



The Importance of Correct FET Biasing
in the eTap2hw Vintage Echo Emulator.

&

Understanding Harmonic Distortion in
Triode or Well Constructed JFET
Amplifier Stages.

By **Dr. Stephen C Mitchell** April 2014

**Dedicated to Piet Verbruggen for his long, difficult and
unselfish work in bringing the eTap2HW design to the
musical community.**

The Importance of Correct FET Biasing in the eTap2hw Vintage Echo Emulator

This document will attempt to show in simple terms how with correct FET biasing that Piet Verbruggen's design can be made to better emulate a classic triode tube guitar amplifier stage.

The transfer function of a triode tends to follow a power law having the exponent 1.5 often termed the "3/2 exponent". What we will attempt to show is how a JFET common source amplifier can be made to approximate this by using the poorly understood but extremely useful Dimitri Danyuk's JFET biasing ideas ¹ coupled with a biasing technique where the JFET drain approaches 66% of the applied voltage not the ~50% of the Fetzer valve calculations.

Let's look at a very basic single triode amplifier in Figure 1 below.

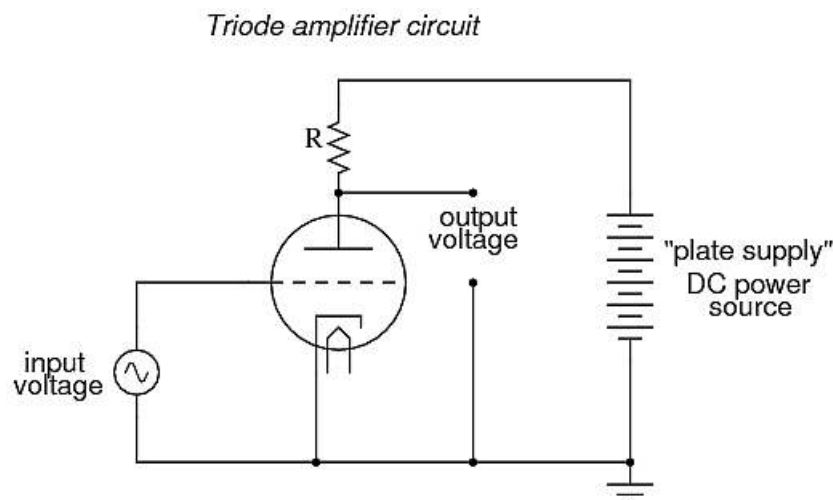


Figure 1: Simple triode amplifier schematic showing plate and the plate resistor connected to the High Tension (HT) voltage, the cathode connected directly to ground and the small input AC voltage (our guitar signal) connected to the grid. The small input is amplified about 30x to produce a large voltage swing across the plate resistor.

The low-voltage AC signal connected between the grid and cathode alternately suppresses, then enhances the electron flow between cathode and plate. This causes a change in voltage on the output of the circuit (between plate and cathode). The AC voltage and current magnitudes on the tube's grid are generally quite small compared with the variation of voltage and current in the plate circuit. Thus, the triode functions as an amplifier of the incoming AC signal (taking high-voltage, high-current DC power supplied from the large DC source on the right and "throttling" it by means of the tube's controlled conductivity).

In the triode, the amount of current from cathode to plate (the "controlled" current) is a function both of grid-to-cathode voltage (the controlling signal) and the plate-to-cathode voltage (the electromotive force available to push electrons through the vacuum). Unfortunately or, as we will see later, fortunately for guitarists neither of these independent variables has a purely linear effect

on the amount of current through the device (often referred to simply as the "plate current"), i.e. triode current does not necessarily respond in a direct, proportional manner to the voltages applied.

In this particular amplifier circuit the nonlinearities are compounded, as plate voltage (with respect to cathode) changes along with the grid voltage (also with respect to cathode) as plate current is throttled by the tube. The result will be an output voltage waveform that doesn't precisely resemble the waveform of the input voltage. In other words, the characteristics of the triode tube and the dynamics of this particular circuit will **distort** the wave shape. So triodes produce a mild natural distortion as a consequence of how they function. Typically they produce asymmetric waveforms, i.e. a sine wave input will be slightly distorted such that the upper and lower halves of the sine wave are amplified in a slightly different manner. Fourier analysis (not to be discussed in detail here) would immediately tell the mathematician that harmonics are produced "distorting" the pure applied waveform. Triodes tend to produce sweet musical sounding even harmonics, see Figures 2a and 2b below for the hot biased triode ².

