (Ia + Ib - Id - Ie)

In our example this is 50 x (115 - 178 + 84 - 23) / (115 + 89 - 42 - 23) = -0.72%

Notice the minus sign. This indicates that the harmonic content subtracts from the fundamental (flattening it) when the fundamental is at its crest. This *usually* happens on third harmonic distortion in tubes.

Fourth Harmonic Distortion

HD4(%) = 25 x (Ia - (4 x Ib) + (6 x Ic) - (4*Id) + Ie)/(Ia + Ib - Id - Ie)

In our example this is 25 x (115 - 356 + 390 -168 + 23) / (115 + 89 -42 - 23) = 0.72%

Discussion

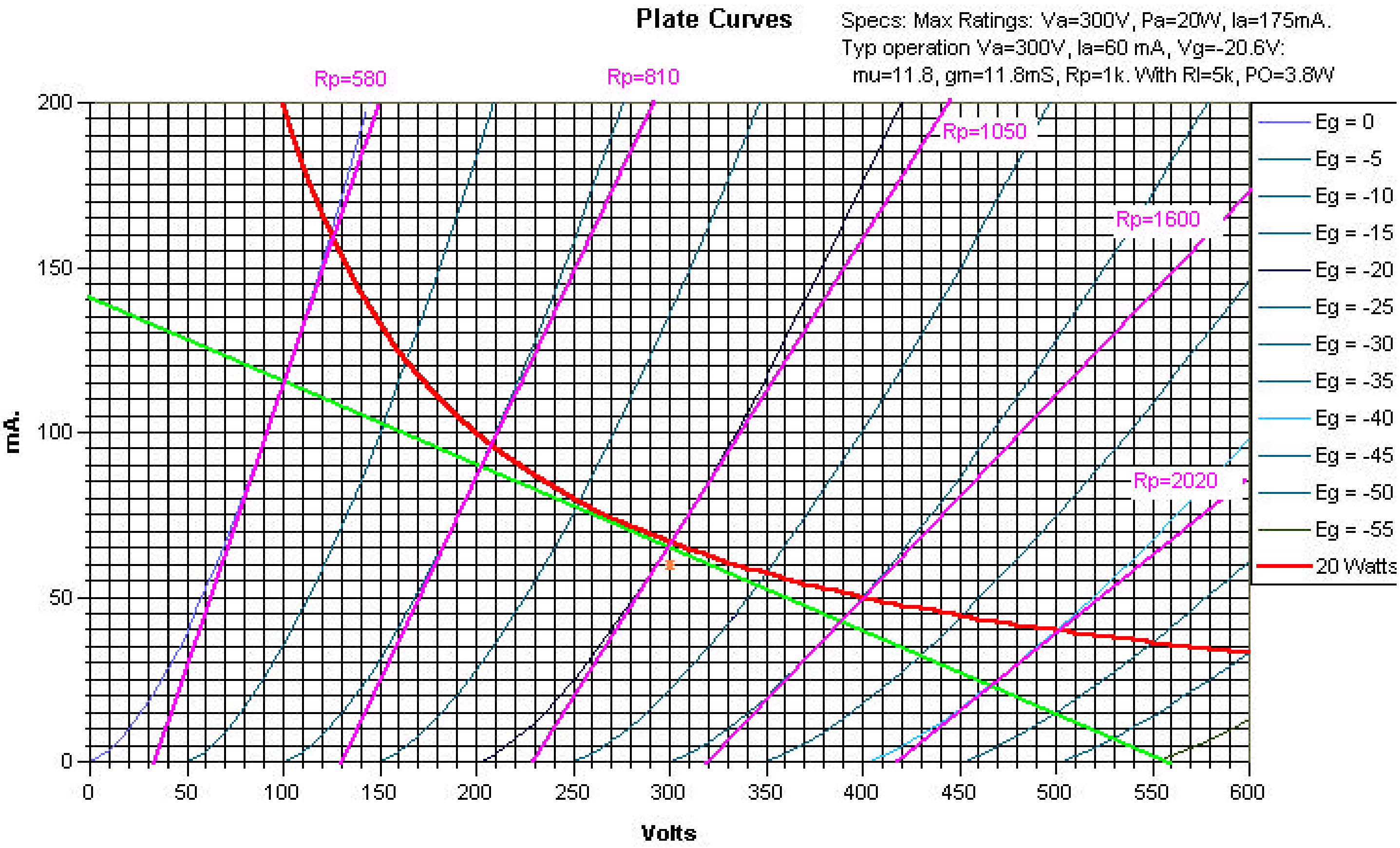
If you don't get numbers you like from the above, you are free to choose different operating points and loads to alter the characteristics of the stage. This may alter the distortion, power output or both. You may freely experiment on paper until you get a "design" you like. You can then correlate the results with your own listening tests. Over time, you'll find there is a correlation between what you predict, and what you hear. Then, you will be able to come up with new amplifiers more rapidly, as you will be able to zero in on what you like by doing a few "paper designs" up front, before committing to a particular tube, transformer, or power supply. This procedure also works for small signal tubes for driver applications, preamps, etc.

Part 2 - Effective Plate Resistance

One of the questions you may hear asked is how to pick an adequate load line for your design. You will hear talk about picking it with respect to the plate resistance of the tube in question.:"Pick the load resistance equal to the plate resistance to maximize power.", "Pick the load resistance equal to twice the plate resistance to maximize power.", "Pick the load resistance higher to minimize distortion.", "If you have a fixed input, the maximum power is ...".

None of that is much help. The biggest problem you have facing you is the load line. This is usually established by the characteristics of the tubes you choose, and available components (output transformers in particular). The bias, high voltage (B+ or HT voltage), and drive are usually determined AFTER you establish an output stage characteristic. Then, if one of those secondary parameters is unrealistic, you "iterate" the output stage characteristics.

Plate resistance is not constant. It varies widely over the operating load line. We will continue to use the same example as previously... my "invented" triode. In the figure below, I have plotted the tangent line to the operating characteristics we used in the previous article at the same 5 points on the load line we used to calculate distortion.



Notice that in this case, the plate resistance varies from 580 ohms to 2020 ohms. So, if you used the 2x Rp "rule of thumb" (or was that rule of middle finger?), which value do you pick? The 1000 ohms specified by the manufacturer, the 580 ohm minimum, the 1050 ohms at "quiescent", the 2020 ohm maximum, or yet another number?

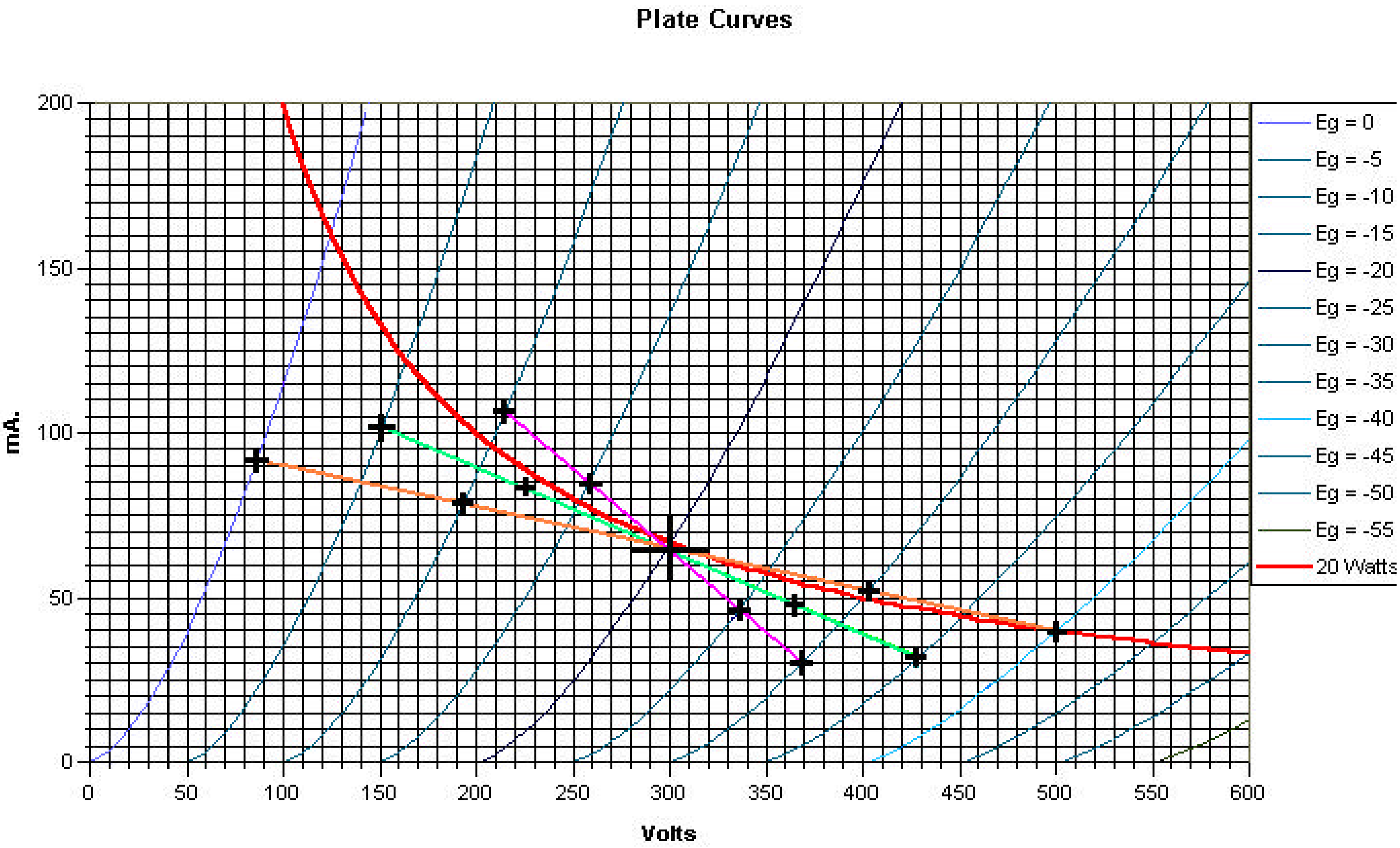
In our operating example the load line varies from about 2:1 Rl/Rp (at minimum current) to about 7:1 Rl/Rp (at maximum current). AND, this assumes a constant speaker impedance. In reality, most speakers vary an additional 2:1 to 10:1 over their operating range, further complicating things.

So, what do you do? You pick an operating point as described in part 1; one that is within the tubes ratings and produces a reasonably wide operating range. If it fills your needs, you're done. If it doesn't, start over again. Moral of story: don't be particularly concerned with the load lines relationship to the plate resistance. As we've just seen, the plate resistance varies.

