Intermodulation Distortion

Pete Millett

ETF.19

Agenda

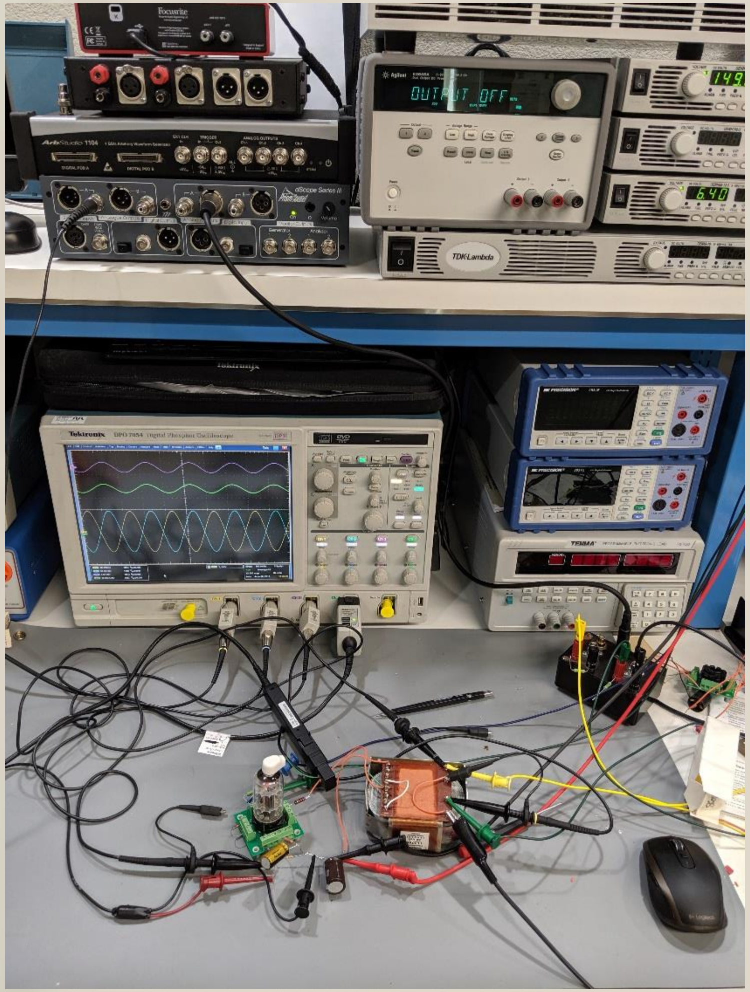
- A little biography
- What is intermodulation?
- Single-ended triode amplifier transfer functions
- Two-tone waveforms and FFTs
- A special case: filament hum IMD
- Listening demo

Biography

- I've been coming to ETF since 2003
- I've been an Electrical Engineer for almost 40 years, live in Colorado, USA and work from a lab in my home
- Mostly a board level hardware guy in consumer and computers, but I've spent the last 15 years working for semiconductor companies
- Have a hobby business doing DIY audio stuff

www.pmillett.com

pmillett@hotmail.com



So, what is “Intermodulation Distortion”?

What is “intermodulation”?

- In an ideal circuit, if you pass two single-frequency tones in, you get only those two tones out
- Nonlinearities in a circuit cause the two signals to affect – or modulate – each other
- The result is that there are tones in the output that were not at the input
- The unwanted tones – intermodulation products – are mathematically related to the input tones

Why do we care?

- We don’t usually listen to tones
- Music is a very complex signal
- However, you can imagine that the sound of one instrument might intermodulate with the sound of another
- Think of a loud bass note and a flute
- Generally IMD “muddies up” the sound or makes it sound harsh
- IMD measurement is regarded as a more telling benchmark than THD measurements

Distortion in a simple triode amplifier

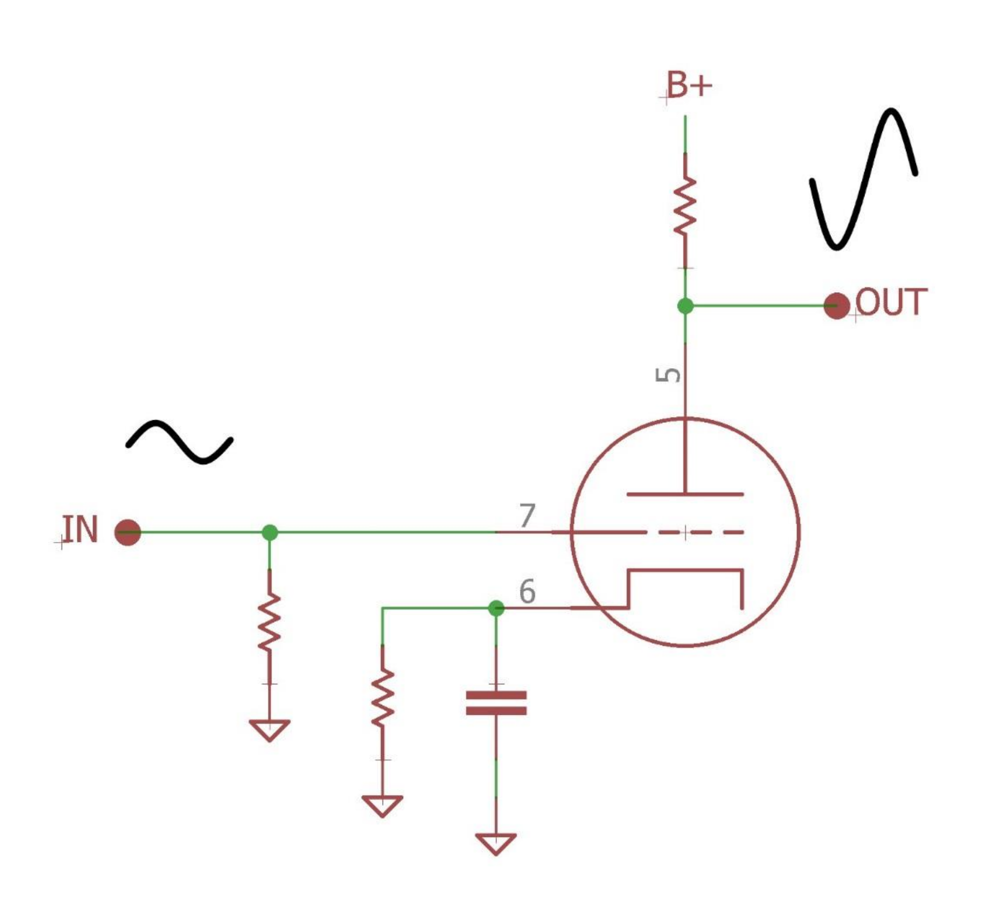
A simple single-ended triode amplifier

- In a simple grounded cathode triode amplifier, the output signal is an inverted, larger version of the input signal
- Ideally,

$$V_{OUT} = -V_{IN} * A + DC$$

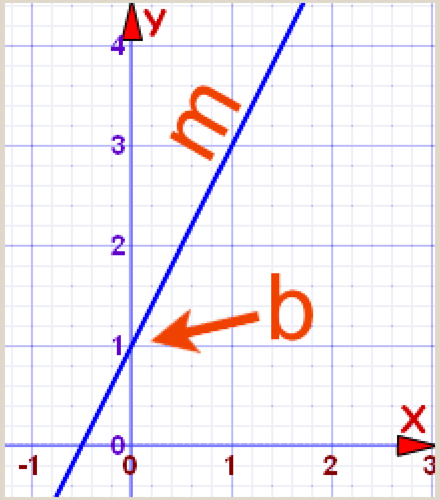
Where A = voltage gain, and DC = the static plate voltage (bias)

- Note that this is a simple linear equation: y = mx + b. Remember high school algebra?