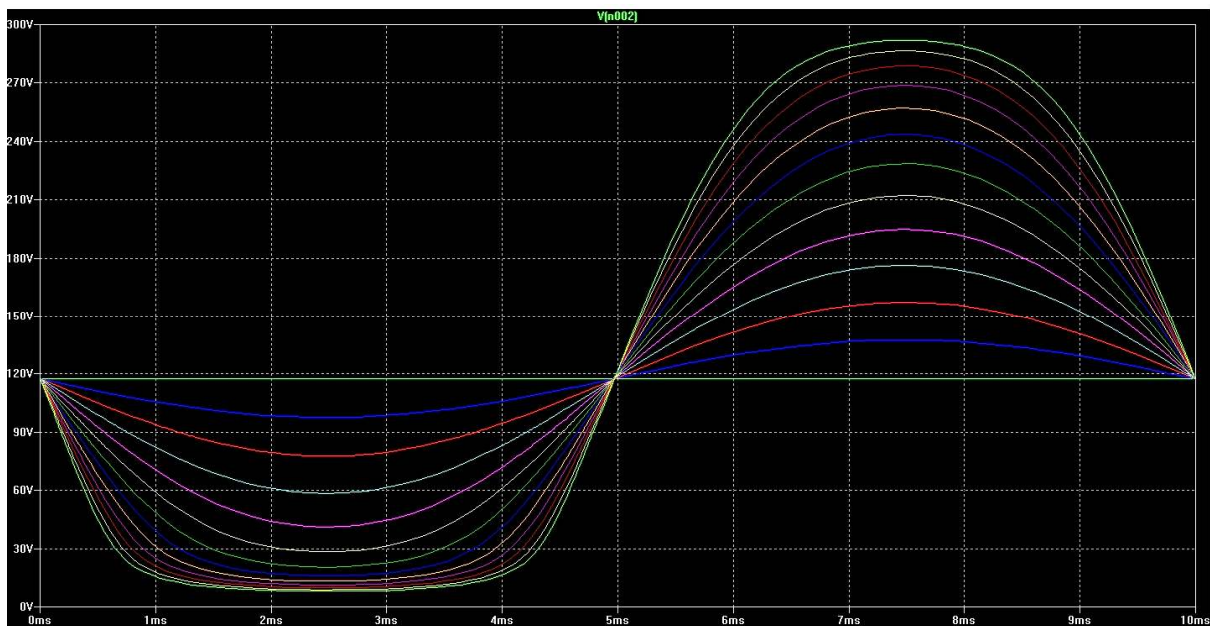


Figure 2a: Spice simulation graphs showing increasing asymmetry of a triode with increasing input amplitude ².

