

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

Part Three: Nonlinear Triodes

by Paul Joppa

The first part of this series discussed the general features of operating point analysis for single ended tube amplifiers, and the second gave specific results and rules of thumb for designing such amplifiers with highly linear triodes. I'm not going to talk about multi-grid tubes (I don't like 'em!) but we can't always have the best tubes so it seemed to me necessary to explore the consequences of using tubes that do not follow Child's Law very closely. That is the subject of this third and final part of the series.

The basic feature of nonlinear triodes is that the plate curves get scrunched up at low currents and high voltages. This means that along a load line, the low-current portion of a signal is attenuated, resulting in increased distortion. There have been a number of attempts to describe this feature mathematically, especially with reference to using the models in circuit simulation software. My approach here is based more on the geometry and physics of the tube, and is also a result of looking for a single parameter by which a tube's linearity can be described.

This model is based on the observation that no tube is perfectly symmetrical, so each electron flow path will have a slightly different gain, i.e. a tube will perform as if it were composed of many smaller tubes in parallel, each with slightly different m or g_m . Over most of the operating region there will be an average value which is fairly stable and the tube looks fine. But near cutoff, some portions of the tube will be cut off while other portions are not, leading to a wide variation in equivalent average gain. To make a low-distortion amplifier, operation in this region should be avoided. Some triodes are much more strongly affected by this than others, so the thickness of this low-current region of nonlinear behavior can vary widely and depends on the tube's nonlinearity factor (and on your tolerance for distortion).

My model for the variation in amplification factor is a Gaussian probability distribution.

This means that the amplification factor is characterized by a mean value and a standard deviation. I call the standard deviation, normalized by the mean value, the "nonlinearity factor" or NLF. The analysis consists of simply calculating the weighted integral of Child's Law over all possible values of the amplification factor to evaluate the current as a function of plate and grid voltages.

To test this analysis, I calculated the plate curves for a 6AS7 (a fairly nonlinear triode) and compared them with the published curves. As you can see, the results are fairly similar. I evaluated the nonlinearity factor by taking several points off the published curves and using them to compute a least-squares fit to my model with m and NLF as the variables.

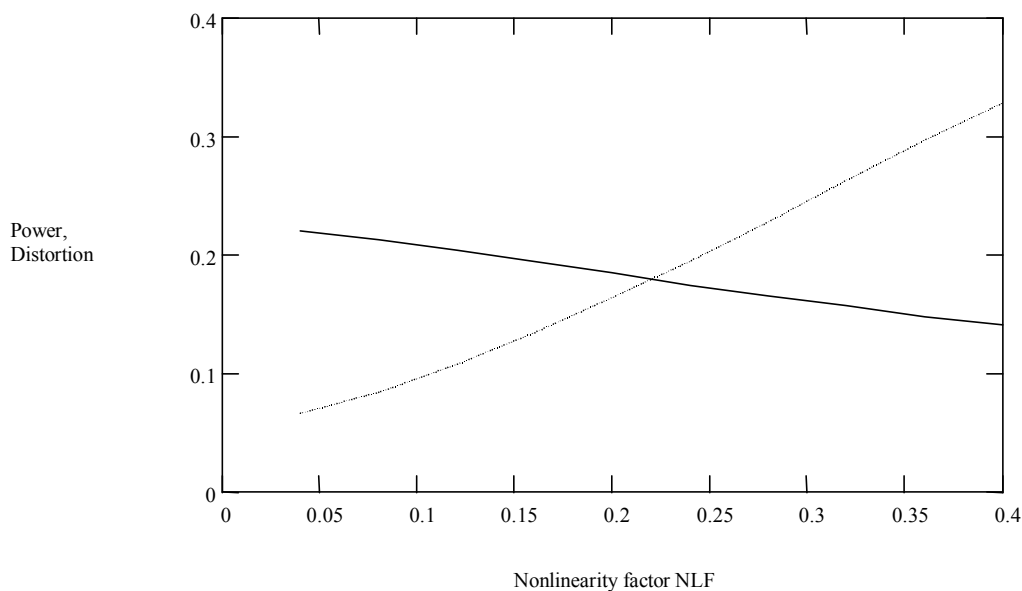
Here are some common tubes and their NLFs, to give you a feel for this parameter: These values are based on published curves rather than actual measurement, though I do plan to set up a measurement scheme someday.

The following plot shows the effect of NLF on power and distortion at a given value of voltage and plate loading - in this case, the usual rule-of-thumb values ($R_0/r_p=5$, $R_L/R_0=.6$). Power is the solid line, distortion is the

Type	NLF
300B	0.071
45	0.093
76	0.13
6922	0.143
6SN7	0.186
6AS7	0.205
6BQ5 (triode con- nected)	0.272