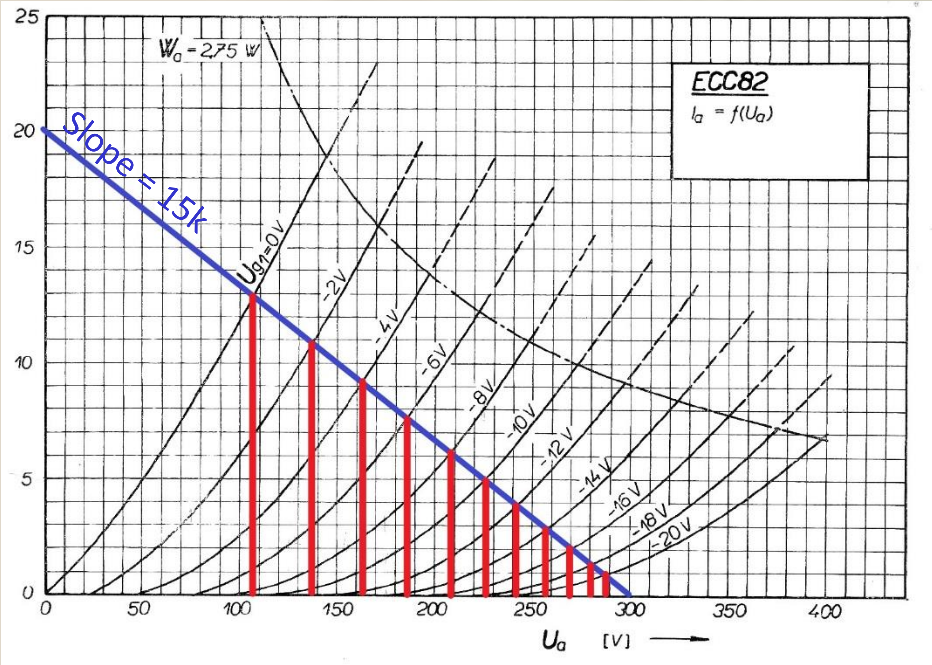
Transfer functions

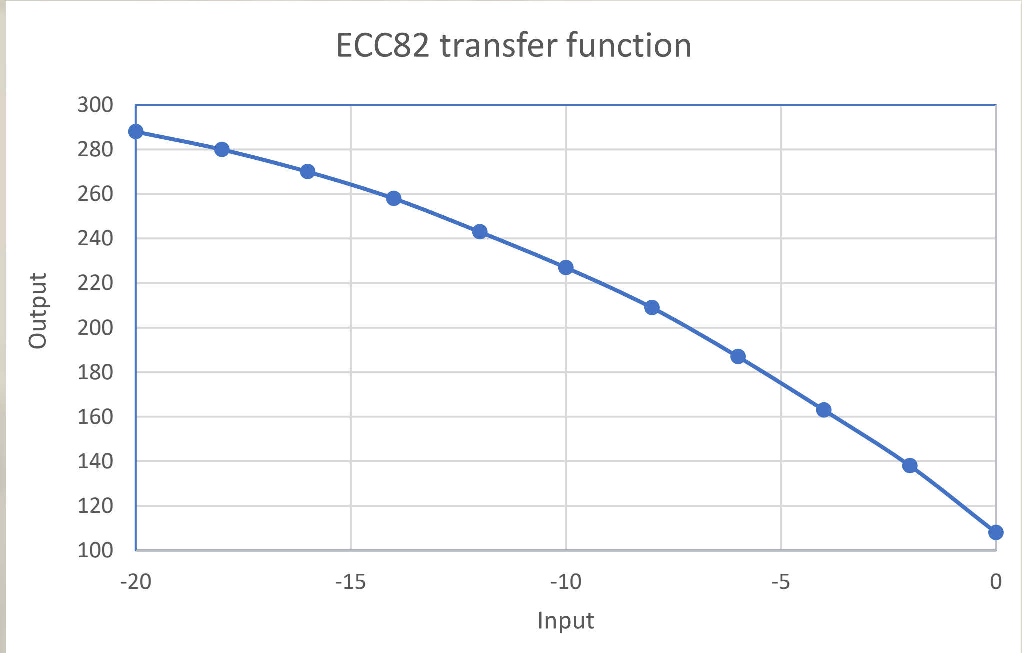
- If we make a graph of an ideal amplifier's output vs. input, we get a straight line, whose slope is the gain of the amplifier
- When we talk about "nonlinearities", it is any deviation from this straight line that we are talking about – NOT the shape of the plate curves (though they are related, as you will recognize with experience)
- You can easily construct the transfer function of a simple resistive loaded triode from the plate curves
- Linearity varies dramatically for a given triode with differing operating conditions (bias point and plate load impedance)



Transfer function of a real triode

- This is an ECC82 with a 15k plate load resistor

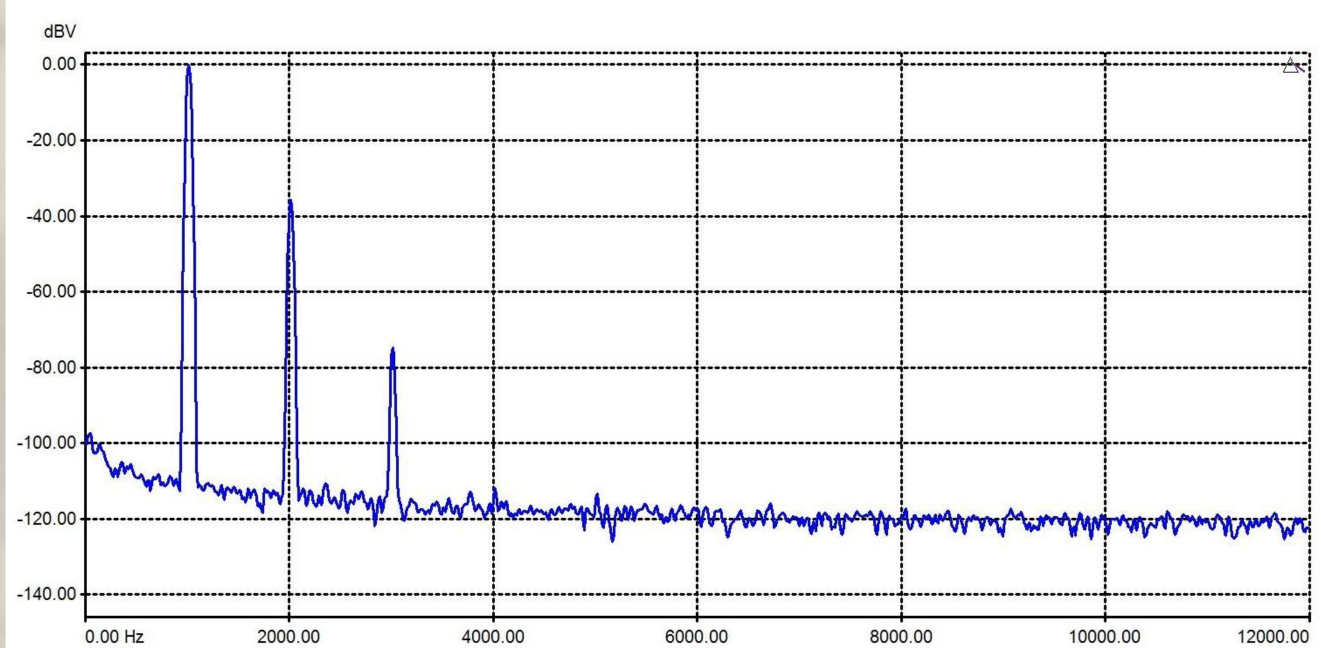




Not a straight line! This is nonlinearity.

Single tone: harmonic distortion

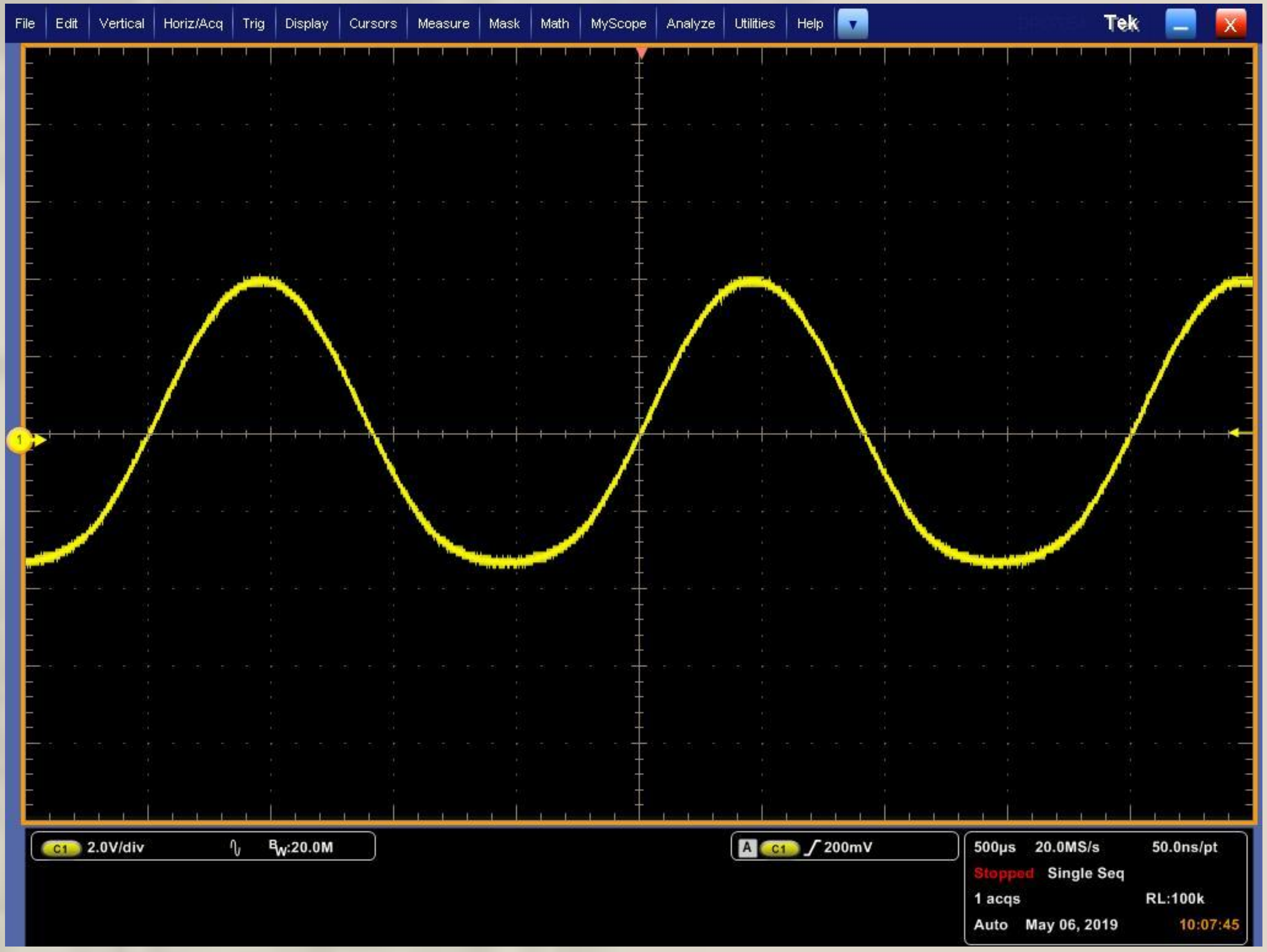
- When you apply a single frequency tone to this (not so linear) single-ended triode amplifier, you get harmonic distortion products
- An FFT (Fast Fourier Transform) plot will show the distortion products, at multiples of the input frequency
- For more on harmonic distortion and FFTs, look up my ETF.04 presentation: http://www.pmillett.com/etf_sod.htm