Effect of Variable Plate Resistance

You might wonder what the effect of the variable resistance is. This will change the damping on the speaker over the signal range. For instance, let's consider a band limited square wave (one with rounded edges that "fits" within the bandwidth of our amplifier). The speaker might "ring" on the "edges" of this waveform. That's usually why higher "damping factors" are usually considered desireable. In this case, the ringing at the edge associated with the high current point will be damped MORE than the ringing at the edge associated with the low current point. This is a case where the amplifier cannot correct for a speaker defect.

There is another, in some sense, worse effect. Let's further "modify" our hypothetical source by placing a smaller, high frequency sine wave component on top of the square wave. I'll stipulate that this signal's frequency happens to be at a relatively low speaker impedance point. Now what happens. The portion of the sine wave riding on the high current part (lower impedance) will have higher "gain" than that portion riding on the lower current part of the loadline. This is an insidious form of intermodulation distortion that is usually not very musically pleasing. You can somewhat minimize this effect during the establishment of your load line. If you followed the procedure I outlined in part one, go back and re-plot the loadline using HALF the resistance, then TWICE the resistance. Don't be particularly concerned about whether the newly plotted loadlines remain inside the power dissipation characteristics. (Why THAT is, is outside the scope of this particular article). Now calculate the distortion FOR APPROXIMATELY THE SAME power output on these 3 loadlines. Continuing with our example, this is shown below. The original loadline (4k) is green, the 8k loadline is orange, and the 2k loadline is magenta. I've shown the current and voltage points needed by black crosses on the curve.



Notice that the input signal levels for the highest impedance is twice that of the lowest impedance, and the original curve is intermediate between these. The points to pick are limited in two ways: The signal for the highest impedance will usually cause the limit at "0" bias. This fixes the max signal. Sometimes the signal at the lowest impedance reaches cutoff. If that happens, choose a maximum level to remove this restriction, and re-derive the points for the other impedances. Caution: If this happens it is usually an indication that the load line you originally picked is not close to optimum).

Results:

Remember the formulas we used:

Po=(Ve-Va)*(Ve-Va)/(8*RL)

HD2=75*(Ia+Ie-(2*Ic))/(Ia+Ib-Id-Ie)

HD3=50*(Ia-(2*Ib)+(2*Id)-Ie)/(Ia+Ib-Id-Ie)

HD4=25*(Ia-(4*Ib)+(6*Ic)-(4*Id)+Ie)/(Ia+Ib-Id-Ie)

The data points are:

8k: Va=86, Ve=500, Ia=92, Ib=79, Ic=65, Id=53, Ie=40.

4k: Va=150, Ve=427, Ia=101, Ib=82, Ic=65, Id=49, Ie=32

2k: Va=214, Ve=369, Ia=107, Ib=85, Ic=65, Id=46, Ie=30

These lead to the following results:

Load Z	Pwr Out	HD2(%)	HD3(%)	HD4(%)
2k	1.5	4.5	-0.4	0.6
4k	2.4	2.2	1.4	-0.3
8k	2.6	1.9	0	-1.9

You can see that the distortion at the lowest impedance is highest, but is comparable at all 3 impedances. If these were wildly different (say 1.5% to 10%), this would be an indication that your amp is likely to sound less than desireable, and it might be wise to choose different operating points.

What else can you do? Feedback is one possibility. I generally have good luck with some slight local feedback from the output stage plate to the driver plate. This does not suffer from a lot of the global feedback effects that shun people away from feedback in general. You are free to go back and start a different set of load lines, to see if you can improve things.

In a later installment, we will see how push-pull operation affects the effective plate resistance.

One additional Clarification

In the example we have been using, the quiescent voltage is 300 volts. In building the power supply for this amp, don't forget to include the voltage drop in the output transformer. If this were, for instance, a 110 ohm winding, the power supply needed would be 307 volts. If this were, in addition, a "self biased circuit" (i.e., bias derived from a cathode resistor), the 20 volts bias would also needed to be included, bringing the power supply required to 327 volts.

Purpose

In this installment we will discuss how to create a composite load line. This is "necessary" to establish the load line for a push pull amplifier, regardless of whether it is going to be Class A or Class AB. We will continue to use the same "invented" tube for this discussion. I will also use Class A, and the same "operating points" we used in the single ended examples. The data points used are consistent with the other 2 parts of this series, you should choose the operating point for your particular case as described earlier.

Building a Composite Load Line

This is again an iterative process, perhaps moreso than the single ended case as it's a bit more involved. Here's a step by step procedure to create a set of "composite curves" and load line.

1. Establish your intended operating point from the single ended curves. For this example, we will choose 300 volts and 65 mA quiescent current (-20 volt bias). This is the same operating point chosen for the single ended case. Note: For Class AB, you may choose a lower idling current point, which will allow a lower impedance loadline (and higher power output) without exceeding maximum allowable power dissipation. For instance, choosing a -25 or -30 volt quiescent point would allow you more "room" to increase tube current. To stay within Class A operation, at least some current must flow in each tube at all bias points, otherwise, you will be operating in Class AB.

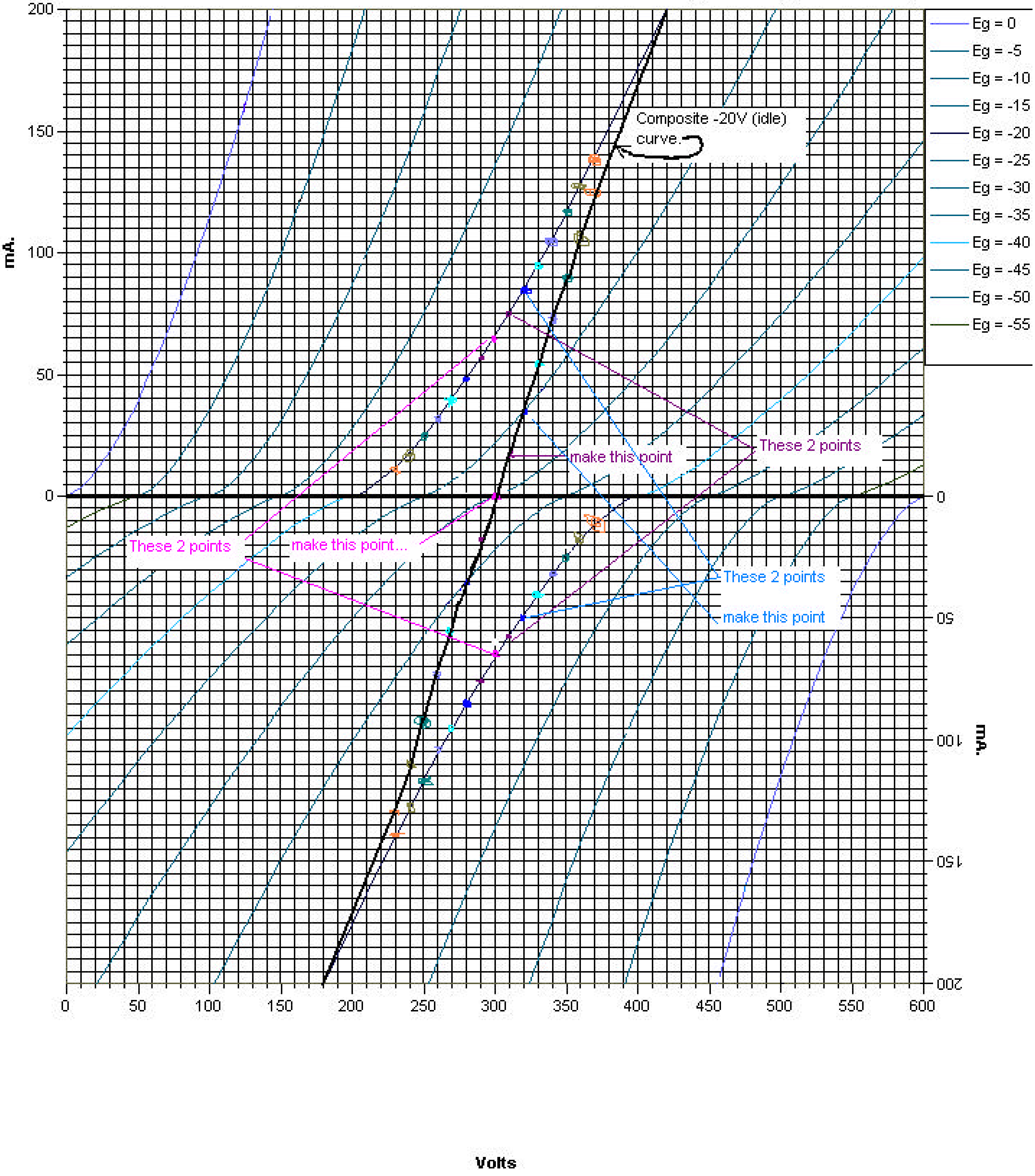
2. Since the plate voltage increases on one plate and decreases on the other plate, we must have a way of representing this. The usual method is to take another set of the same tube

curves, turn them around (so the maximum current is "down" and highest plate voltage is to the "left", and position them so that the quiescent voltages line up vertically, and the zero plate current lines touch each other as shown below:

Plate Curves

Composite curve for -20 volt bias and 300 v quiescent (65 mA per tube).

Specs: Max Ratings: Va=300V, Pa=20W, Ia=175mA.
Typ operation Va=300V, Ia=60 mA, Vg=-20.6V:
mu=11.8, gm=11.8mS, Rp=1k. With Rl=5k, PO=3.8W



3. Now, for the chosen bias point, create a new line (labeled "composite" curve) as follows (we are going to look at ONLY the -20 volt bias lines, one on the "upper" part of the graph, one on the "lower" part of the graph:

1. At the quiescent point (300V), subtract the currents (65-65=0 mA). This is the magenta points on the curves. Draw the "dot" at 300V, 0 mA on the composite curves.
2. Step to the next convenient voltage, (the dark magenta ones) note the currents in the upper and lower parts of the graph, subtract the two, and plot this point on the composites.
3. The next points are the ones shown in blue. Continue until you have the entire curve "dotted" for the -20 volt lines. The new "plate curve" for -20 volts is shown in the graph above.

4. You have now established one "line" of the composite curves. This is the line of varying the plate voltage symmetrically about the quiescent point while maintaining a constant grid voltage. (classic plate resistance line).

5. Now consider another set of lines for your graph. This will be the -25 volt line for the "upper" set and the -15 volt line from the lower set. (We have put a 5 volt signal into the push pull stage). Again, for each plate voltage, subtract the two currents (for instance, 310V -25V bias upper and 290 volt -15V lower) and plot the dot. Continue until you have the -25/-15V line filled in. Note that if your quiescent grid voltage was, for instance, -30 volts, the second line you would add would use the -35/-25V lines instead of -25/-15V lins.

