Load impedance and operating points for single-ended triode amplifier stages

Part Two: Linear Triodes

by Paul Joppa

In Part 1 of this series, I described how the operating point (plate voltage Eo and current Io) and load resistance RL are related. In this part, I will use those observations to look at single-ended amplifier performance for triodes that follow closely the simplest expression for plate current as a function of plate and grid voltages, called "Child's Law". I call these tubes linear because they are capable of higher power output at lower distortion than those that deviate significantly from this behavior. Child's Law states that:

$$Ib = K^*(Eb + m^*Ec)^{3/2}$$

In this equation, Ib is plate current, Eb is plate-to-cathode voltage (hereafter called simply "plate voltage"), and Ec is the grid-to-cathode voltage (hereafter called simply "grid voltage"). This formula is based on a number of simplifying assumptions, probably the most important of which is that the cathode/grid/plate geometry is geometrically simple. It has been derived exactly for concentric cylinders and for infinite flat plates. If you look closely at a type 76 tube, you can see that it was designed with a cylindrical structure. Similarly a 300B was clearly designed with a planar structure. Both of these tubes are known for their high degree of linearity.

Based on this formula, I worked out the performance on the computer for a variety of operating conditions. I found that with two non-dimensional ratios I could summarize hundreds of computer analyses. Before introducing them, let me mention the operating resistance R0, which is the ratio Eo/Io, as described in Part 1. I call it a resistance because it has the dimensions of a resistor - in fact, it is the value of a resistor that would draw the same current as the tube if it were substituted. Then the first non-dimensional ratio I will use is R0/rp, where rp is the tube's plate resistance. The second ratio is RL/R0, the ratio of load resistance to operating resistance. In part 1, I said that a load resistance equal to R0 was a good initial guess; now we'll examine some variations of this and see the effect.

The ratio RO/rp should be at least 4 to give a reasonable operating box without risking grid current. Sometimes you are forced to use a lower value, such as when the plate resistance is very high, but the output power and voltage become severely restricted in this case. I evaluated operation for values of R0/rp from 2.5 to 10, which corresponds to a higher Eb than most tubes are rated for.

I varied the load ratio RL/R0 from 0.25 to 1.0. It is not completely impractical to operate as low as 0.25 if R0/rp is small, although at higher values of R0/rp this will result in cutoff for a substantial portion of the cycle and therefore high distortion.

Shown below are contour plots of power (normalized to the plate dissipation PD) and second harmonic distortion at full output. As you can see, low R0 and high RL produce the lowest distortion, but also the lowest power. The best tradeoff is with high RL (for lower distortion) and high R0 (for more power output).

This study has led to a set of "rules of thumb" that approximately summarize these results, and work reasonably well for linear triodes (for nonlinearities, see Part 3.) These give a good starting point, but each tube and circuit is unique. I don't pretend these are the very best operating points, only that they are a pretty good starting point.

R0/rp = 5 RL/R0 = 0.7

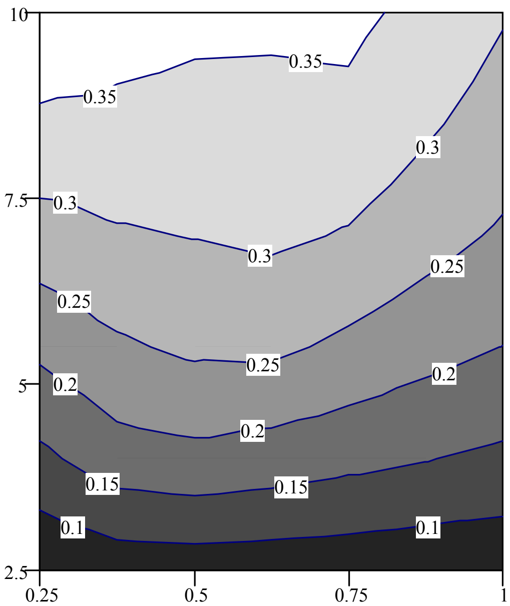
> actually, as long as R0/rp is greater than 4, RL/R0 = (R0/rp - 1.5)/(R0/rp) is pretty good.
>
> The minimum value of RL/R0 to avoid cutoff is (R0/rp - 3)/(R0/rp)
>
> Incidentally, for a plate dissipation of PD watts, it's handy to know that Eb = sqrt(R0 PD)