Waveforms and FFTs

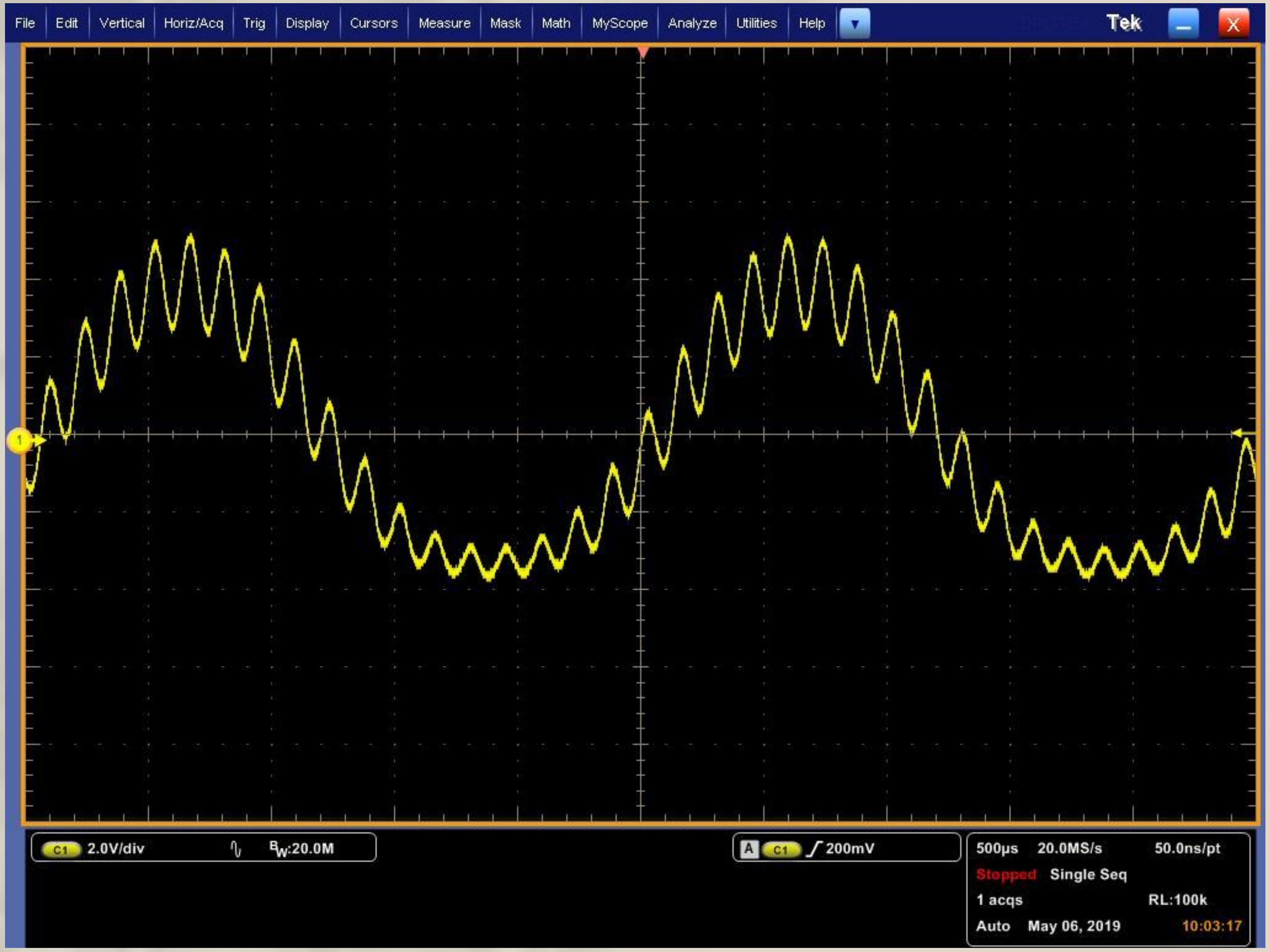
A bad amplifier

- Here is an oscillograph of the output of a particularly nonlinear amplifier, with a 400Hz input signal. You can see the asymmetry – this is mostly even order harmonic distortion.



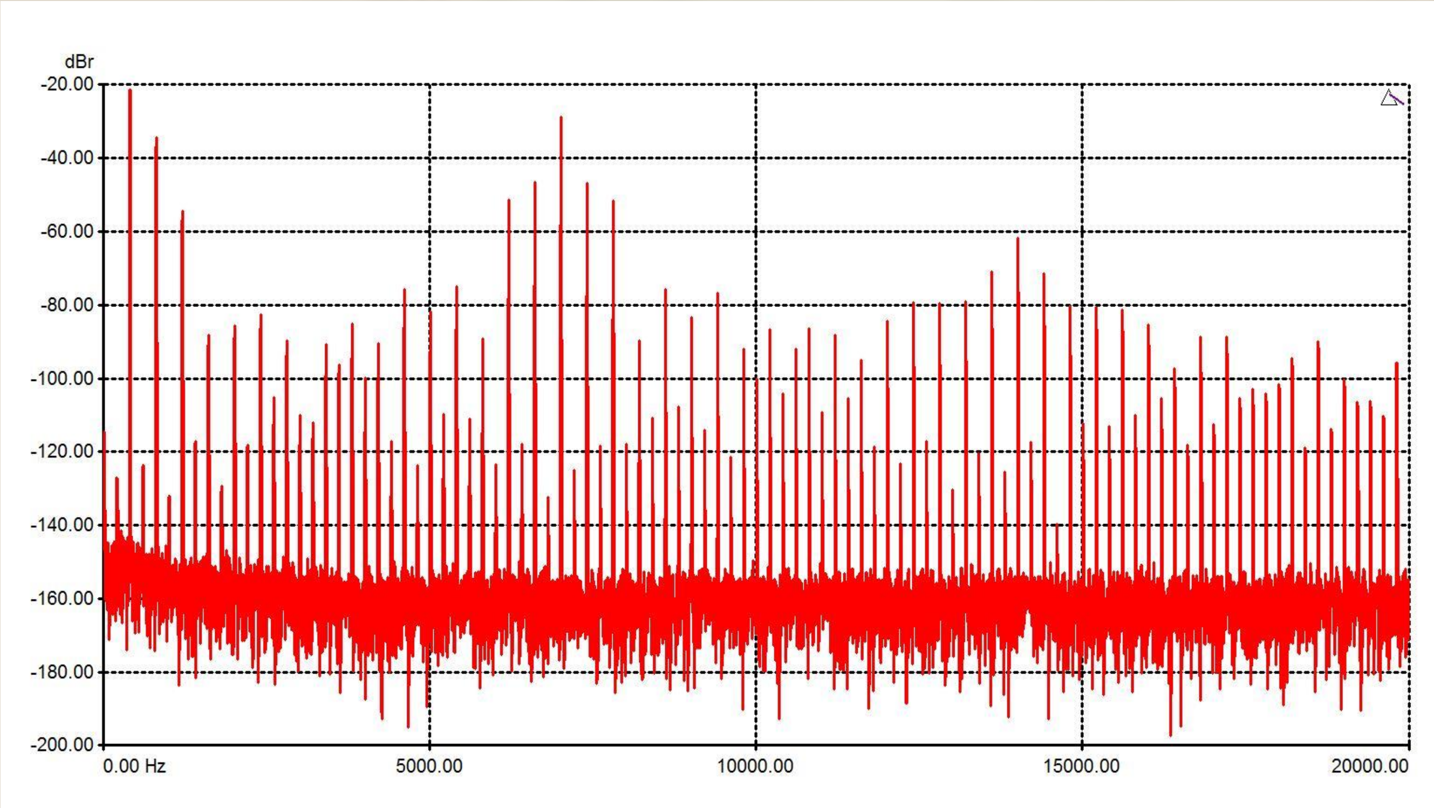
Two tones: intermodulation

- Here is an oscillograph of a this same nonlinear amplifier, with a two tone input (400Hz and 7kHz)
- The amplitude of the HF signal varies with the LF signal
- Any amplifier with harmonic distortion will also create IMD!