6. Next do the same for the -30/-10, the -35/-5 and -40/0 volt lines. Then do the same for the -15/-25, the -10/-30, the -5/-35 and the 0/-40 volt lines. This completes the composite curves. The last 4 curves should be mirror images of the previous 4 you filled in. Noticing this saves you some time.

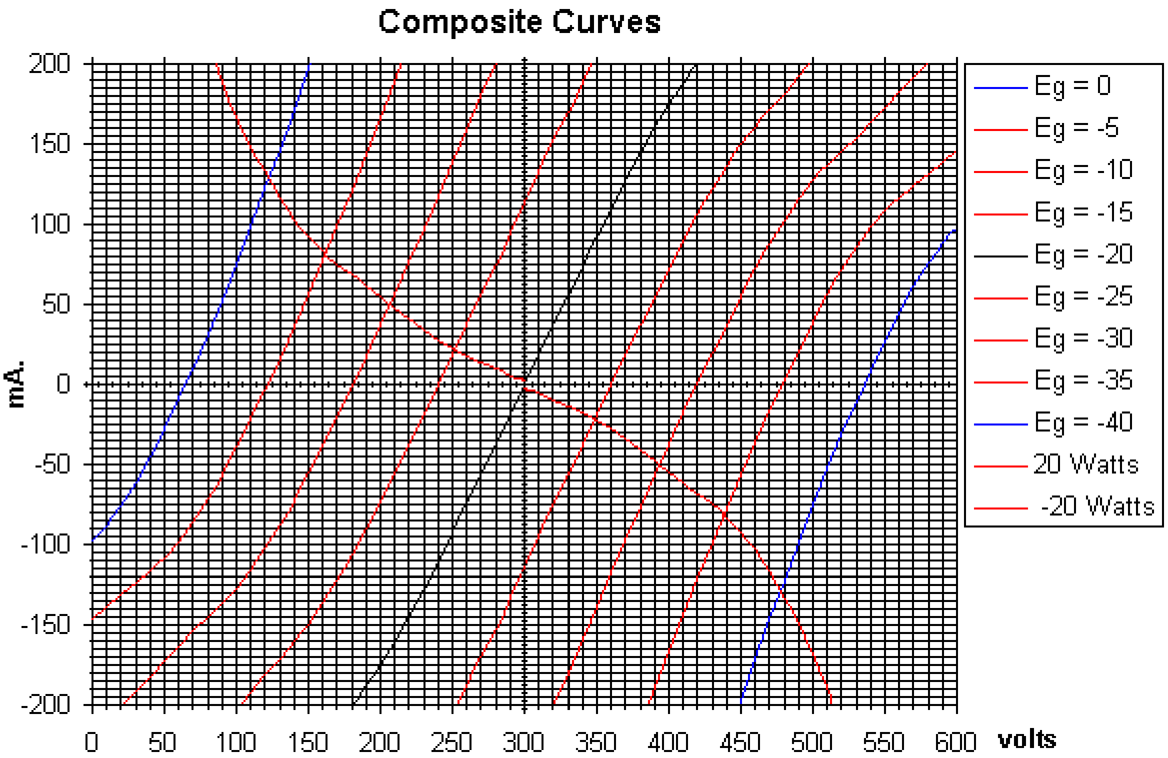
7. The last thing to do is fill in the maximum power dissipation curve. There are now going to be 2 of them, one for the one tube, one for the other. These will be symmetrical about the quiescent point. It is usually necessary to graph only half of the curve. The following is for the "upper" tube. Here's how to do it:

1. Get the current at the quiescent point. (In our case that's -20 volts, 300V, 65 mA.) Each tube will be drawing this current. Now find the current allowable via the power formula: I=P/E. In our case this is 20 watts at 300 volts or 66.7 mA. Since the "opposite" tube is pulling 65 mA, subtracting this from our 66.7 ma gives 1.7 mA, which is the most (lets call it unbalanced) current we can pull. Draw a dot at 300V, 1.7 mA.
2. Move to the next "convenient" grid line. Since, in our case, the gain is about 10, this will correspond to moving "left" by 50 volts to 250 volts. At this point the tube we have 250 volts on

the upper tube, and the power formula states we could draw 20/250=80 mA. However, the "lower" tube has 350 volts on it, but is biased at -25 volts. Looking this point up on the original single ended load line indicates 57.5 mA. Subtract the 2 to obtain 22.5 mA. Draw a point at 250 volts, 22.5 mA.

3. Repeat at 200 volts. The formula produces 100 mA. From this we subtract the "lower tubes" contribution to the current at -30 volts(grid) and 400 volts(plate) which is 45.2 mA. Subtracting this from 100 mA produces 54.8 mA. Draw a dot at 200 volts and 54.8 mA.
4. Repeat at 150 volts (20/150=133 mA). The lower tube is biased at 450V and -35V grid (40 mA) so the maximum current is 133-40=93 mA. Draw a dot at 150V, 93 mA.
5. Repeat at 100 volts. The formula produces 200 mA, the lower tube biases at 500V and -40V grid (32.5 mA) so the maximum current is 167.5 mA.
6. Now connect these with a nice smooth curve.
7. Rotate for the lower tubes power condition... -1.7mA at 300V, -22.5mA at 350V (250V on the lower tube), 54.8 mA at 400V, 93 mA at 450V and 167.5 mA at 500V and draw that condition.

You should now have a graph that looks like this...

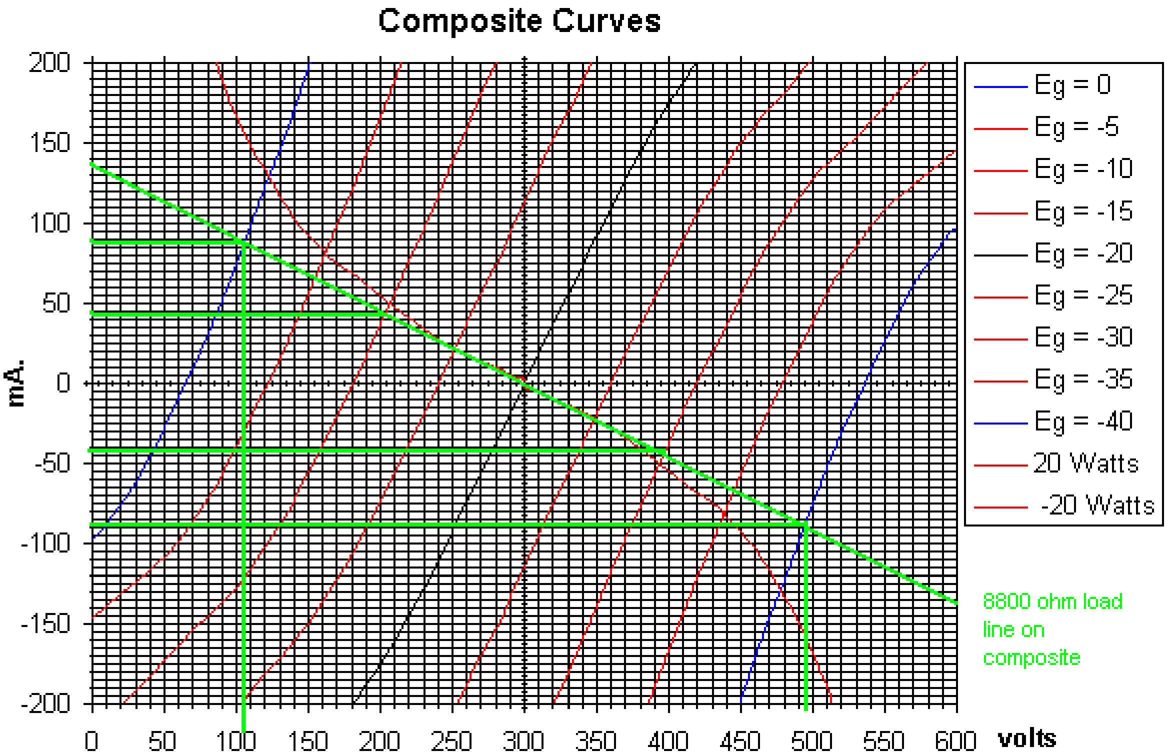


By the way, if you have access to a spread sheet, this makes manipulating these things a LOT easier. The data for all these examples is in an Excel spread sheet. Feel free to load it if you like: Spreadsheet Data (platcurv.zip) Hint: If you replace the data in the spreadsheet with the data for the tube of your choice, most of the work is done for you, as there are embedded graphs for single ended and composite curves in the spreadsheet. There are a couple of items of interest to note in the curve above. You can definitely see the effect of transitioning from

Class A to Class AB region; this is where the slope more-or-less abruptly changes in the curves above. The other thing to note is how much more linear the composite curves are than the SE case.

Push Pull Load Line

The same rules we used in the single ended case apply, with one exception: The impedance you plot is the impedance AS SEEN BY A SINGLE TUBE. Thus it is 1/4 the plate to plate load impedance. Lets use a 8800 ohm plate to plate load. In this case, each tube sees 2200 ohm load, and one "point" on the loadline is the 300 volt "0" mA quiescent value. Another convenient point is at "0" volts (namely, 300 volts drop across the 2200 ohm load). By ohms law, this is i = e/r = 300/2200 = 136 mA. As in the SE case, we need to obtain the same 5 currents and 2 voltages to give us the power output and distortion prediction. This is shown below:



Remember the formulas we used:

Po=(Ve-Va)*(Ve-Va)/(8*RL)

HD2=75*(Ia+Ie-(2*Ic))/(Ia+Ib-Id-Ie)

HD3=50*(Ia-(2*Ib)+(2*Id)-Ie)/(Ia+Ib-Id-Ie)

HD4=25*(Ia-(4*Ib)+(6*Ic)-(4*Id)+Ie)/(Ia+Ib-Id-Ie)

These work, with the RL value equal to a single tubes load (2200 ohms in our example).

The values from the graph are: Va=104V, Ve=496V, Ia=89, Ib=44, Ic=0, Id=-44, Ie=-89.