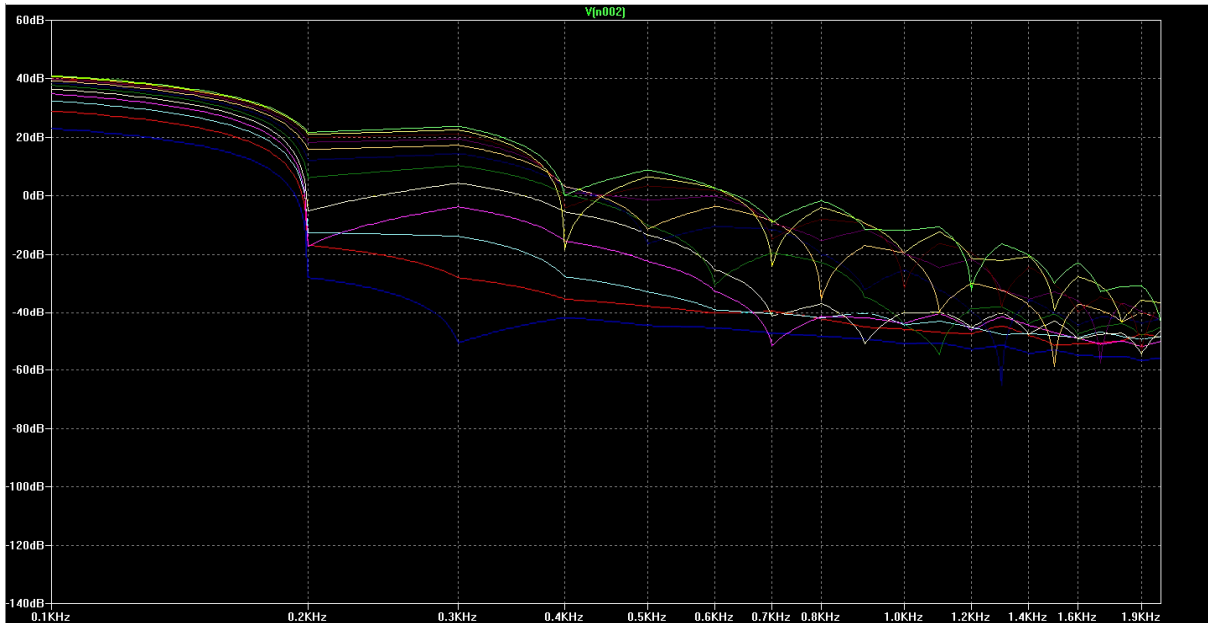


Fig 2b: Spice Fourier analysis of the harmonics produced by the waveforms of Fig 2a above. Each vertical grid marker is at a harmonic frequency.

As one can see the biasing is set at approximately 120v of the available 300v output.

Triodes can also be biased in a cold mode and the output waveforms take on a compressed and very asymmetric structure, see Figure 3a below.

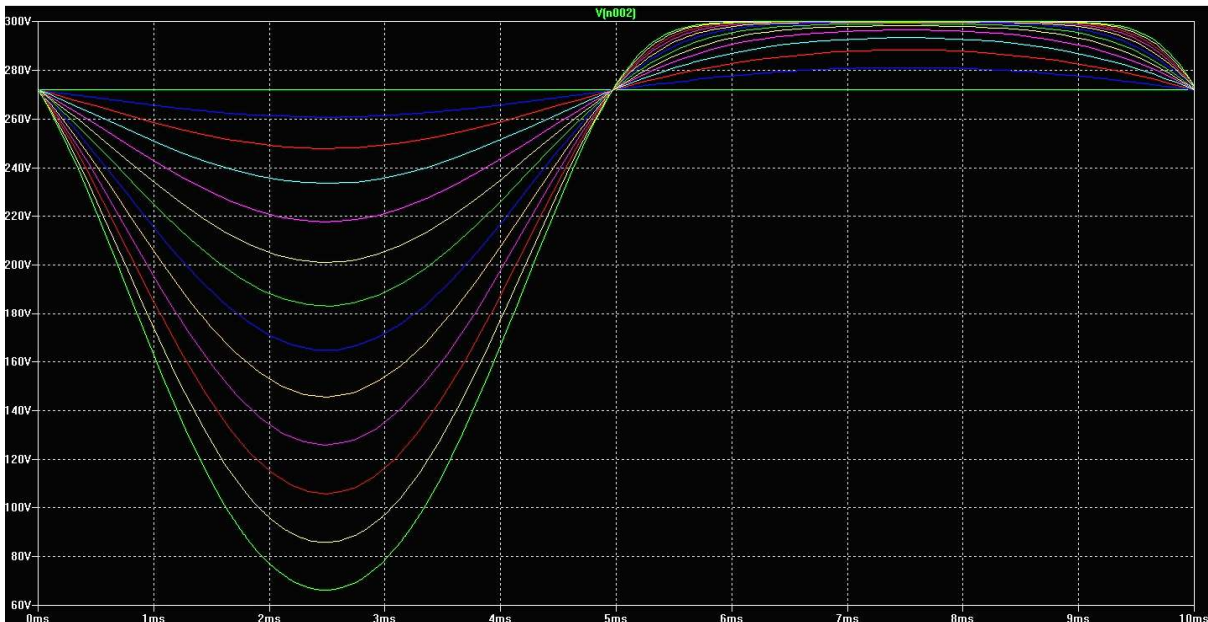


Figure 3a: Spice simulation of a cold based triode. Showing extreme compression in the upper half of the waveform and very off-centre (cold) biasing.