IMD in the frequency domain (FFT)

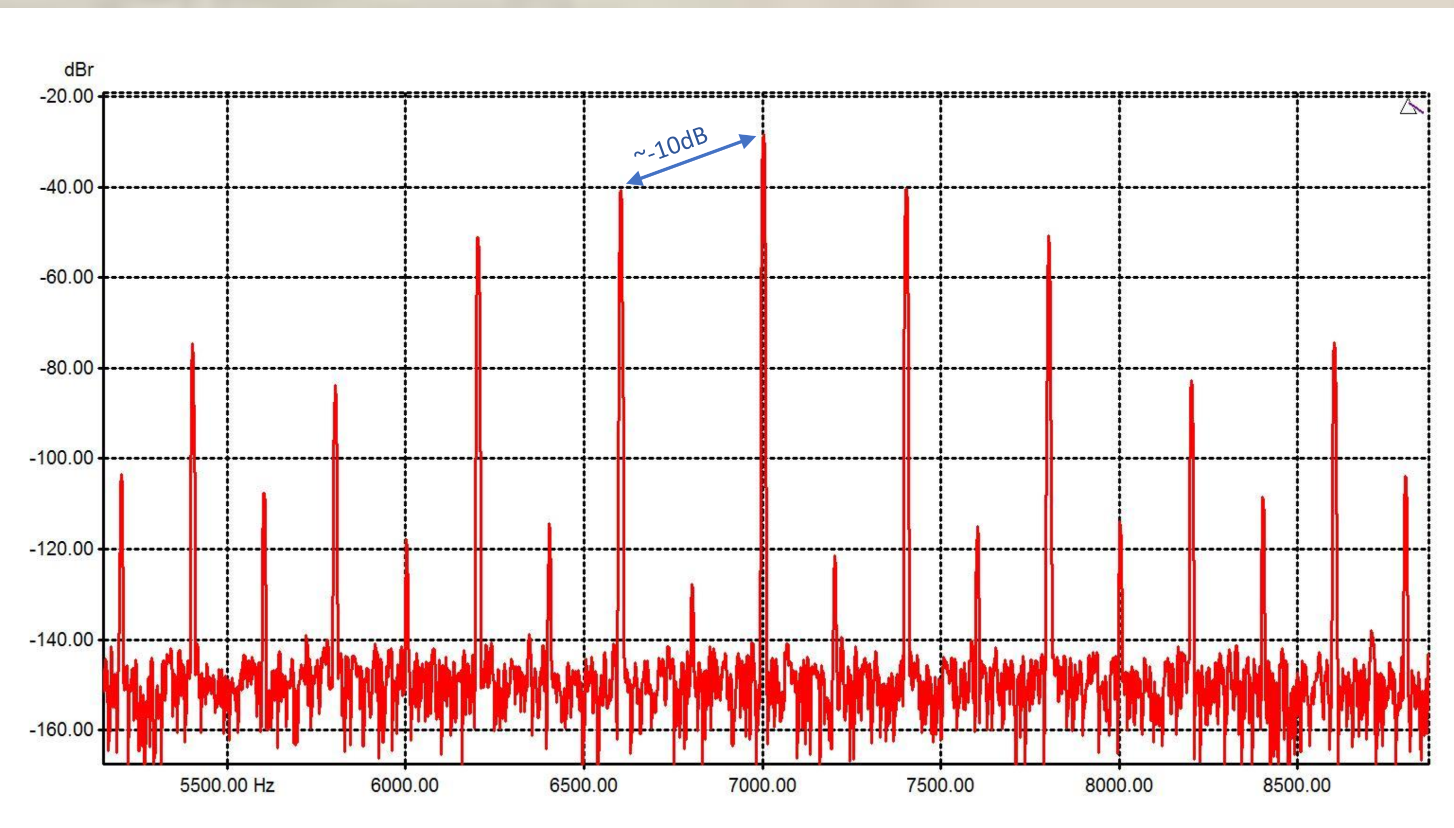
- Here is the same signal in the frequency domain (an FFT)



Not pretty!

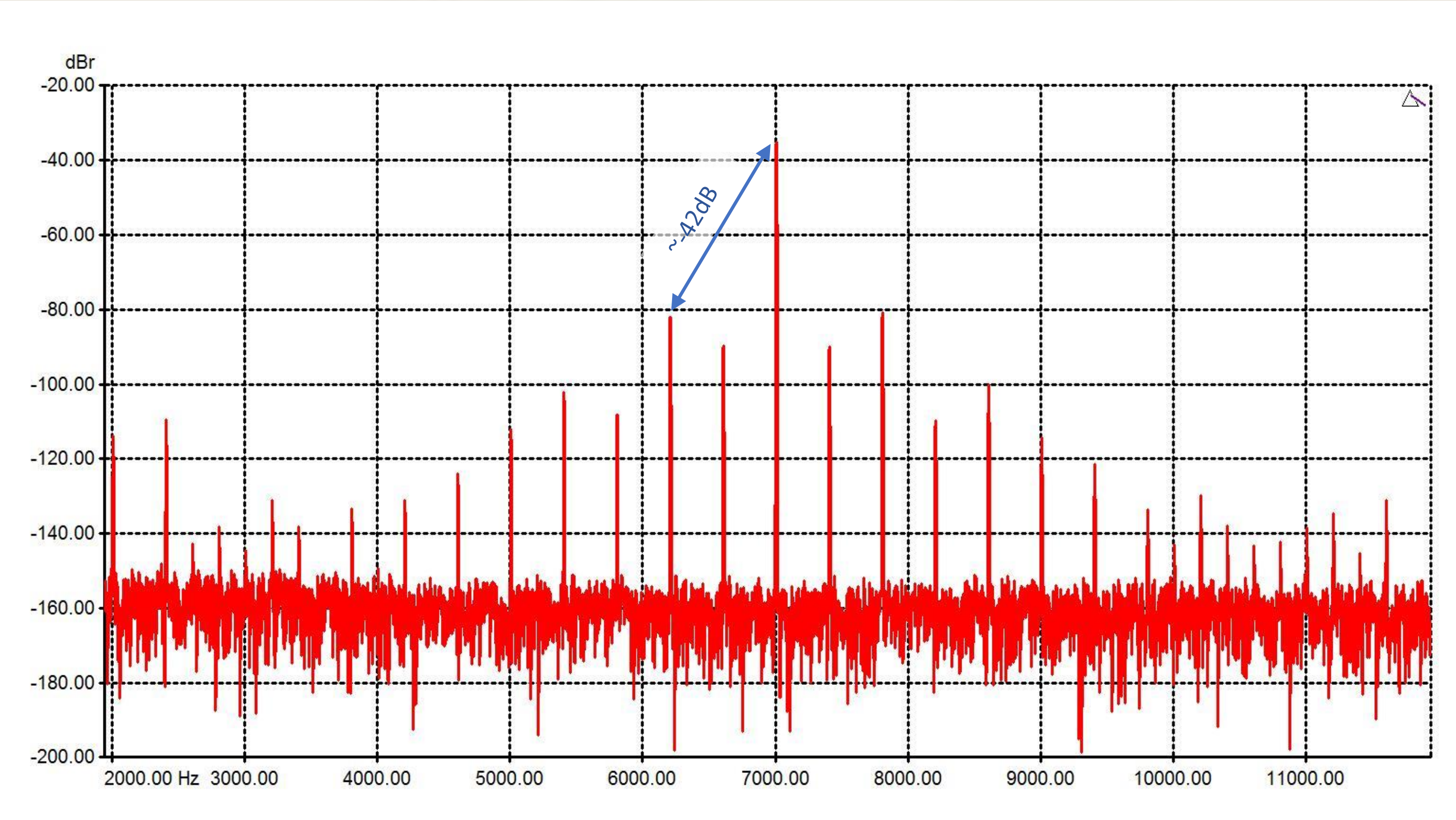
IMD in the frequency domain (FFT)

- If we zoom in on the 7kHz peak, we can see peaks – sidebands – at 400Hz intervals. These signals were NOT in the input, they were generated by the nonlinearities of the amplifier. These are intermodulation products.



Effect of operating conditions on IMD

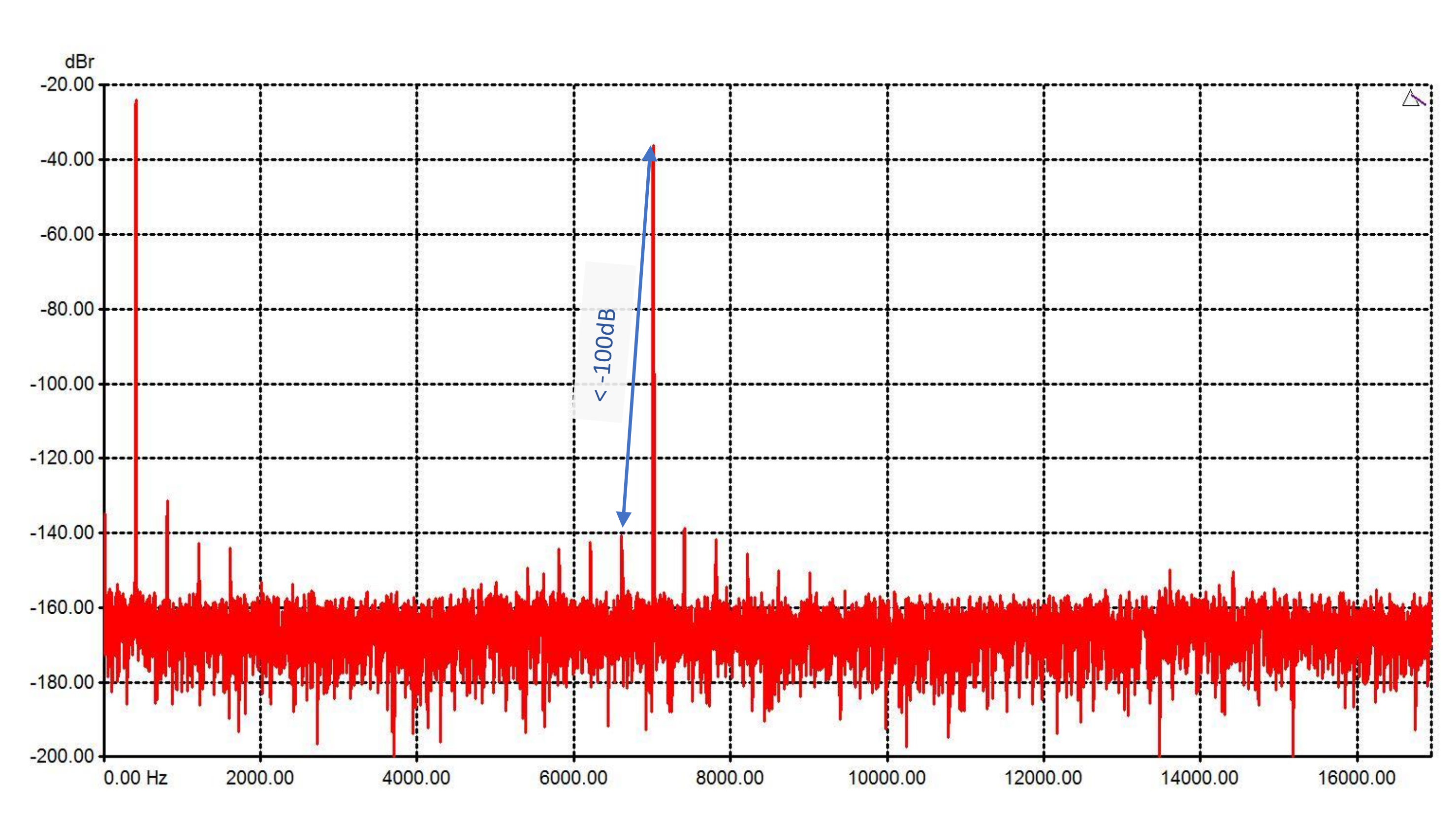
- If we re-bias this amplifier to a more linear region, things are better



Not as bad!