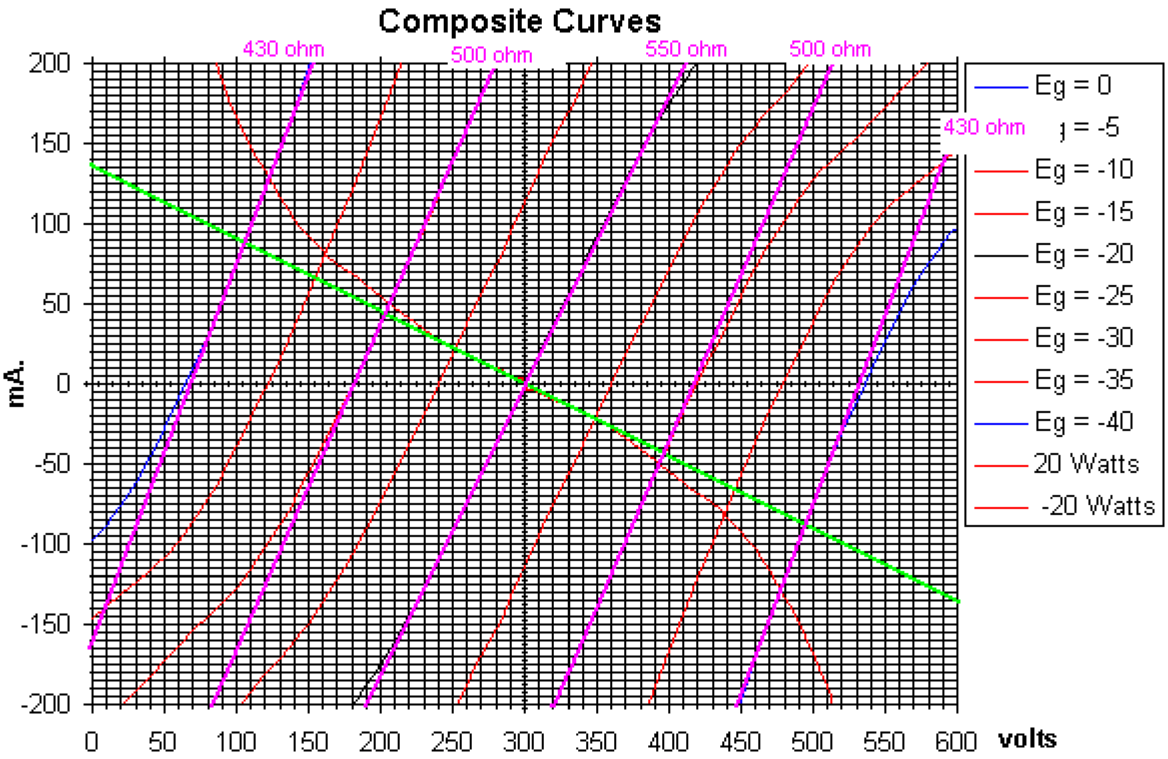
Power Out	HD2(%)	HD3(%)	HD4(%)
8.7 watts	-0-	0.38	-0-

Notice in the push pull configuration, even order distortion "cancels". Also, of more importance is the fact that the ODD order is reduced over the single ended case, even though the power output is more than double the SE case (clearly we could "parallel" 2 tubes SE and use half the impedance to get twice the power at the same distortion which would be 8.4 watts, and 0.7% third order distortion).

For those with the spreadsheet, it is left as an exercise for the student to see what happens if you don't feed the push pull stage with *exactly* the same signal level. For instance, allow the top tube to vary 0 to -20 volts to -40 volts bias, and have the bottom tube vary -35 to -20 to -5 instead of -40 to -20 to 0. Hint: you will get back some of the even order distortion products, but retain the other advantages of push pull.

The Effect of Plate Resistance on the Composite Curves

You might have noticed that the plate resistance, demonstrated on the composite curves seems to be much more constant than the single ended case. In Class A, this is definitely true. Using the tangent slope method we get:



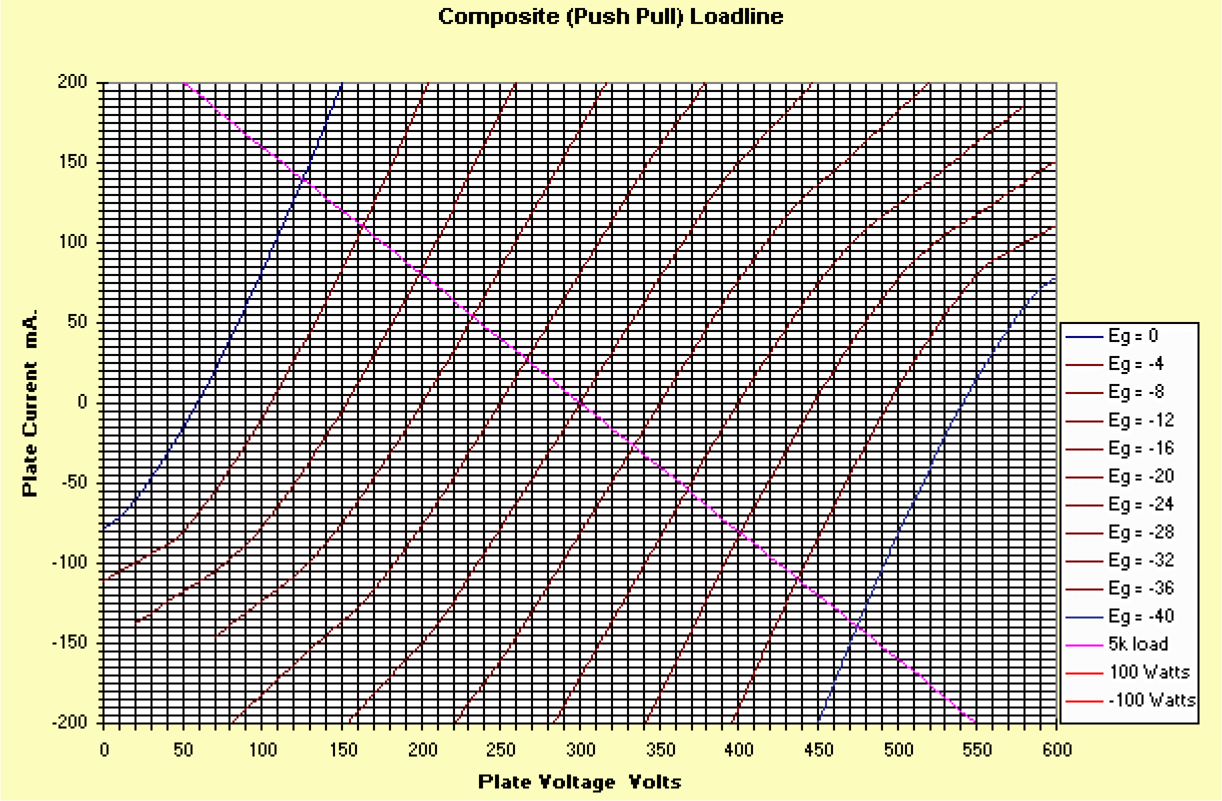
In this case, the plate resistance is seen to vary from 430 to 550 ohms. In the SE case, RL/RP ratio varied from 2:1 to 7:1 over the operating range. In the case of the push pull arrangement, this variation is cut to 4:1 to 5:1 over the operating range. The effect of speaker load variation will be cut down as well.

I hope this little tutorial has de-mystified load line creation and manipulation. We have gone thru how to create both a single ended and push pull loadline, shown the effects of non-ideal plate resistance, and provided some formulas to allow you to predict power output and distortion from your design.

Part 4: The Effect of Bias Change on Composite Loadlines - from Class A through Class AB to Class B

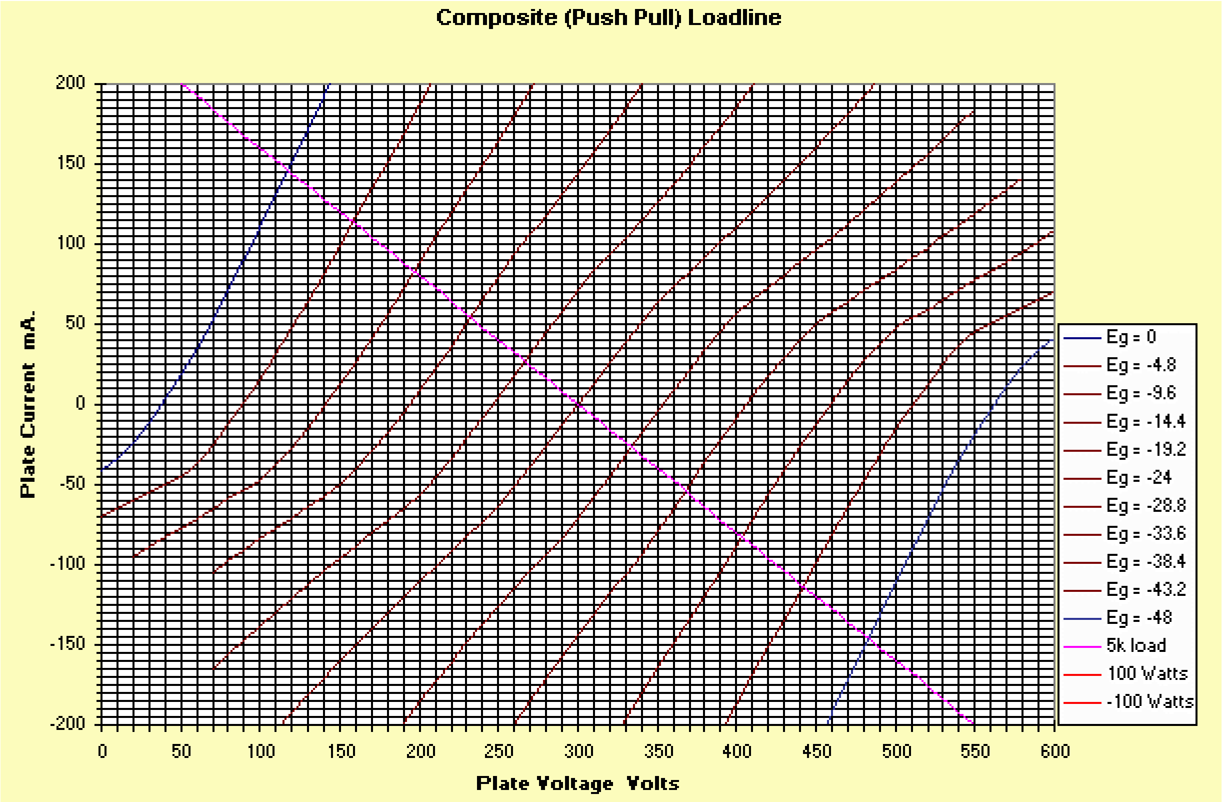
There has been some speculation whether there is a large or small difference in the sound quality of a Class A or a Class AB amplifier. This rather short part of our series shows the effects of altering the amplifier bias. For consistency, the same "invented" tube is used.

This first curve is pure Class A, with both tubes drawing current during the entire cycle.