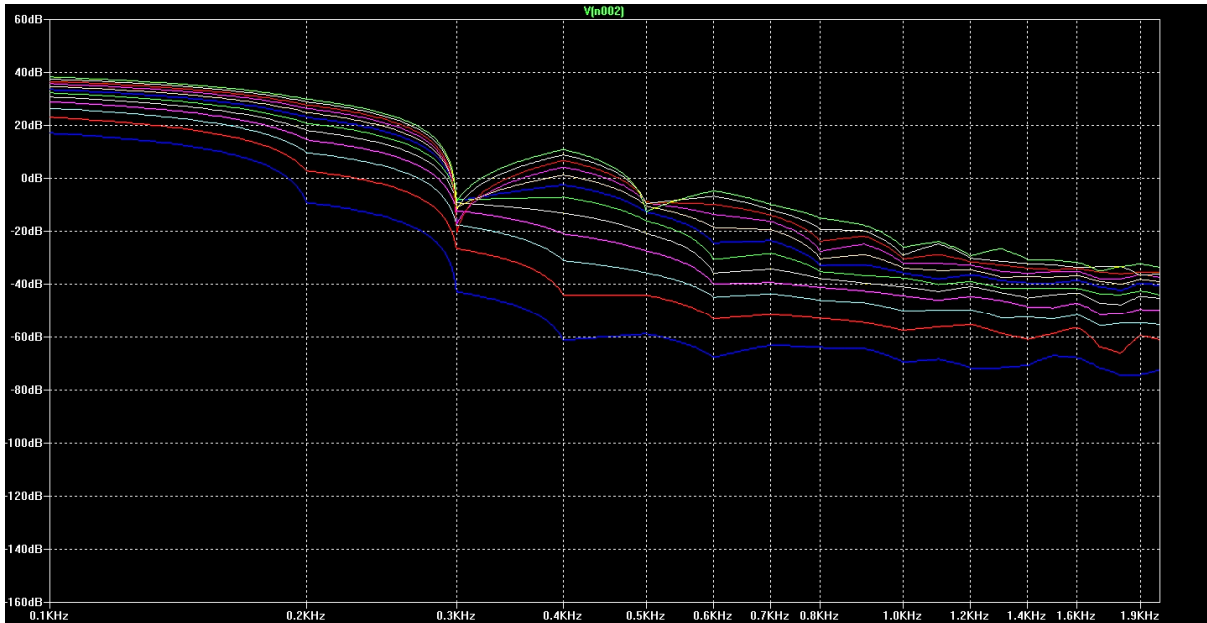


Figure 3b: Spice Fourier analysis of the complex cold-biased harmonics from Figure 3a above. Each vertical grid marker is at a harmonic frequency position.

OK, so now we've seen what the triode does to enhance and sweeten our guitar signal and also we know that the simple triode amplifier is used in the majority of manufacturers' guitar amplifiers therefore we need to see how the simple JFET Common Source Amplifier as used in Piet's eTap2hw motherboard can be made to follow or approximate this triode behaviour.

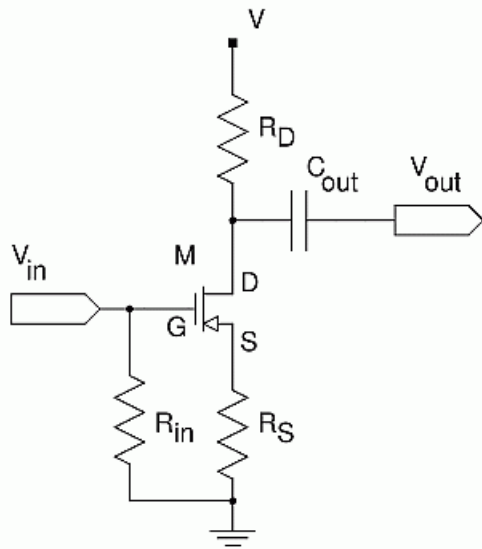


Figure 4: The simple Fetzer JFET Common Source Amplifier similar to that used in Piet's eTap2hw motherboard.