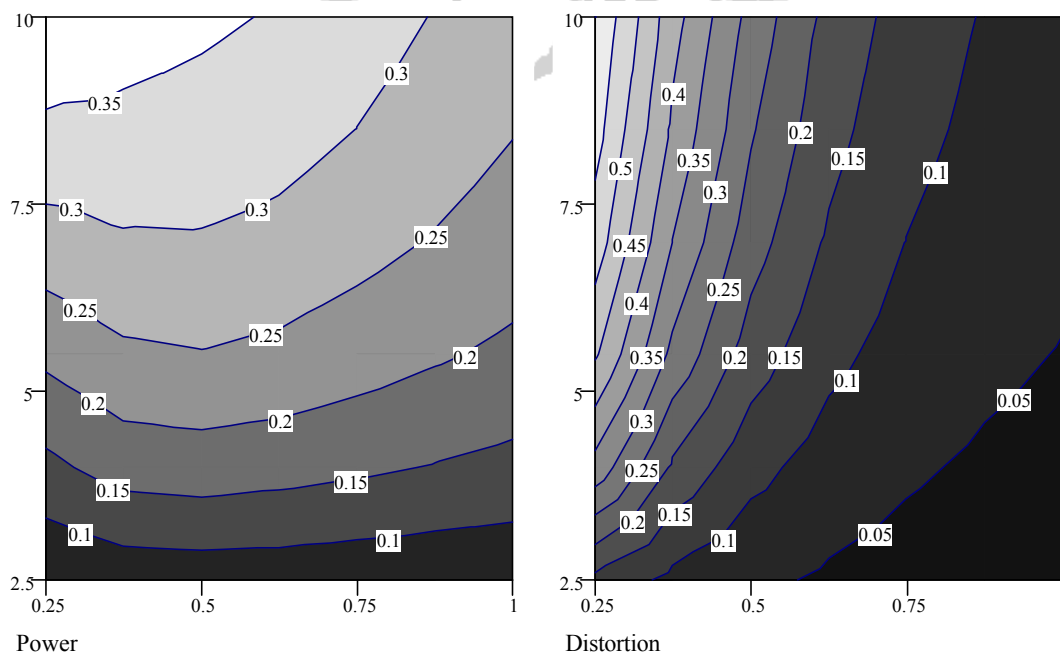
dotted one. Notice how increased NLF slowly reduces power but rapidly increases distortion. In this case, an NLF below 0.1 is needed to obtain less than 10% distortion.

Here are some contour plots similar to the ones in Part 2, showing power and distortion as



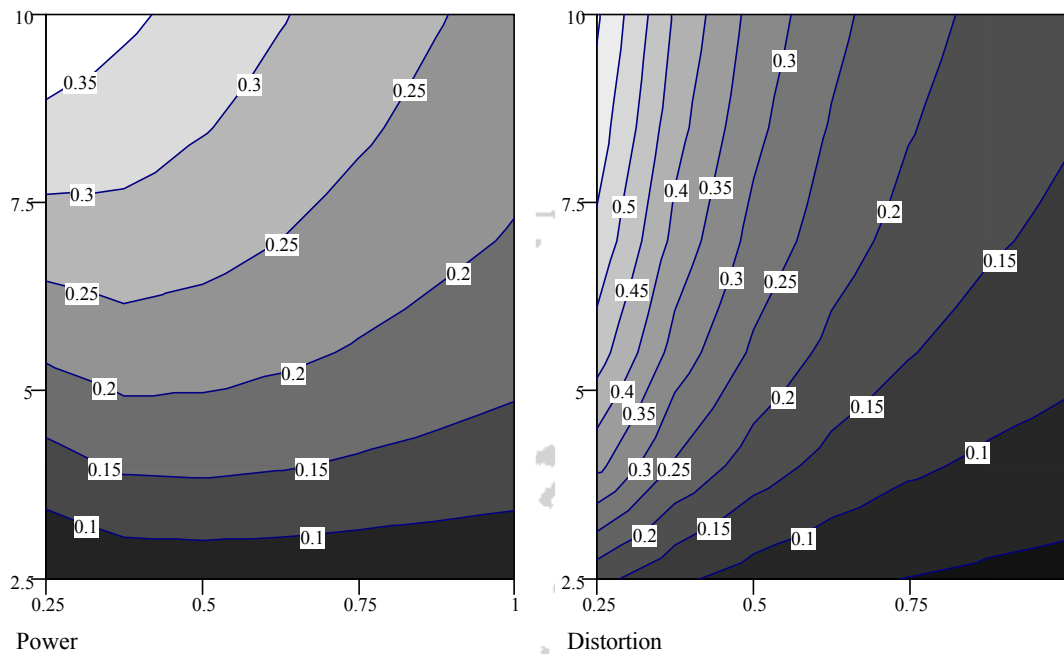
functions of R_0/r_p and R_L/R_0 . The first one is for an NLF of 0.1. This is about as low as you can get in the real world - only 300Bs and 45s are better, of the few I have looked at. Overall they are similar to the NLF=0 plots shown in Part 2, with just a bit more distortion especially at high values of R_0 .

Now here are some power and distortion plots for NLF= 0.2. As you can see, the only way to get low distortion from a tube with a high NLF is to run it at low voltage (and hence high current). j.c.morrison among others has advocated this kind of operation; presumably this is the reason. Note



that it will not be very efficient. However, a wide variety of load impedances give essentially the same performance, which is an advantage.

Finally, here's a set of plots for $NLF = 0.4$. This would be a pretty high-distortion tube, maybe like the big Russian 6C33C-B. There's just no way to get much power out of it at any reasonable distortion



level, at least without massive injections of negative feedback. In fact, a 2A3 at 15 watts plate power will put out more audio watts at 5% distortion than a 6C33C-B at 65 watts plate power.