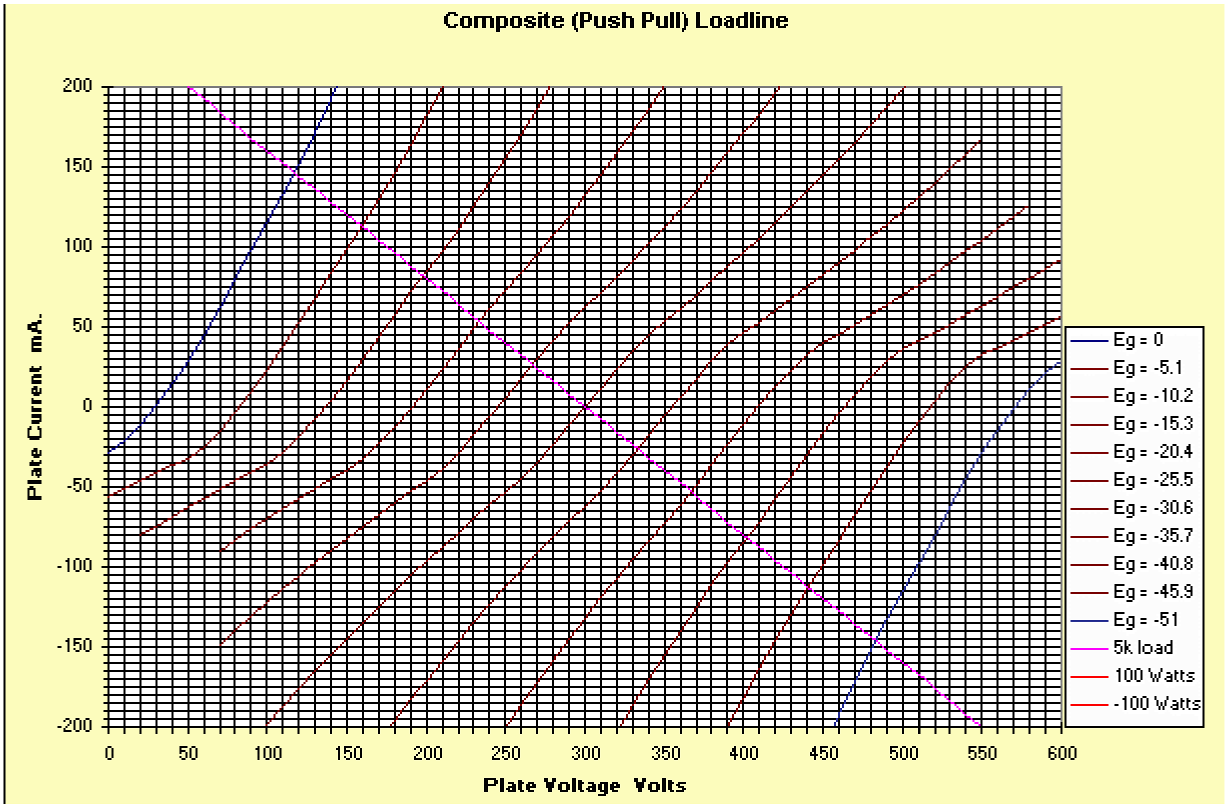
Notice the very constant plate resistance, and very smooth composite set. Very little distortion will be heard, whether the load is resistive (as shown), or very highly reactive (the load line looks like an ellipse instead of a straight line).

This next curve is the limit of pure class A operation. The bias has been increased (the grid biased more negative) so that one tube just reaches zero current as the other one reaches maximum current.



Notice that while the curves are still very straight, a "kink" is starting to become evident as the second tube cuts off.

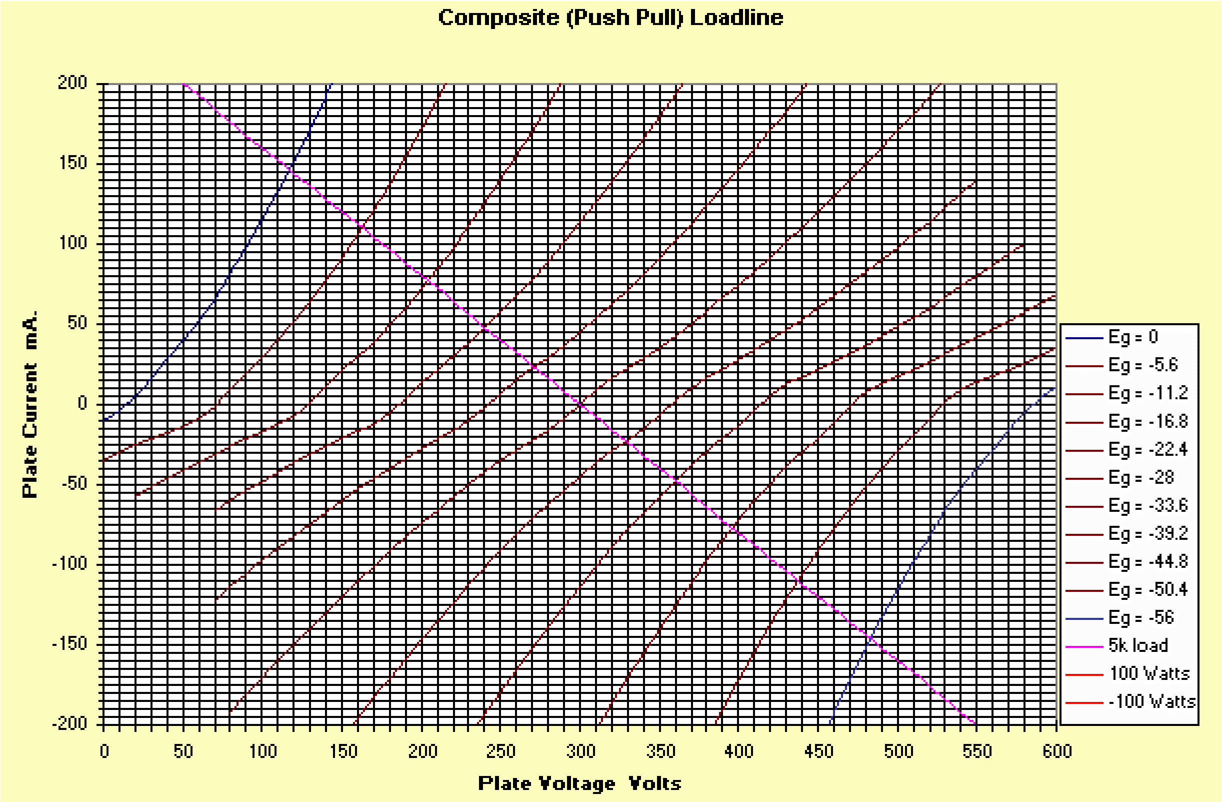
The third curve is typical Class AB biasing, where the tubes are really operated in Class A for all but the highest power outputs.



Notice that there is a gradual transition towards sloppiness of the curves. There are three things to note in the Class AB operation:

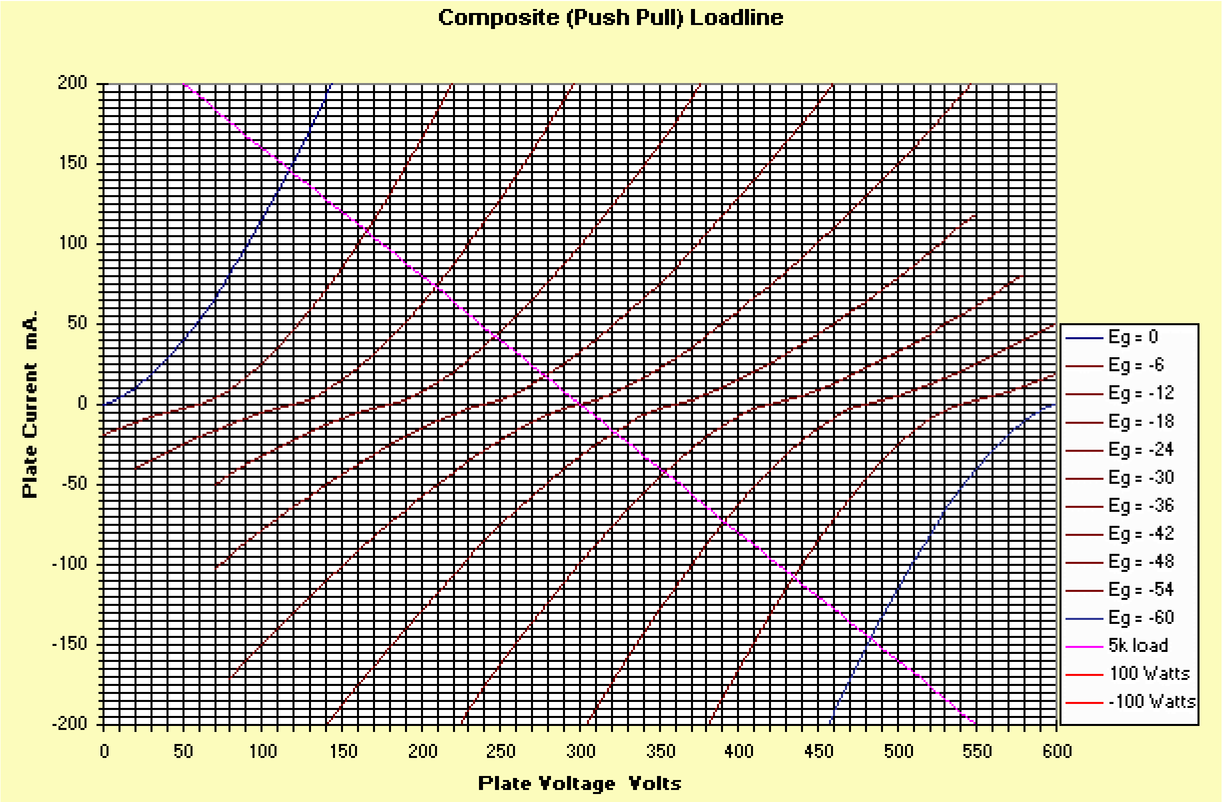
1. The plate resistance is still constant THROUGH the load line.
2. For Reactive loads, the load will hit some really variable portions of the plate resistance. This will have audible effects if your speakers are reactive, but probably be unnoticeable on a really "resistive" speaker.
3. There is a "common wisdom" that the plate resistance will change in Class AB when one tube turns off, since the plate resistance "changes from two parallel tubes to one, so the resistance doubles". Nonsense. The curves clearly show this does not happen. In fact, the effective plate resistance is slightly lower in those portions where one tube only is conducting.

In this next curve, the bias is increased even further. There is still significant idle current, but the transition to one tube operating occurs at much lower power levels.



In this curve, you can see fairly clearly the "crossover" region. The gain is definitely lowered for small signals. Some may think this is a form of xpansion. What it is, is a form of really obnoxious distortion. Yet for smaller signals, the amplifier is STILL running class A.