Dimitri Danyuk ¹ produced a complex mathematical paper describing ways of emulating the triode behaviour. Some of these ways were far too complicated to consider for the DIY constructor consisting of, for example, several JFET transistors and as many as 19 operational amplifier stages. However, what became apparent, as one began to understand the maths, was that there was a

relatively simple way to change the normal JFET transistor square law transfer to one approaching the triode 3/2 law mentioned earlier. Danyuk¹ deduced that, by careful calculation and selection of the source resistor for a JFET whose parameters are accurately known, this 3/2 law would follow for a limited range of input voltage. The RunOffGroove³ website produced a calculator such that, if you know the JFET pinch-off voltage and saturated drain current, you can enter these along with the applied voltage (9v or close in the case of Piet's eTap2hw) and the optimum source and drain resistor values will be calculated. However two problems were discovered, firstly a small part of Danyuk's math was slightly incorrect and "cold" biasing to generate the necessary compression was lacking. The maths problem was rectified to correct Danyuk's K-factor from 0.83 to the proper 0.8409 and this is presented below in the form of a graph showing normalised input voltage versus transfer exponent, Figure 5.

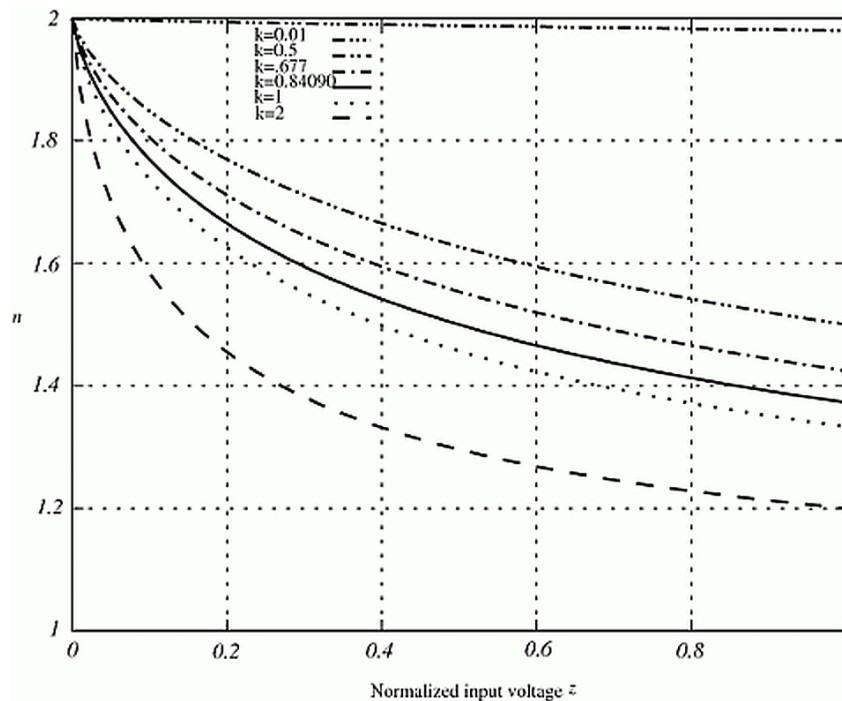


Figure 5: Normalized input voltage (Z) versus Transfer Exponent (n)⁴.

Examining the solid black line representing Danyuk's K-value 0.8409 it can be seen immediately that it holds close to the "magic" 3/2 or 1.5 exponent for the largest range of input voltage. Thus this biasing and calculation of the "magic" source resistor gives us the best chance of producing triode-like harmonics. It's also easy to see from this graph why eTap2hw users refer to the "sweet spot" of the input level control as a correct setting ensures the proper value of input to follow the k=0.8409 curve. The diagrams below show input sine wave, output waveform and harmonics generated (courtesy J.C.Maillet).

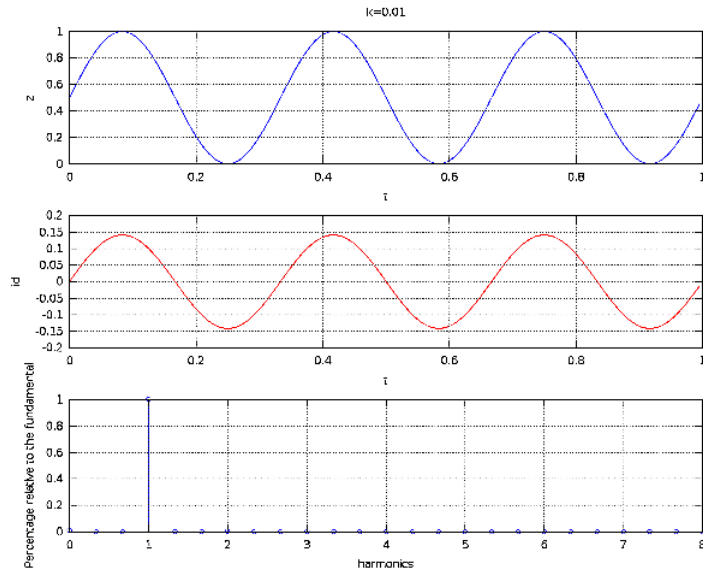


Figure 6a: Incorrect biasing gives $k=0.01$ which is too low to generate a “distorted” waveform hence no harmonics.