Ec = 0.7 Eb/m for R0/rp = 5

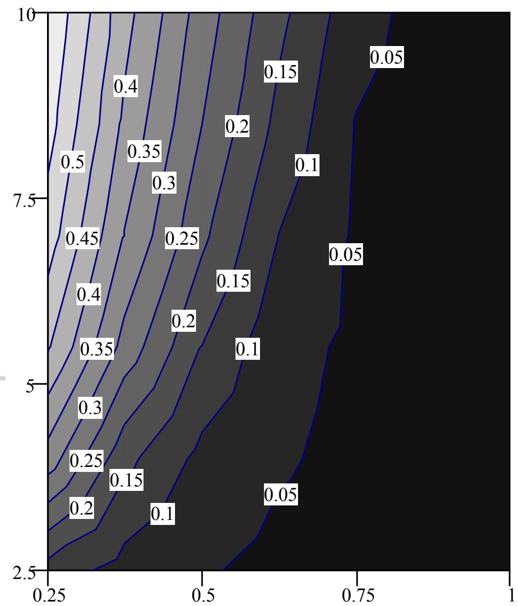
> actually, Ec =(Eb/m) (1 - 1.5 rp/R0) in general

Hence Rk = 3.5 rp/m

> R_k is the cathode resistor
>
> actually, Rk = (R0-1.5 rp)/m in general. If RL/R0 = (R0/rp - 1.5)/(R0/rp) as recommended above,



Power



Distortion

then Rk = RL/m.

To complete the circuit for a single stage, we need the values for coupling and bypass capacitors, and for transformer or choke loaded stages, the load inductance. Assuming that the capacitors have a -3dB frequency of 5 Hz, we can estimate:

Bypass capacitor Ck = 65,000/Rk microfarads,

coupling cap Cc = 30,000/Rg microfarads (Rg is the grid resistor)

Now it is not so easy to make large inductors, so I generally assume that the minimum inductance value is that for which the impedance equals RL at 40 Hz. This will give a small-signal frequency response down less than 1 dB at 40 Hz and less than 3 dB at 20 Hz, with a power bandwidth down 3 dB at 40 Hz. This value is:

Minimum choke or transformer primary inductance = RL/250 henries

For a simple example, consider a 2A3 amplifier. The plate resistance rp is 800 ohms according to the RCA manual. If we choose R0 = 5, then Eb/Ib = 4000. For RL/R0 = 0.7, we get a load impedance of 2800 ohms. Plate voltage is sqrt(15 R0) at 15 watts, or 245 volts, and since PD = 15, Ib = 15/245 = 61 mA. Grid voltage should be about -41 volts, if m is 4.2. The cathode resistor would be 667 ohms with a bypass of 97.5 microfarads. These values are pretty close to the RCA recommended operating point of 250 volts at 60 mA into a 2500 ohm load with 45 volts grid bias through a 750 ohm cathode resistor. With a maximum grid resistor of 500k ohms, a coupling cap of 0.06 microfarads would be big enough. Finally, a transformer of at least 10 henry inductance is needed for acceptable bass.

I have found these simple rules of thumb to be very useful when first developing a new design, or examining the possibilities for a particular transformer, tube, or power supply. Often there are reasons for varying these values (for instance, in my 300B amp the power supply and output transformer could not handle the estimated current of 80mA; I dropped it to 55mA which gave me more distortion but was still acceptable), but it’s always nice to know where you are to start with. I hope you will find these rules as helpful as I have.