This final curve is just the threshold of Class B. One tube turns OFF just as the other one starts to conduct. This won't sound very good.



Notice there is no "magic" of the transition from one class of operation to the next, but rather a gradual transition.

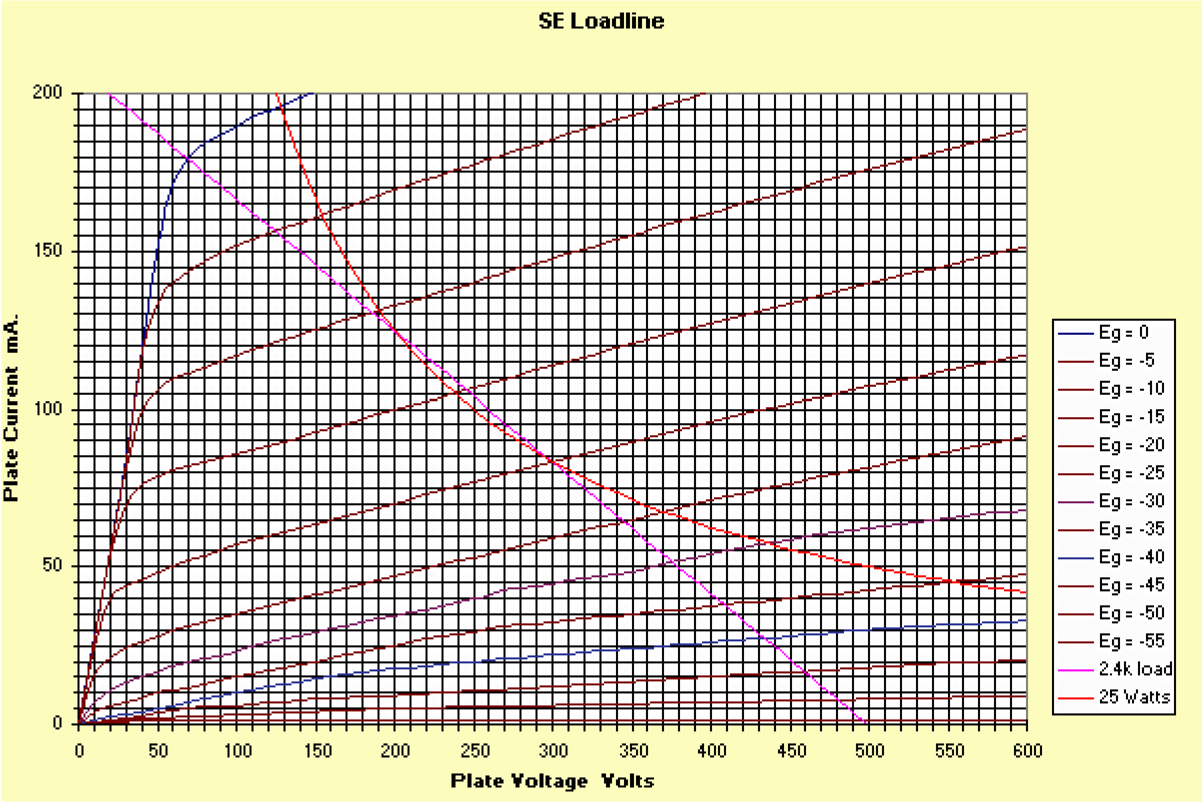
By the way, the curves were collected by a "screen scrape" of the Excel Spreadsheet. I've set these up as easily modifiable curves in the spreadsheet. The file has been zipped to download easier. It's at: http://members.aol.com/sbench102/platcurv.zip

Hope you've enjoyed this series.

Of Loadlines, Power Output and Distortion - Part 5 - The Pentode

Purpose

In the preceding parts of this series, we concentrated on loadlines and triode operation. In this article we will explore establishing a loadline on a pentode vacuum tube (valve), determine the power available from this loadline, and the distortion predicted from this loadline. This will allow the reader a step by step way to calculate the parameters for his design. I have again chosen to "invent" a tube for illustrative purposes. My pentode has the following parameters:



Establishing a Load Line: (very similar to a triode for S.E. applications)

1. Get the tube characteristics for your design (shown above for my example). If not already on the characteristics, plot the maximum power dissipation curve (voltage * current = spec'd power).
2. Select a reasonable quiescent operating point for your design. Often this is described in the manufacturers typical operation. For instance, a reasonable starting point for my example would be 300 volts and 83 mA. Whatever you pick MUST BE within the tube's ratings. Put a dot on the tube characteristics at this point.
3. Now start drawing a potential load line. This is a straight line whose "slope" is the primary "impedance" of the transformer. How do you do this? Pick a point somewhere about DOUBLE the quiescent voltage and zero plate (anode) current. Draw a line (called "loadline" in the curve below) thru these 2 points extending to the 0 plate volt axis. Did your loadline go above the max power curve you drew? Not good. Go back, pick a different zero current point. Is the voltage at no current more than twice the "rated" voltage? Not good. Go back and pick another point. Within spec? Good. Now determine the impedance. Z=(maxvoltage-quiescent voltage)/quiescent current. Alternately, you can pick an impedance to suit available plate transformers. In this case,

if you go outside the safe boundaries, you must choose a new quiescent point. This is where picking a loadline for the triode and the pentode differ. Maximum power output and more-or-less minimum distortion for the pentode occurs where the load line goes through the "knee" of the curve. This is illustrated above for a load of 2.4k. Notice I have "exceeded" the tubes rating over a small portion of the curve. You can do this, as the power dissipation over the full conduction cycle is still within the tube rating. Make sure the idle condition is within the ratings, however.

4. Having now chosen a tentative loadline, we need the following information from it......
    1. The required grid bias (you'll need to supply the grid with this value of DC voltage).
    2. The quiescent voltage (called Vq)
    3. Voltage where the grid bias voltage is zero (called Va).
    4. Voltage where the grid bias is double the quiescent value (called Ve). Note... if the plate current reaches zero before you get to this bias, you've got a bad operating point, go back to step 3 and try again.
    5. Current at 0 volt grid bias (called Ia). If this current is above the maximum rated tube current, go back to step 3 and try again. Hint: If its off the scale, chances are the current is too high.
    6. Current at half the quiescent bias voltage. (Called Ib.)
    7. Quiescent Current.(Called Ic.)
    8. Current at 1.5 times the quiescent bias voltage (Called Id).
    9. Current at twice quiescent bias voltage. (Called Ie).

For our example, the data is as follows:

Va= 70V, Vq=300V, Ve=433V, Ia=180mA, Ib=130mA, Ic=83mA, Id=51.5mA, Ie=28mA. In addition, 40V p-p are required from the driver stage, and a 2.4k plate transformer is required.

Rectification Effects

In any device with even order distortion (not just second harmonic as sometimes stated), the average current of a Class A stage will change depending on the signal level. If the distortion is relatively low, the effect is relatively unimportant, if the distortion is high, this effect becomes increasingly important. (It is also more important for self bias than fixed bias, as the bias voltage is a function of the average current).

This effect modifies all tube operating characteristics. The degree can be seen by comparing the quiescent current (83 mA in our example) with the average current as taken from the "extremes": that is, (Ia+Ie)/2. In our example that value calculates to

104mA (note that since this is reasonably different, we can expect relatively high distortion). The effect requires an iterative plot of the load line on the tube characteristics as described in part 1 of this series. Note the quiescent dissipation is still 300*0.083, or in this case 24.9 watts. The non-linearity shown here is getting dangerously close to what can be ignored, but, as we will see, the distortion in this example is too high anyway.

Power Output

Po = (Ve-Va)*(Ve-Va)/(8*loadimpedance).

In our example this is (433-70)*(433-70)/(8*2500)= 6.9 watts. This number is an approximation in that it assumes low distortion.

Second Harmonic Distortion

HD2(%) = 75*(Ia + Ie - 2*Ic)/(Ia + Ib - Id - Ie)

In our example this is 14% (!)

Third Harmonic Distortion

HD3(%) = 50*(Ia - (2*Ib) + (2*Id) - Ie)/(Ia + Ib - Id - Ie)

In our example this is -1.1%

Notice the minus sign. This indicates that the harmonic content subtracts from the fundamental (flattening it) when the fundamental is at its crest. This *usually* happens on third harmonic distortion in tubes.

Fourth Harmonic Distortion

HD4(%) = 25*(Ia - (4*Ib) + (6*Ic) - (4*Id) + Ie)/(Ia + Ib - Id - Ie)

In our example this is -2.2%

It is also possible to get an indication of how distortion varies with power output. In the example we just used, we picked 0, -10, -20, -30 and -40 volt bias points. We could also use -10, -15, -20, -25 and -30 points to see what happens at lower levels.

Applying the same formula to these points gives us 187 and 376 volts, and 130, 110.5, 83, 69.5 and 51.5 mA. This, in turn, calculates to 1.9 watts and 9.7% second harmonic, -1.5% third harmonic, and -8.5% fourth harmonic. This means the 2 watt level with this tube will also be pretty distorted!

Push Pull Operation (composite loadlines for pentodes)

We will discuss how to create a composite load line for a pentode. This is "necessary" to establish the load line for a push pull amplifier, regardless of whether it is going to be Class A or Class AB. We will continue to use the same "invented" pentode. As we will discover, establishing a realistic loadline for a pentode is slightly different than for a triode, due to the shape of the characteristic curves.