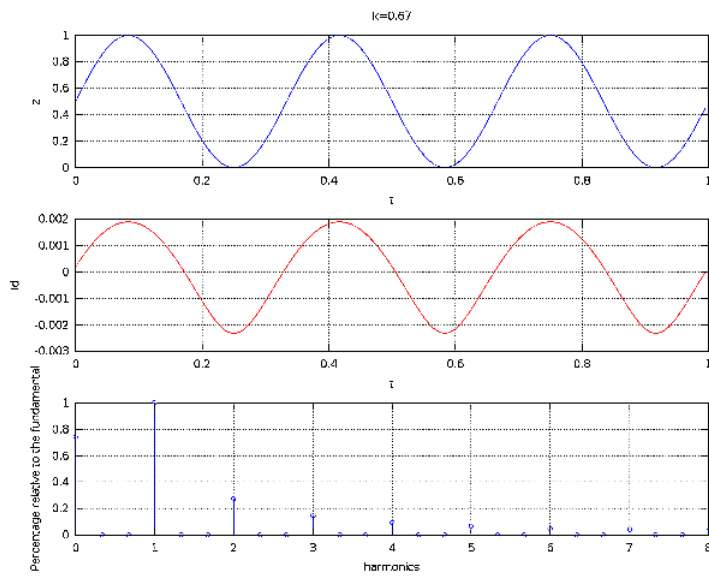


Figure 6b: Now $k=0.67$ is approaching our ideal k factor. Here waveform distortion and slight compression is beginning.

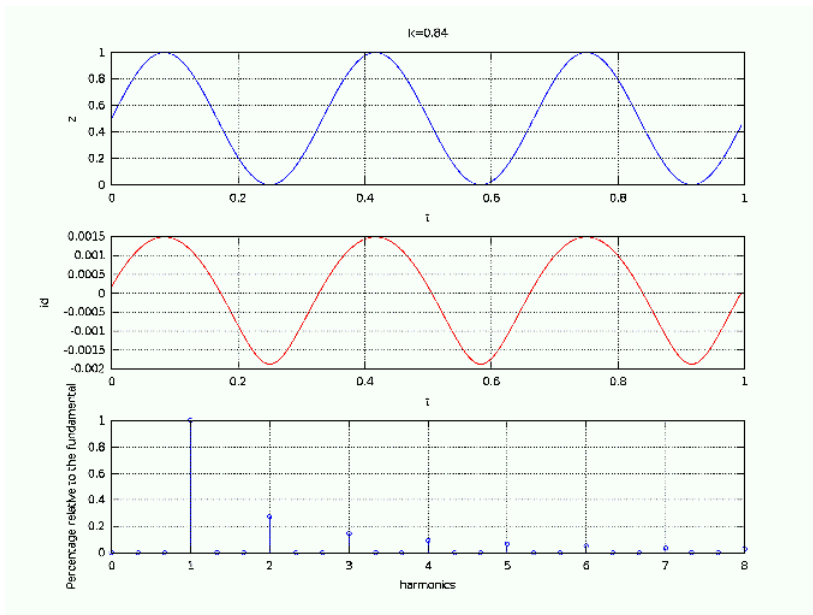


Figure 6C: $k = 0.84$ ideal and waveform shows compression, asymmetry and harmonics.