What we really want

- This shows what you see in an FFT with very low IMD

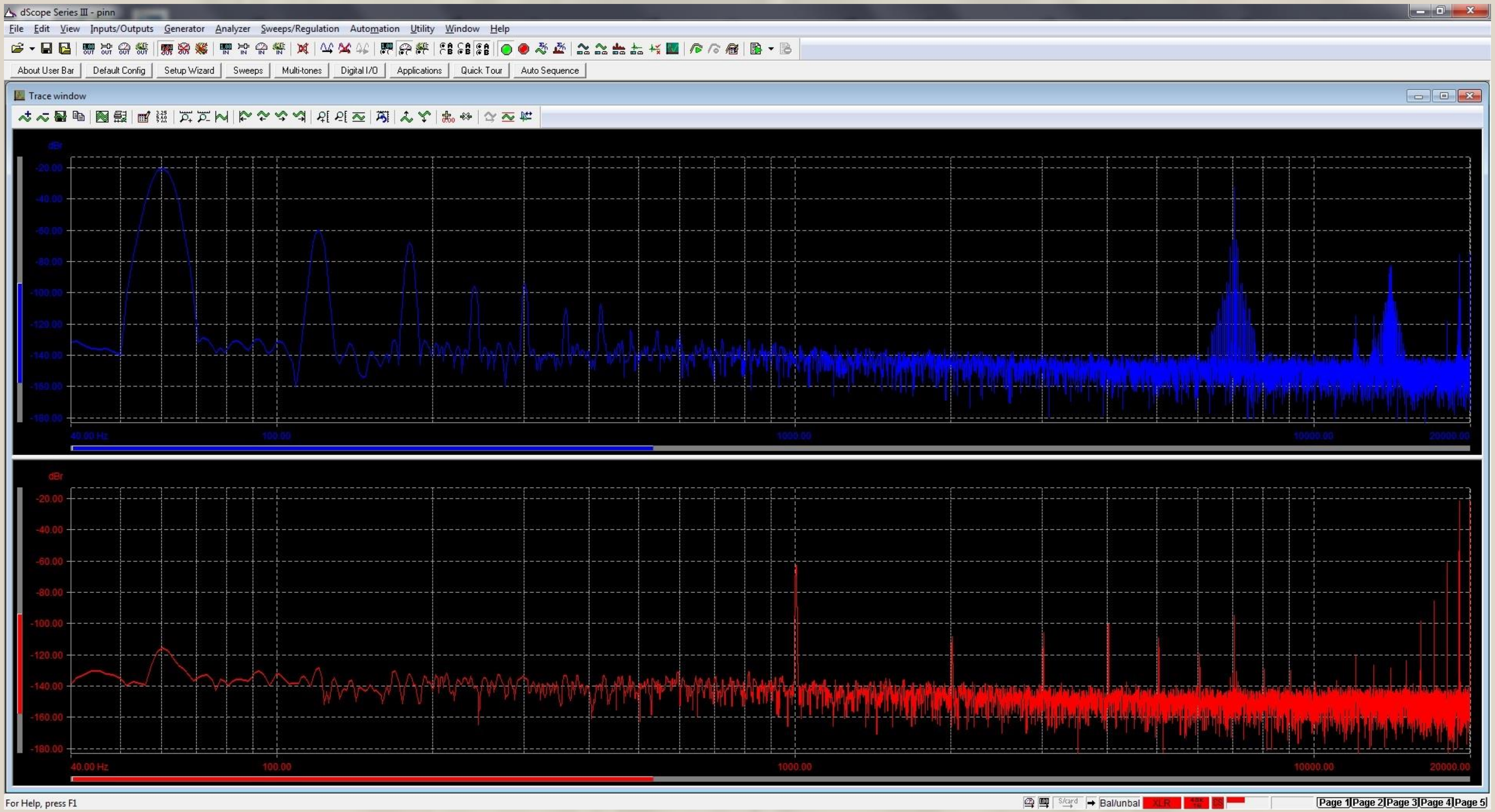


Cheating!

IMD measurement techniques

- Measuring IMD involves applying a two tone input signal, and measuring the amplitude of the undesired output products
- Any two tones van be used, but there are two main standards used: SMPTE and CCIF (also called DFD)
- SMPTE IMD measurements use a low amplitude high frequency signal and a high amplitude, low frequency signal, usually 7kHz and 60Hz at a 1:4 ratio, and the amplitude of 6940Hz and 7060Hz is measured
- CCIF IMD measurements uses two equal amplitude high frequency signals, usually 19kHz and 20kHz, and the amplitude of the resulting 1kHz product is measured

SMPTE and CCIF spectra



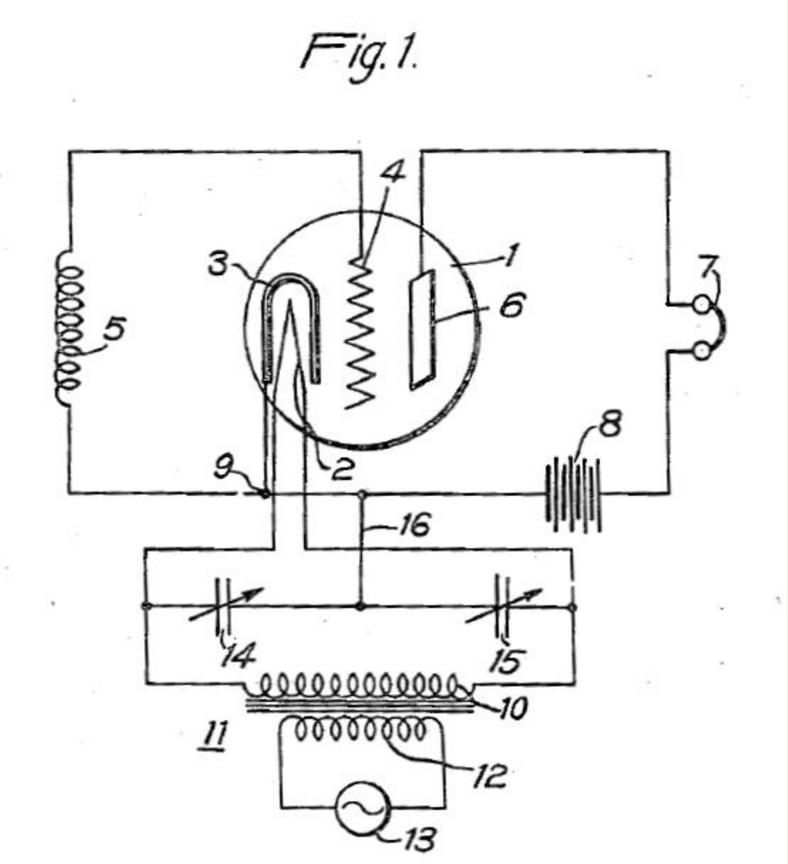
Hum Intermodulation

A special case: hum intermodulation

- “Hum intermodulation” is a phenomena that occurs in tube amplifiers – most severely in directly heated tube circuits when the cathode is heated with AC
- I believe there are three components of hum intermodulation: thermal modulation, filament asymmetry-related modulation, and IMD that is produced from hum coupled into the audio path
- Note that ripple on B+ will also intermodulate with the signal
- Reference works of Steph Bench and Dmitry Nizhegorodov:
  - http://diyaudioprojects.com/mirror/members.aol.com/sbench/humbal.html
  - http://www.dmitrynizh.com/filament-ac-freq.htm
  - http://www.dmitrynizh.com/filament-ac-harmonic.htm

US Patent #2,078,666 – 1937 – The IDHT

"The hum is due, in part, to the variation in temperature of the electron-emitting means and, in part, to modulation of the space current by the magnetic field surrounding the heater element. The hum is also due, to a great extent, to variations in the potential of both grid and plate with reference to the thermionic emitting element or cathode."