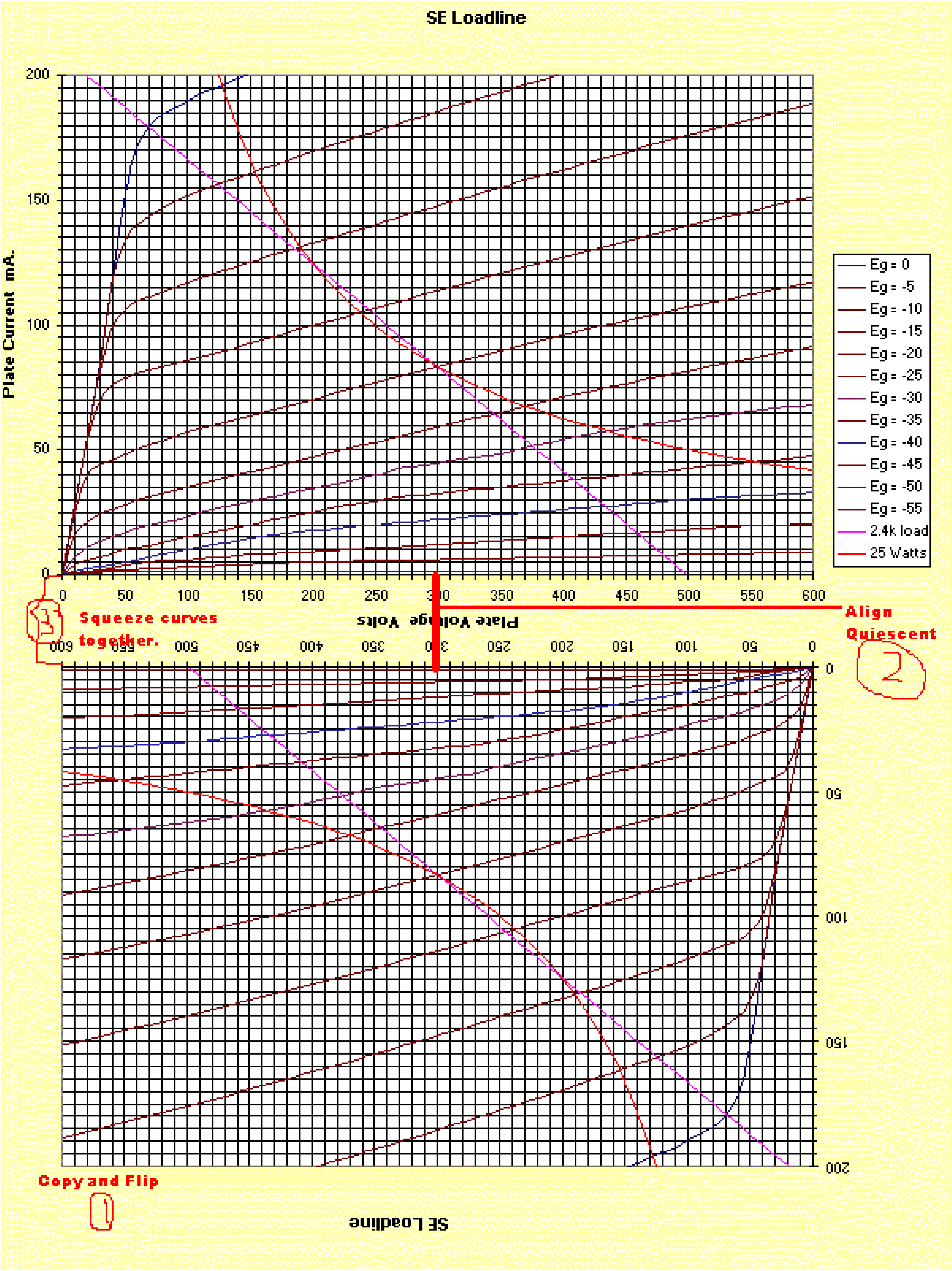
Building a Composite Load Line

This is again an iterative process, perhaps moreso than the single ended case as it's a bit more involved. Here's a step by step procedure to create a set of "composite curves" and load line.

1. Establish your intended operating point from the single ended curves. First let's consider an obvious Class A case, by choosing the same bias point we used for the single ended case: 300 volts and 83 mA quiescent current (-20 volt bias). Note: For Class AB, you may choose a lower idling current point, which will allow a lower impedance loadline (and higher power output) without exceeding maximum allowable

power dissipation. For instance, choosing a -25 or -30 volt quiescent point would allow you more "room" to increase tube current. To stay within Class A operation, at least some current must flow in each tube at all bias points, otherwise, you will be operating in Class AB. In this article we will consider -20 volt bias point (requiring a swing on each of the grids of 0 to -40 volts, -25 volts (which is still technically class A, since there is some current still flowing at -50 volts bias) and -30 volts, which is Class AB, since no current flows at -60 volts bias. This is actually an important distinction with pentodes. Since the "cutoff" characteristics tend to be sloppier than a triode, most so-called Class AB amplifiers are really Class A, as some small current is flowing even at the most negative point. As we will see, truly Class AB has some pretty bad crossover (notch) distortion.

2. Since the plate voltage increases on one plate and decreases on the other plate, we must have a way of representing this. The usual method is to take another set of the same tube curves, turn them around (so the maximum current is "down" and highest plate voltage is to the "left", and position them so that the quiescent voltages line up vertically, and the zero plate current lines touch each other as shown below. I've shown the steps to do this on the curves below: that is, copy the curves, turn one around, then merge the curves as:



3 Squeeze curves together.

Align Quiescent 2

Copy and Flip 1

3. Now, for the chosen bias point, create a new line (labeled "composite" curve) as follows (we are going to look at ONLY the -20 volt bias lines, one on the "upper" part of the graph, one on the "lower" part of the graph:

5. At the quiescent point (300V), subtract the currents (83-83=0 mA). Draw the "dot" at 300V, 0 mA on the composite curves.
6. Step to the next convenient voltage, say 310/290 volts, and subtract the currents. Plot this point.
7. Step to the next convenient voltage, say 320/280 volts, and subtract the currents. Plot this point. Continue until you have the -20 volt bias point established.

4. You have now established one "line" of the composite curves. This is the line of varying the plate voltage symmetrically about the quiescent point while maintaining a constant grid voltage. (classic plate resistance line).

5. Now consider another set of lines for your graph. This will be the -25 volt line for the "upper" set and the -15 volt line from the lower set. (We have put a 5 volt signal into the push pull stage). Again, for each plate voltage, subtract the two currents (for instance, 310V -25V bias upper and 290 volt -15V lower) and plot the dot. Continue until you have the -25/-15V line filled in. Note that if your quiescent grid voltage was, for instance, -30 volts, the second line you would add would use the -35/-25V lines instead of -25/-15V line.

6. Next do the same for the -30/-10, the -35/-5 and -40/0 volt lines. Then do the same for the -15/-25, the -10/-30, the -5/-35 and the 0/-40 volt lines. This completes the composite curves. The last 4 curves should be mirror images of the previous 4 you filled in. Noticing this saves you some time.

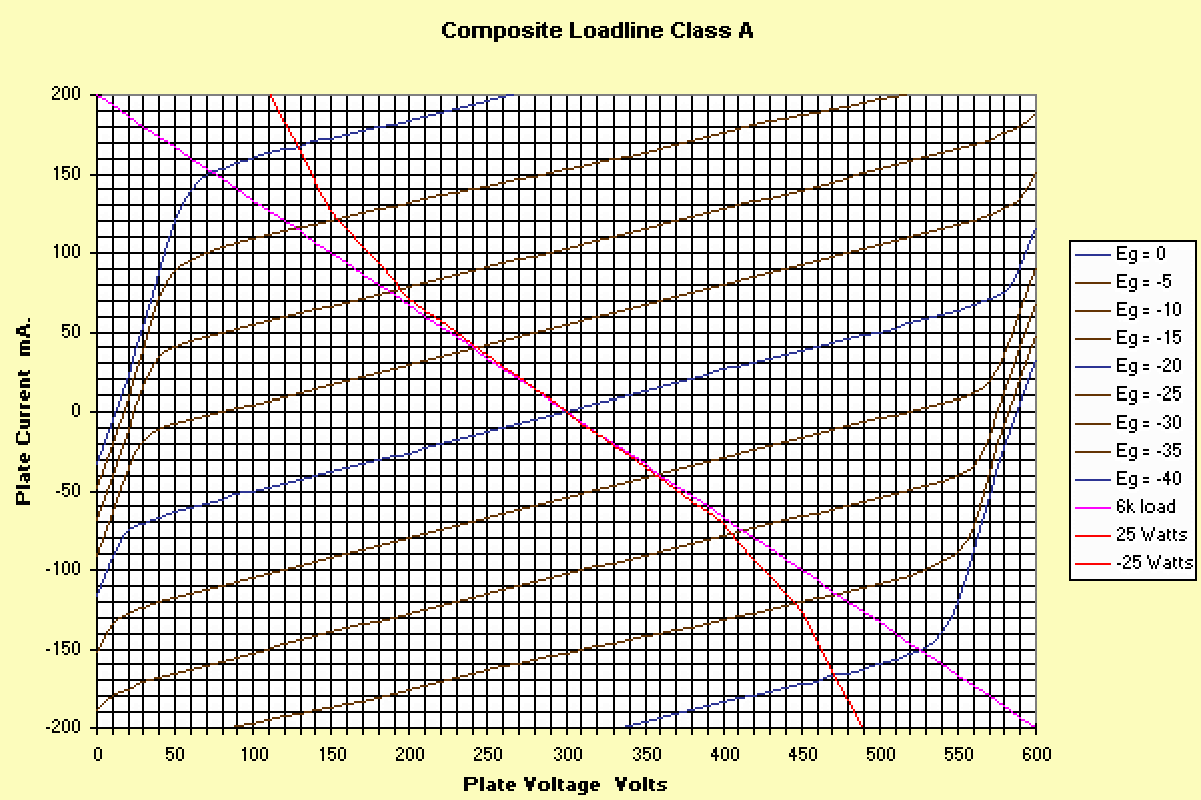
7. The last thing to do is fill in the maximum power dissipation curve. There are now going to be 2 of them, one for the one tube, one for the other. These will be symmetrical about the quiescent point. It is usually necessary to graph only half of the curve. The following is for the "upper" tube. Here's how to do it:

1. Get the current at the quiescent point. (In our case that's -20 volts, 300V, 83 mA.) Each tube will be drawing this current. Now find the current allowable via the power formula: I=P/E. In our case this is 25 watts at 300 volts or 83.3 mA. Since the "opposite" tube is pulling 83 mA, subtracting this from our 83.3 ma gives 0.3 mA, which is the most (lets call it unbalanced) current we can pull. Draw a dot at 300V, 0.3 mA.
2. Move to the next "convenient" grid line. This will correspond to moving "left" by about 60 volts to 240 volts. At this point the tube we have 240 volts on the upper tube, and the power formula states we could draw 25/240=104 mA. However, the "lower" tube has 360 volts on it, but is

biased at -25 volts. Looking this point up on the original single ended load line indicates 65 mA. Subtract the two to obtain 39 mA. Draw a point at 240 volts, 39 mA.

3. Repeat for a series of grid conditions just like we did for the triode case.
4. Now connect these with a nice smooth curve.
5. Rotate for the lower tubes power condition: it's a mirror image remember.

You should now have a graph that looks like this...



Push Pull Load Line

The same rules we used in the single ended case apply, with one exception: The impedance you plot is the impedance AS SEEN BY A SINGLE TUBE. Thus it is 1/4 the plate to plate load impedance. Lets use a 6000 ohm plate to plate load. In this case, each tube sees 1500 ohm load, and one "point" on the loadline is the 300 volt "0" mA quiescent value. Another convenient point is at "0" volts (namely, 300 volts drop across the 1500 ohm load). By ohms law, this is i = e/r = 300/1500 = 200 mA. As in the SE case, we need to obtain the same 5 currents and 2 voltages to give us the power output and distortion prediction.

