

Why Use A BJT? - The Problem With JFETs

While there seem to be several reasonably convincing triode emulators using jfets, they all suffer from the basic jfet problem which is the extreme variability of their main parameters. This can be factored out to some extent when the jfets are used as part of a linear amplifier but is a serious obstacle when it comes to designing a reproducible non-linear circuit. The variations can cover a five to one range, necessitating selection of components or the provision of trimming. Even after trimming there remains a variation in gain or clipping level.

Bipolar transistors, on the other hand, are extremely predictable and well behaved. The non-linearity of the transfer function g_m , or $\Delta i_c / \Delta v_{be}$, although varying with temperature, is well defined.

First, some well known results:

Typically, at a room temperature of 18C and for a bias current of 1mA, considering variations about the bias point and normalising we have

$$i_c = \exp(40 \cdot v) - 1$$

This can be expanded as a power series in v :

$$i_c = 40.0 \cdot v + 800.0 \cdot v^2 + 10666 \cdot v^3 + 1.06667e+5 \cdot v^4 + 8.53333e+5 \cdot v^5 + \dots$$

At first glance this seems to be hopelessly non-linear, but if we confine v to small values such as 10mV, the picture is somewhat more benign, as might be expected of a power series.

$$i_c(v=10\text{mv}) = 400\text{m} + 80\text{m}(v^2 \text{ term}) + 10\text{m7}(v^3 \text{ term}) + 1\text{m07}(v^4 \text{ term}) + 85\text{u}(v^5 \text{ term})$$

At lower levels, the second order term dominates even more. In fact, it is a well known result that the distortion of a voltage driven transistor stage is mostly second harmonic and is proportional to the peak input voltage, being 1% at 1mV, 10% at 10mV.

It may seem strange at first to be modelling a triode with an essentially square law non-linearity approximated by an exponential rather than seeking to achieve the 3/2 power of Child's law but there are two reasons why this approach is valid:

1. Many triodes (including the ECC83) actually follow a square law rather than a 3/2 law. Using data from the ECC83 datasheet, try plotting anode current against anode voltage squared at a fixed grid voltage.
2. We are emulating the behaviour, not the underlying physics, so there is no need to consider operation outside our region of interest. The basic biasing of the stage, for example, is taken care of separately from the modelling of the dynamics.

So, we have our basic non-linear element, although it only works at millivolt levels.

Further considerations:

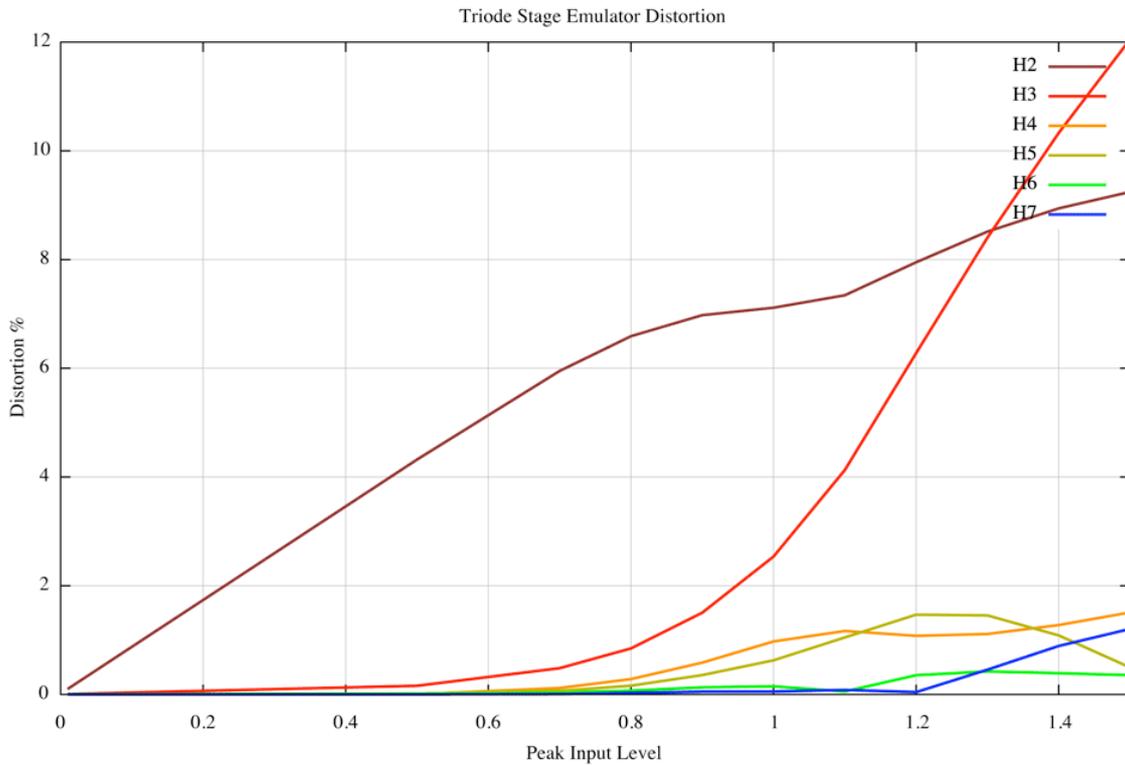
The dynamic output resistance of the transistor is high; its behaviour is often compared to that of a pentode. The triode, on the other hand, has a relatively low output resistance caused by the internal feedback where both the grid and the anode influence the electric field at the grid. The feedback factor is $1/\mu$ and our emulator must include this.