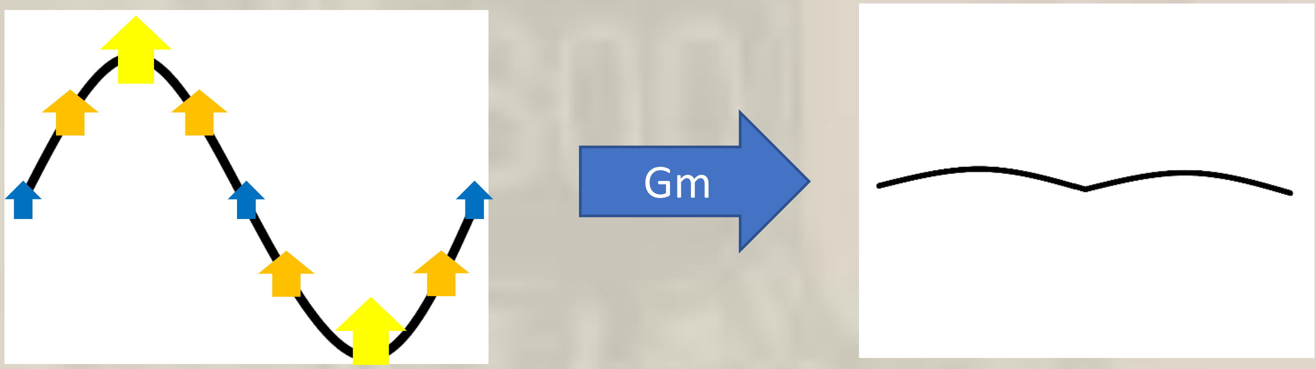


Thermal modulation

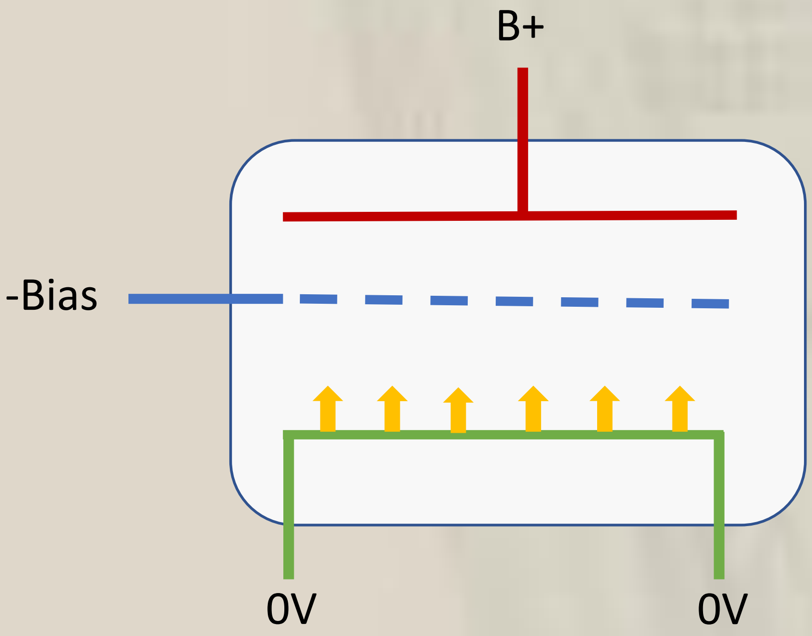
- When heated with AC, a filament is actually heating and cooling at twice the applied frequency
- The gain of a triode amplifier varies with the triode's transconductance, which varies with cathode emission
- When heated with AC, a filament has small changes of emission at double the AC heating frequency, as the filament heats and cools

However… this effect isn't that big…

It is worst with filaments with low thermal mass, which can heat and cool quickly. It is essentially non-existent with indirectly heated tubes.

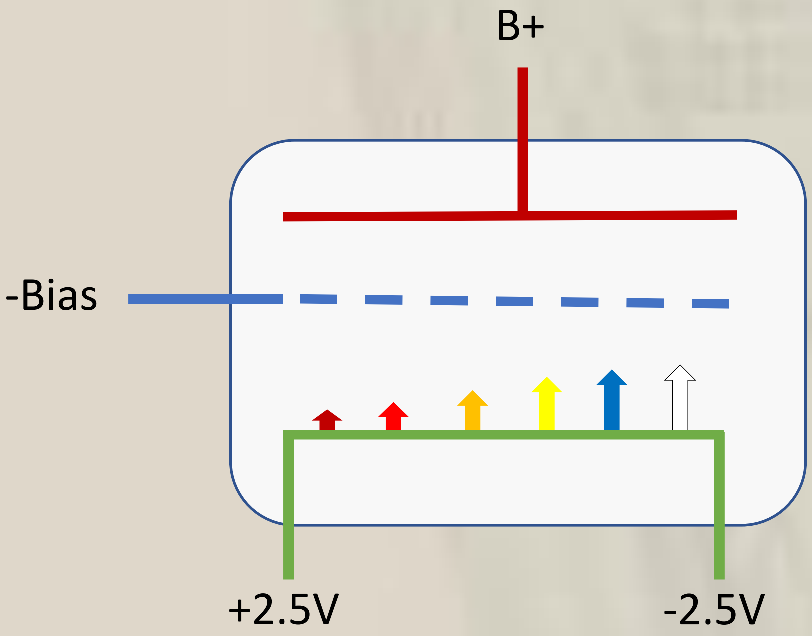


Filament emission



- When the filament is heated with AC, twice per cycle, both ends of the filament are at 0V (or at least at the same DC voltage)
- At this time, the voltage difference between every point on the filament and grid is equal

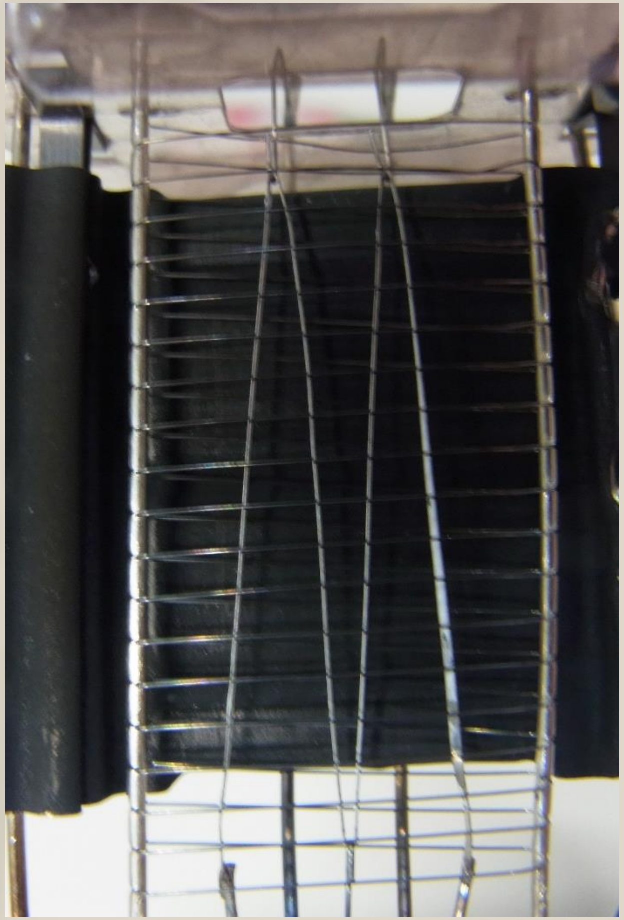
Filament voltage influences effective bias



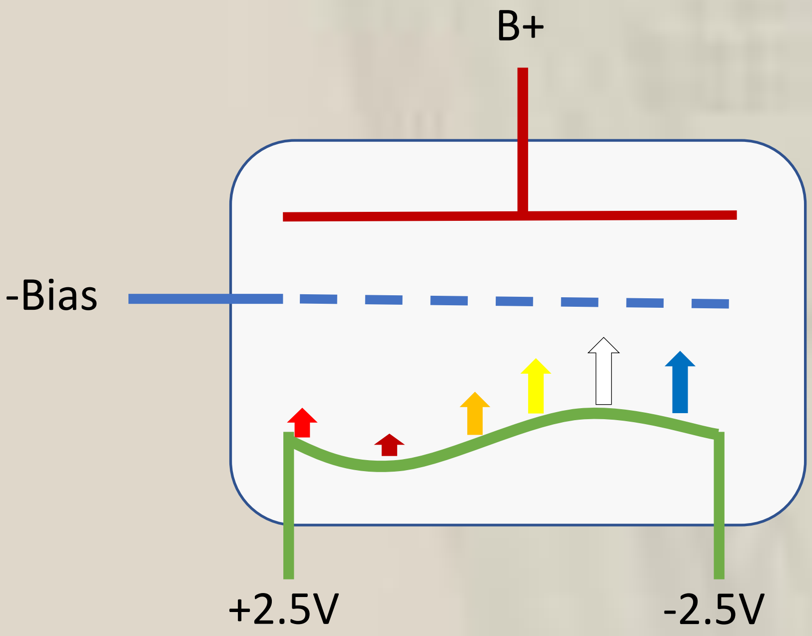
- As the voltage applied to the filament changes, so does the *relative* voltage between each part of the filament and the grid
- Effectively, the bias voltage is now different at different points on the filament, and one end emits more electrons than the other
- If the tube were perfect, the *average* grid-filament voltage should be the same throughout the AC cycle – and there would then be no hum from this

Tubes are imperfect!