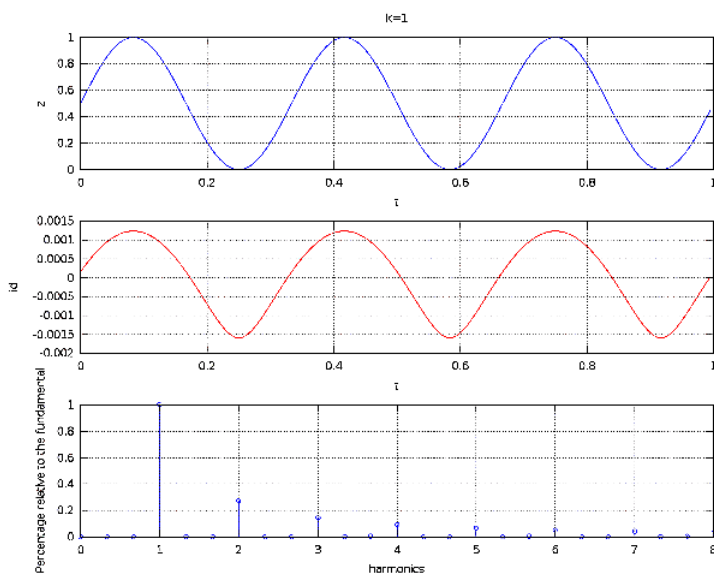


Figure 6d: Even when exceeding the ideal k value at $k = 1$ there is still some compression and harmonic generation. This proves that the JFET amplifier is suitable as a triode-like emulator solution and has a reasonable tolerance.

By following the Workshop bulletin on Piet's Echotapper blog⁵ to set the JFET biasing more accurately than when using the standard supplied 6k8 drain and 2k2 source resistors, the near to ideal k -value can be set. The Workshop bulletin also shows how to raise the drain terminal biasing to approximately 66% of V_{cc} and ensure that more compression will occur for a given input voltage so further approximating the triode "cold bias" ideas.

Several eTap2hw users have now successfully followed this biasing and also taken advantage of the white noise reduction techniques with pleasing results.

To finish here, Figure 7, is an oscilloscope image of a J201 JFET in Piet's motherboard (red trace ~60% bias), which looks as it should. Note: now that extra work has been done on Piet's gain stages to further improve JFET gain then harder clipping and enhanced harmonics are available should you wish to employ the modifications with the added bonus of reduced noise. Again see the Workshop Bulletin, Number 5, on Piet's Blog for details. Below are a few paragraphs to help understand how triode and JFET harmonics add their pleasing musicality.

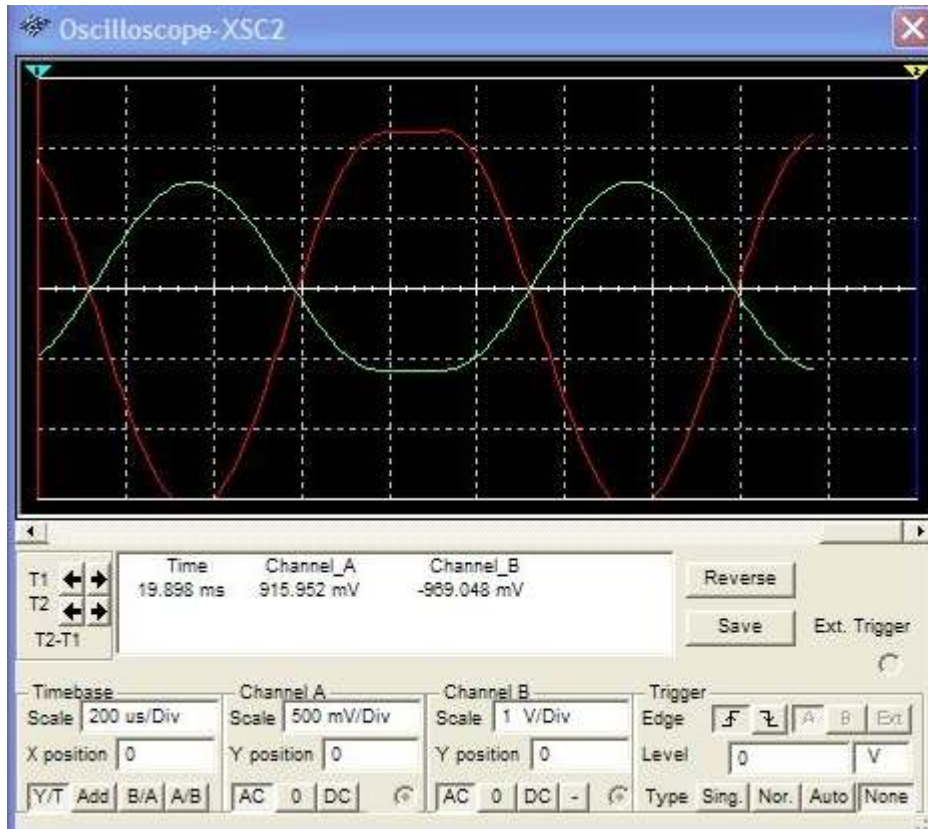


Figure 7: J201 output signal trace from Piet's motherboard for a 500mV 1kHz sine wave input.