Remember the formulas we used:

Po=(Ve-Va)*(Ve-Va)/(8*RL)

HD2=75*(Ia+Ie-(2*Ic))/(Ia+Ib-Id-Ie)

HD3=50*(Ia-(2*Ib)+(2*Id)-Ie)/(Ia+Ib-Id-Ie)

HD4=25*(Ia-(4*Ib)+(6*Ic)-(4*Id)+Ie)/(Ia+Ib-Id-Ie)

These work, with the RL value equal to a single tubes load (1500 ohms in our example).

The values from the graph are: Va=71V, Ve=529V, Ia=151, Ib=77, Ic=0, Id=-77, Ie=-151.

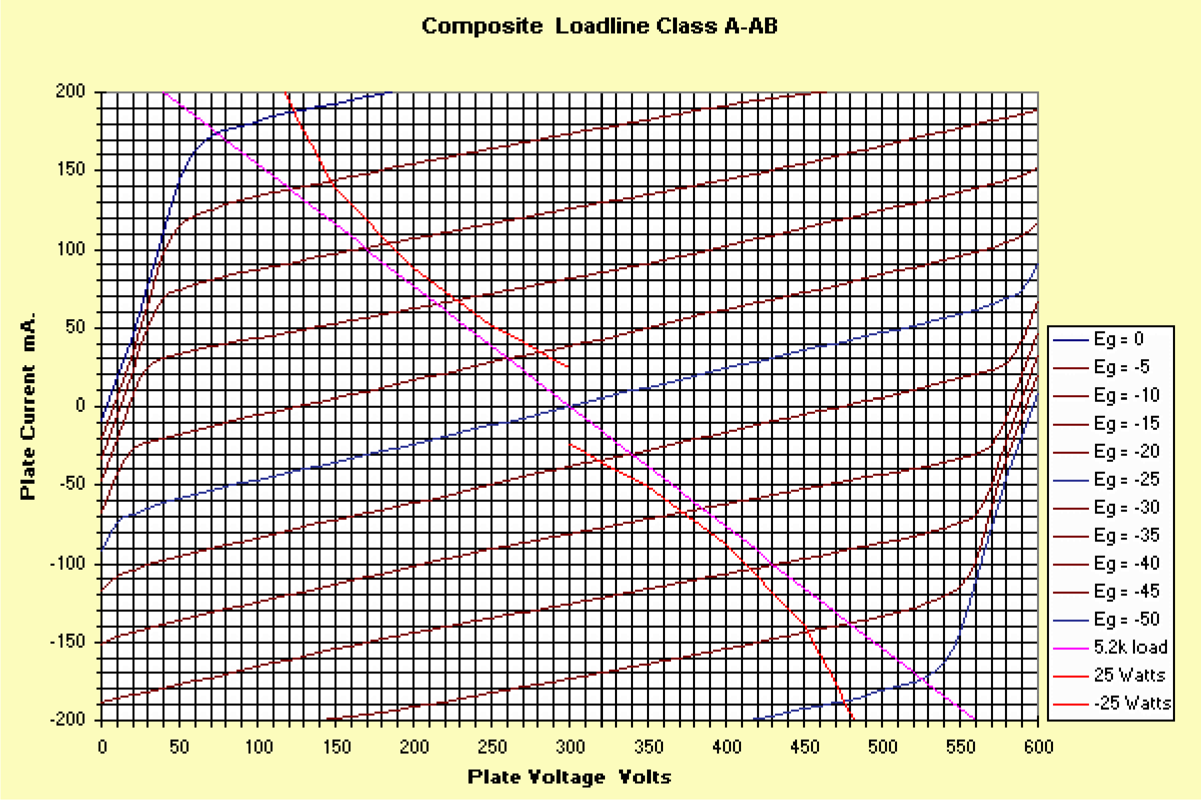
Power Out	HD2(%)	HD3(%)	HD4(%)
17.5 watts	-0-	0.7	-0-

Notice in the push pull configuration, even order distortion "cancels". Also, of more importance is the fact that the ODD order is reduced over the single ended case, even though the power output is more than double the SE case. Even more important is the significance of the picked load. Again, we picked a loadline that goes through the "knee" of the composite curves. We will show below, that as the bias conditions are altered, the "best fit" impedance changes also, which is quite a change from the triode case.

This is one case where the operation of these two device types is quite different.

The Effect of changing the bias on Pentode Composite Curves

Let's choose a -25 volt bias on the tubes, which will drop the idle current to 60 mA. As I mentioned above, technically, this is still Class A operation. The curves look like this:



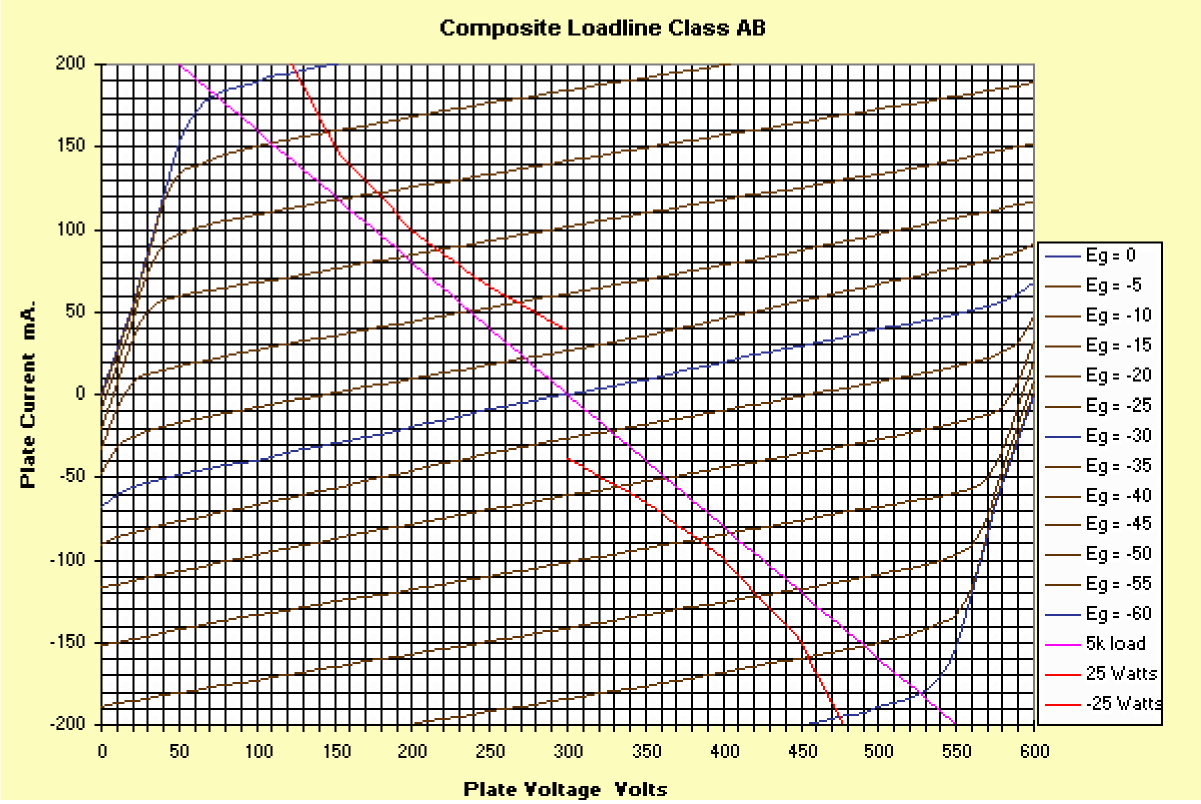
One important item to note is that now, an appropriate load line is 5.2k instead of 6k. (Substantially lower load impedance produces lower power and higher distortion, as does substantially higher load impedance.)

For this condition, The seven values picked from the curve are 74V, 526V, 174, 83, 0, -83 and -174 mA.

Power Out	HD2(%)	HD3(%)	HD4(%)
19.6 watts	-0-	1.6	-0-

Notice the available power output has increased, but so has the distortion.

This is even more obvious if we move the class of operation into true Class AB:



Now, the appropriate loadline has decreased to 5k, but the power output has reached 20 watts.

We can pick 0, -15, -30, -45 and -60 volt points (which gives us full 20 watts output) or choose intermediate points. This is summarized in the following table:

Power Out	HD2(%)	HD3(%)	HD4(%)
20 watts	-0-	2.5	-0-
8.9 watts	-0-	5	-0-

1.5 watts	-0-	3.4	-0-

Now you can see the effect of the "compressed" curves around zero bias. The distortion is actually greater at low levels than at maximum output. This is the effect of crossover or notch distortion.

Steve Bench - Biography

I have over 30 years of engineering experience, primarily in the telecom arena. I have done hardware, software and system architectural designs. I have contributed as a Technical Specialist as well as Director Level engineering management (of 30 people). I offer a very broad knowledge base, as well as depth in the traditional Telecom/Telephony marketplace.

Current Status:

Employed by Applied Digital Access in San Diego.

Past Employment History:

Digital Transmission Systems (and Able Telecom): 10/91 to 8/98: "Chief Technologist". Architected, designed, developed, and supported several products during this timeframe. I was mentor to many engineers, and I held several "telecom" classes for executive and engineering staff. Some key project developments: ISDN extended range "U" interface for D4/SLC Channel bank. Several "port" cards for channel banks/access D&I multiplexors: voice, data, combined very high density cardsets. Also T1 interface as well as switching power supply designs.

Verilink Corporation: 12/88 to 10/91: "Director of Engineering". Primarily an engineering management position, architected a new generation of network access products that is still the flagship product of that organization. Also developed a very extensive TL1 based T1 monitoring unit. Managed up to 30 people, with hire/fire/review and budgetary responsibilities. Originally hired as Verilink's first software manager.

Fujitsu America: 2/85 to 12/88: "Manager of Systems and Hardware Engineering". The system was a distributed processing PBX. Various applications were developed for PBX support, whereby the PBX handled the call processing, and the "application processors" handled the unique applications. I was responsible for determining the "dividing line" as well as coordinating the efforts of four geographically isolated development organizations.

Ericsson Communications: 6/78 to 2/85: "Technical Specialist/Hardware Manager". Two "lives" in this organization. Developed a new generation Analog Subscriber Carrier product, and provided technical support for "americanization" of a PBX product line. Also responsible for keeping the corporation current from a "standards body" view.

Motorola Communications Division: 6/68 to 6/78: "Senior Staff Engineer". One of the primary contributors to Motorola's first vehicle location system. Member of Motorola's Patent Review Board. This was my engineering entry position, and developed into a technical leadership position.

I have 10 issued US patents, and several currently pending.