- A real directly heated triode is far from perfectly constructed!
- Filaments are often not symmetrical top-to-bottom and not perfectly centered within the grid structure
- Some grid wires may be closer or farther from the filament on one end
- Emissivity may vary from one end of the filament to the other



The result: intermodulation



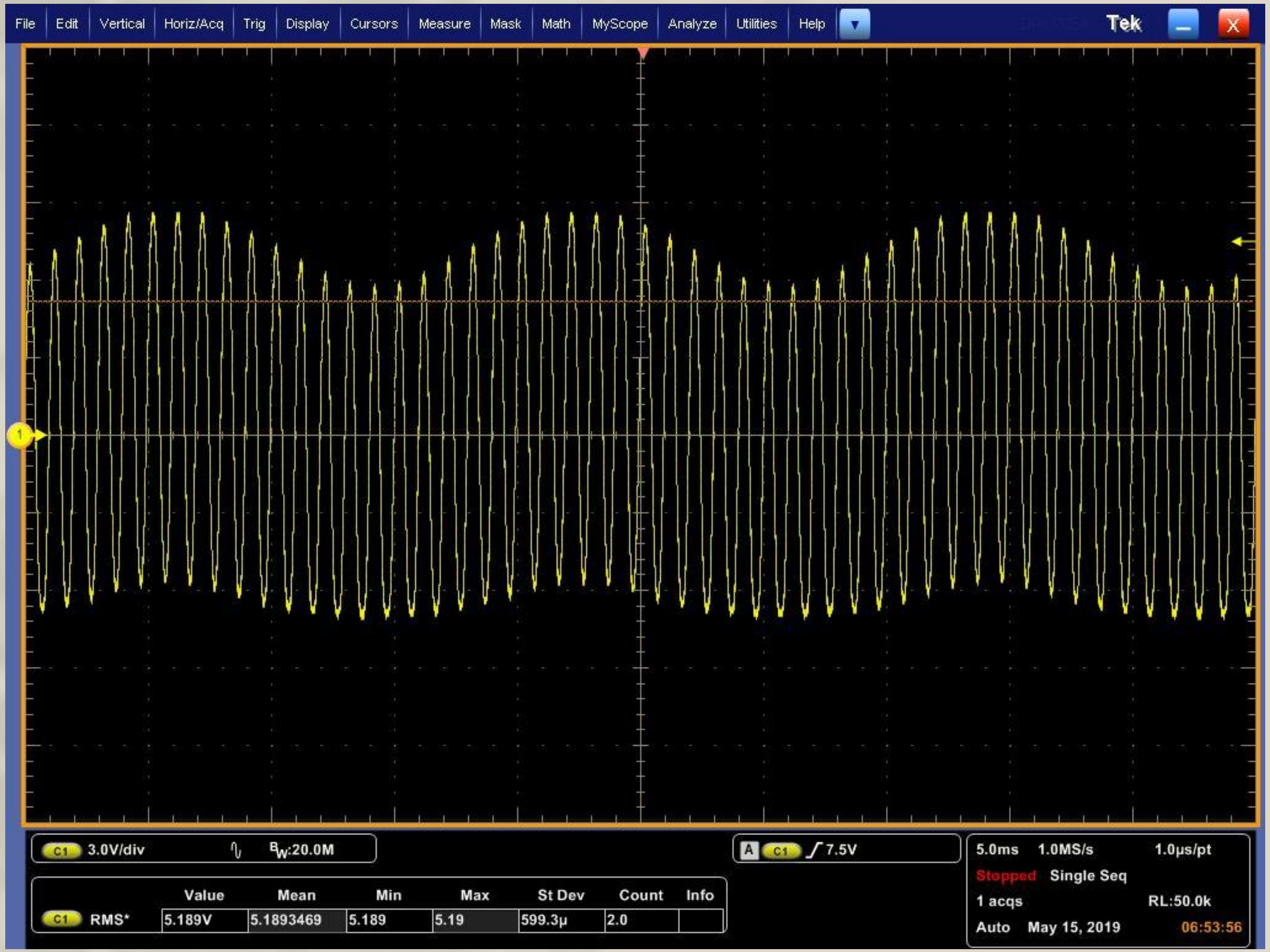
- Asymmetries result in varying emission at different points in the AC waveform
- The result is varying gm at different points in the waveform
- As before, this gm variation modulates the desired signal

Coupled-hum IMD

- Any line frequency interference that is coupled into the audio path will also intermodulate with the desired signal, due to harmonic distortion in the amplifier
- Coupling can be capacitive – like AC mains wiring run next to signal wiring – or magnetic, especially between power supply transformers or chokes and input or interstage transformers
- Ripple on B+ also causes this
- This is probably the main form of hum IMD in indirectly heated tube circuits?

Harmonic distortion induced hum IMD

- You can see the effect here. This shows a 1kHz signal with a huge amount of 60Hz hum.
- The amplitude of the 1kHz signal is being modulated by the 60Hz signal.