A further design improvement is on the way in the form of a new circuit containing four FET stages with adjustable "harmonics" drive and input volume to further enhance harmonics' production.

Understanding Harmonic Distortion in Triode or Well Constructed JFET Amplifier Stages.

It is necessary when trying to understand the musical tone of a distorted waveform to realise that clipping a waveform, i.e. removing the peaks of that waveform, is just the same as superimposing several other waves on top of the original wave. If you could manually superimpose the correct waves on top of each other that would be the same as you hear from a clipped waveform (it is worth thinking about analogue musical synthesisers to help understand this fact). This is important to understand because the ear is able to analyze this waveform and break it back up into its constituent frequencies. Hence, it will hear notes superimposed on each other regardless of whether this was a synthetic waveform or a single waveform that was being clipped. In effect, extra notes are generated when the waveform is distorted. When examining a waveform, sharp edges such as the square wave corners are high MHz frequencies superimposed on the fundamental, kHz range, frequency(ies). So perhaps we should think of the original valve guitar amplifiers of the 1940s onwards as “musical tone generators”. Hence the effort to make Piet’s JFET stage “come to life” and sound as musically correct as possible, similar to the Valve powered Meazzi echo machines of the 1950s/60s that it emulates so well.

The fundamental frequency of the wave is not changed by clipping and represents the most dominant note, so the original note can always still be heard. The way in which clipping occurs means that all the new notes produced must be harmonics of the root note, there is simply no way to produce other frequencies than this simply by clipping a single waveform. E.g. clipping a 330Hz signal can produce frequencies of 660, 990, 1320 up to 13.2 kHz and so on, but it cannot produce notes in between these multiples. So here we have a useful tool allowing the ability to predict the extra notes created by distorting the fundamental note and work out whether or not they will sound good when mixed with the fundamental note; we already know from scales, keys, chords that some notes sound good together.

Now we can see that the harmonics produced in clipping are the major factor of good and bad sound, i.e. what sounds musical to us or not. Certain harmonics will fit together musically while others do not. It’s the effect that these harmonics have on guitar amp tone and on the timbre of musical instruments in general that makes for a pleasing sound experience, e.g. even order harmonics are more than often the same fundamental note which is repeated in octaves

So to sum up, the JFET amplifier stage in Piet’s eTap2hw, when correctly biased, will add significant warmth because the transfer curve shape is correct especially for those of us with solid-state amplifiers. The lucky owners of valve amplifiers should already benefit from the triode 1st stage as even clean valve amplifiers will generate significant pleasant harmonic content, e.g. even order harmonics are often the same note in different octaves, e.g. 2nd, 4th, 6th, 8th harmonics of A2 (110Hz) are A3 (220Hz) A4 (440Hz) E5(660Hz) and A5 (880Hz). As you can see these fit together

beautifully in for example an open A chord where the E fits with all the A harmonics etc. In general, the low order harmonics dominate the slightly overdriven tone with the lowest 2nd and 4th harmonics dominating hence the pleasing musical “correctness”. Even if you have a valve guitar amplifier there is benefit to be gained from correctly biasing Piet’s JFET to ensure generation of musical even order harmonics.

Stephen C Mitchell April 2014

References:

Many sources of information have been used to formulate the JFET amplifier and operational amplifier modifications to the eTap2hw motherboard some of these are given below.

1. D.Danyuk, “Triode Emulator”, The Audio Engineering Society preprint 6008, presented at 116th AES Convention, 2004, May 8 – 11, Berlin, pp. 1-8, reprinted in 23 Tonmeistertagung VDT Int. Audio Convention Proceedings, 2004, Nov. 5-8, Leipzig, paper PS-01.
2. Matt’sBlog o’ Stuff: http://matthelyar.blogspot.co.uk/2011_06_01_archive.html
3. <http://www.runoffgroove.com/fetzervalue.html>
4. <http://www.diale.org/triode.html>
5. eTap2hw Workshop Bulletins: <http://www.echotapper.nl/wp/?p=1584>