Next, the triode doesn't follow the same non-linear law all the way down to cutoff. It smoothly enters a quasi-exponential region where the gain tails off.

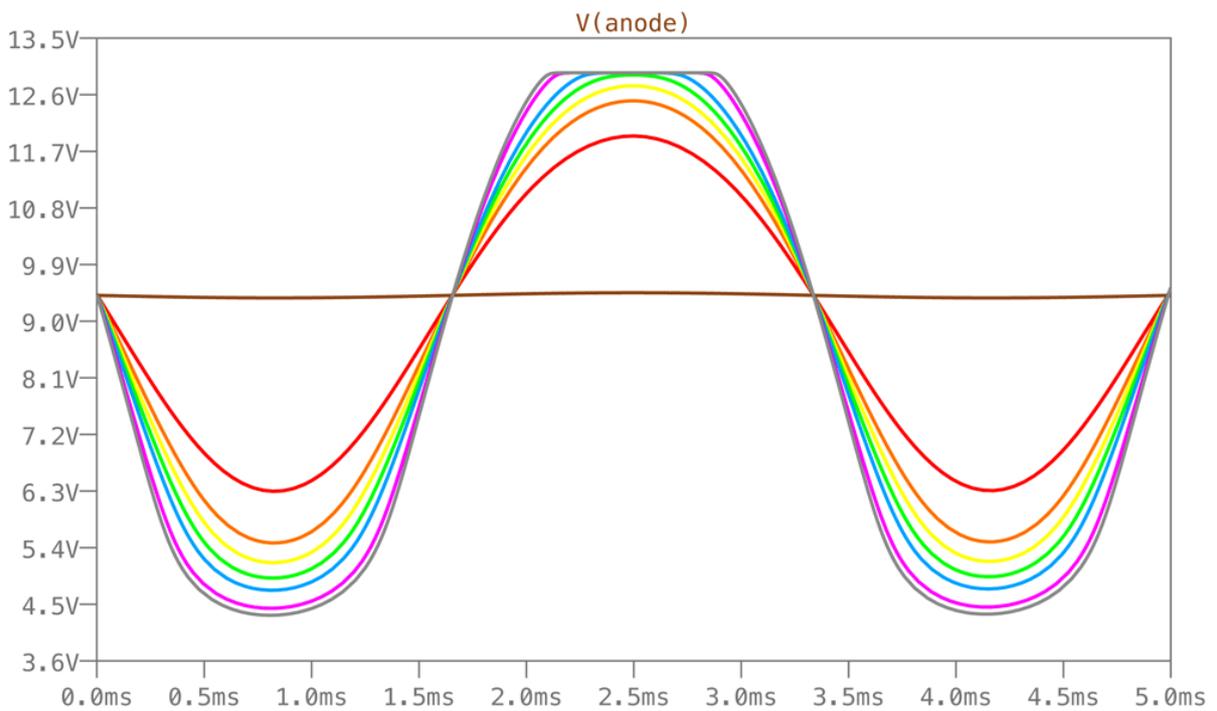
Finally, the input resistance of the triode falls rapidly when the grid voltage is brought above that of the cathode and the grid current rises.

Distortion and clipping

The variation of distortion with input level:



Waveforms related to output level:



The circuit as it stands clips by cutoff for negative excursions of the input and by grid current for positive excursions, Distortion just before clipping is about six percent, which is on the high side of ECC83 performance. Juggling the feedback, the anode load and the current subtracted at Q2 emitter via R10 allows variation either way.

Noise

A major difficulty when attenuating the signal to the 10 - 15mV required to drive Q1 is achieving adequate noise performance. Q1 is a medium power transistor known for its low extrinsic base resistance and hence good noise performance at low impedance levels. The source resistance for Q1 is kept low at 22Ω, roughly equal to the emitter resistance. The extra signal power required to do this comes from op amp U1. The main sources of noise are Q1, R22, R1 and U1. The noise contributions of the other transistors are negligible and any general purpose type of reasonable gain will do. The A-Weighted noise at the output is 14μ8V, corresponding to 4μ7V at the input. This is 5dB higher than an equivalent ECC83 stage including the input buffering resistor R1 but is, of course, free from any hum. The A-Weighted signal to noise ratio would be over 76dB for a 30mV input. As can be seen from the above graph, input clipping occurs at about 1.4V peak or 1V rms, at which point the signal to noise ratio would be 106 dB

Output resistance, μ and g_m

The g_m of Q1 is 44mS. The effective μ of the stage is $3k3/22 = 150$. The anode resistance is, therefore, $r_a = \mu/g_m = 3k4\Omega$. This is much lower than that of a conventional small signal triode but is in proportion to the 7k5Ω anode load. Note that g_m is a measure of variation and is not affected by subtracting a fixed current at Q2 emitter.

In a high voltage version of the circuit, g_m would be maintained at the same value, since it is a function of Q1 emitter current and is very much constrained by noise considerations. The value of R6 would be increased, raising μ and hence the anode resistance. The anode load, R11, would increase necessitating a much reduced base current through Q3, which might then need to be a Darlington pair.

Miller Capacitance

The circuit as drawn does not include any capacitance between anode and grid. Instead, C1 is included to provide some high frequency filtering. If desired, a capacitor can be connected between the anode and the input. In order to achieve the same effect as the 2pF C_{ag} of an ECC83, say, it would have to be roughly ten times larger to account for the lower overall gain. This capacitance, when viewed from the grid, would appear to be non-linear. Whether this is an effect worth reproducing is unknown.

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