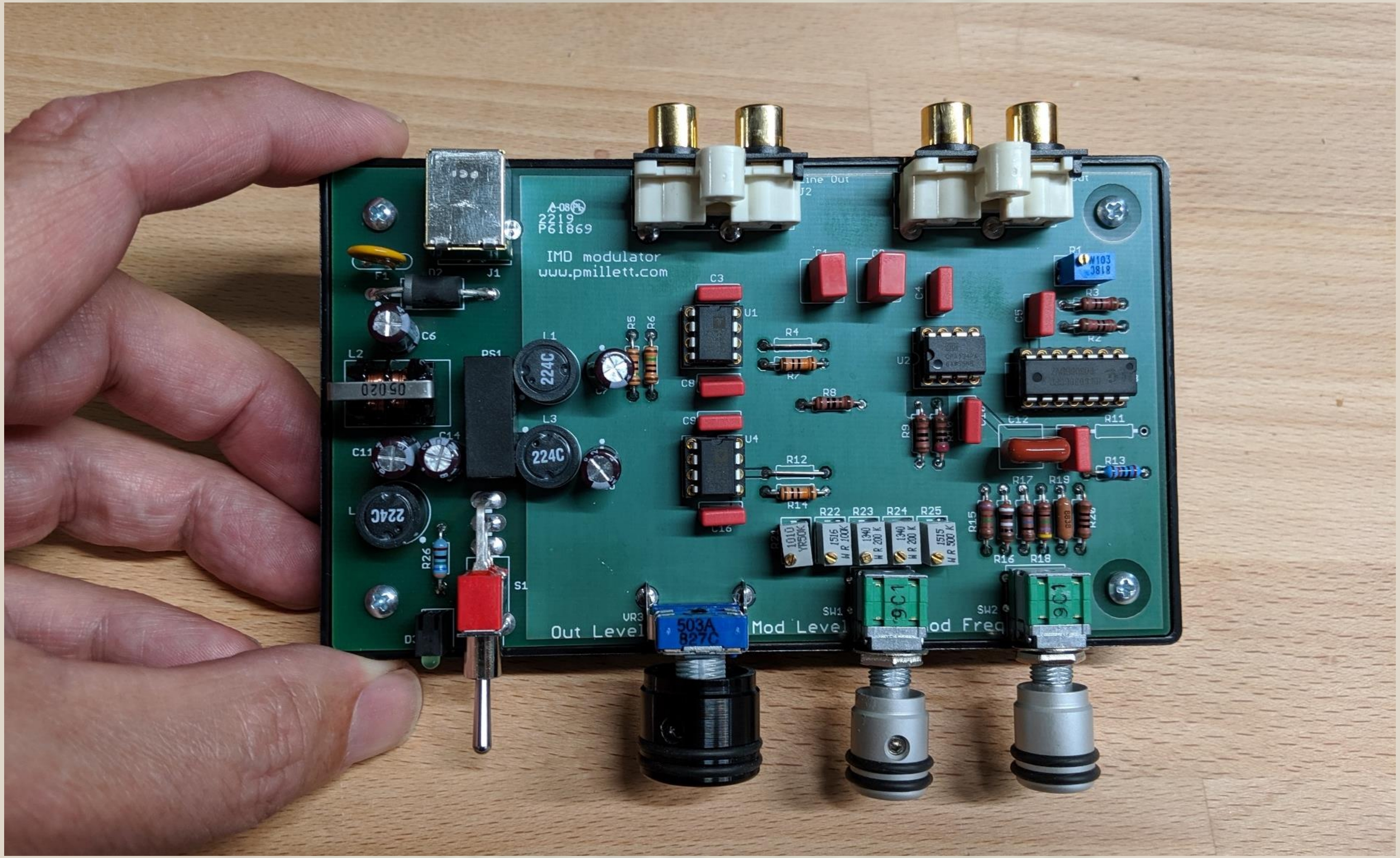


Let’s hear this distortion…

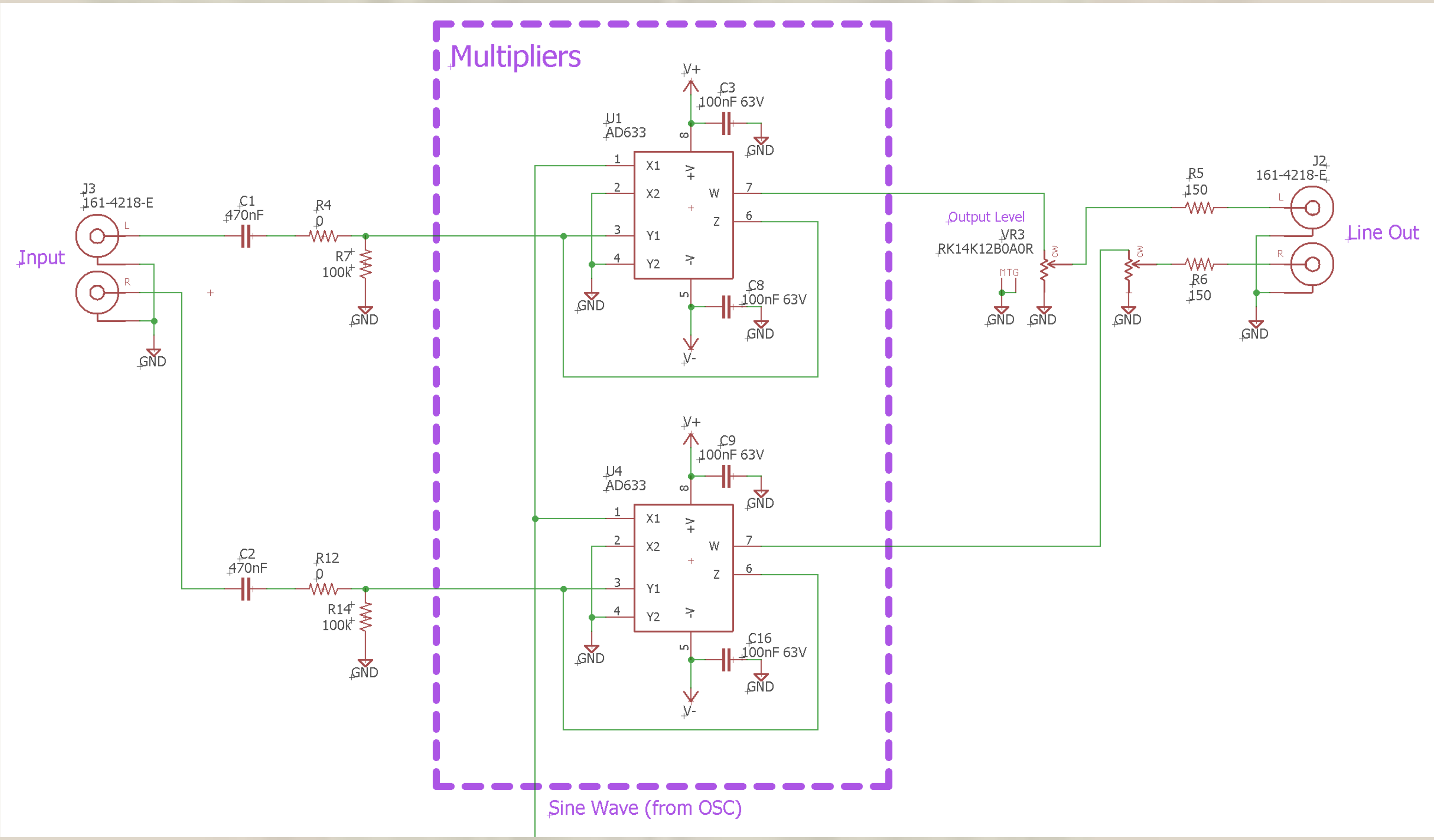
Listening demonstration

- I built a circuit to demonstrate IMD - especially hum IMD
- I hoped to be able to demonstrate this using a real triode, but the effects are too subtle. So I built a circuit that can generate extreme levels of IMD.
- The circuit uses multiplier ICs to amplitude modulate the music signal with an adjustable sine wave signal
- This generates pure IMD – and very little harmonic distortion

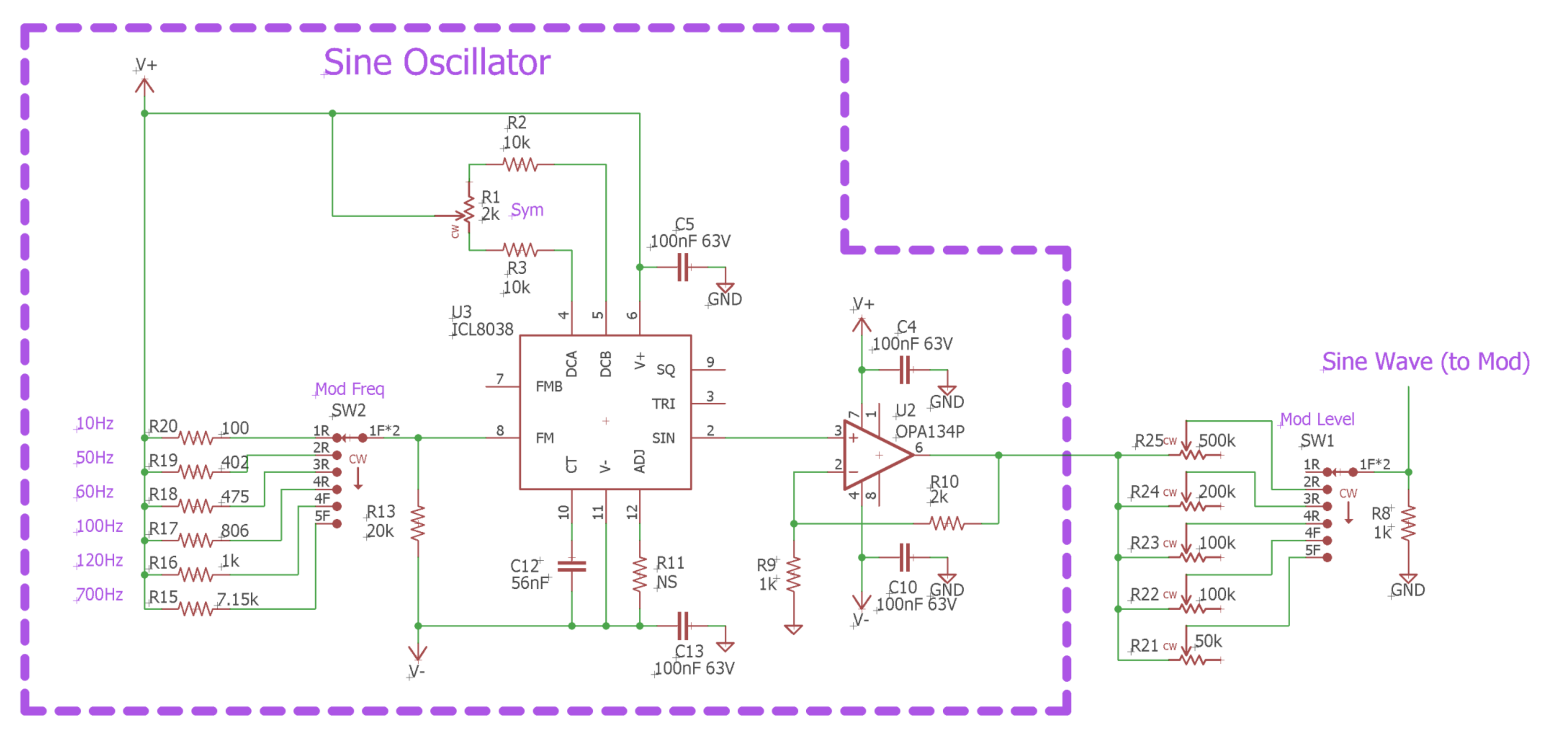
The “IMD Modulator”



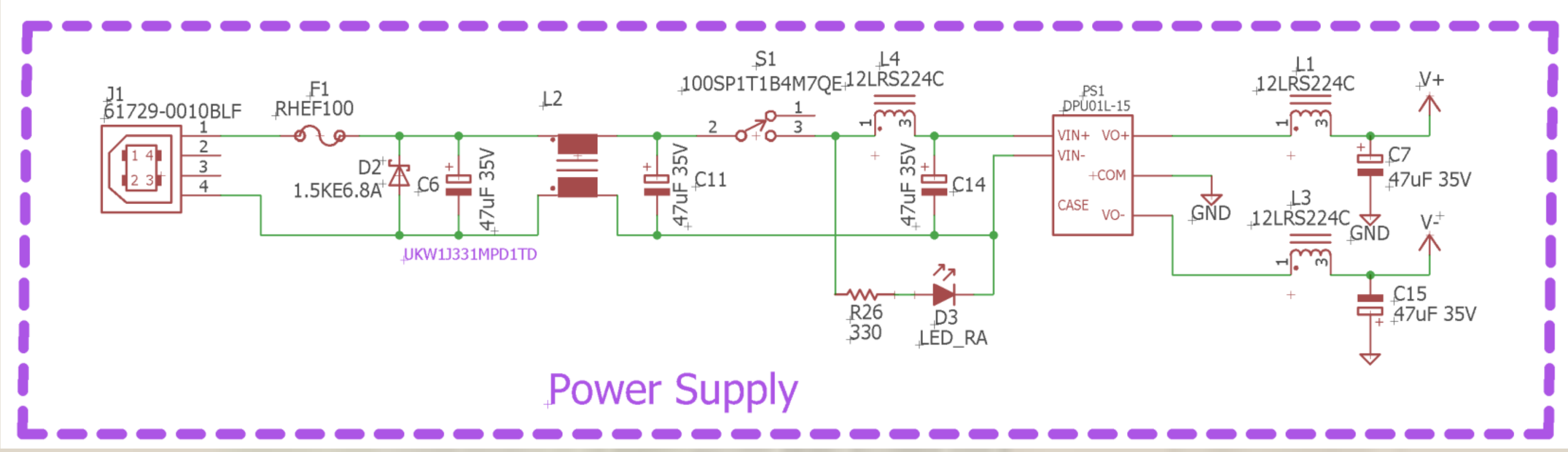
The circuit - Modulator



The circuit – Sine Oscillator



The circuit – Power Supply



Settings

- The IMD modulator has two adjustments: Oscillator frequency, and modulation depth (as well as an output volume control)
- The frequency is selectable around normal line frequencies (and 2x those frequencies), as well as one low frequency (around 10Hz) and one high (around 700Hz)
- The modulation level (level of the first sideband) can be adjusted between none and -8dB, which is 50% IMD
- I’ll use audio generated from my laptop via a USB DAC for the demo

Listening to Sine Waves?

- Most of us don't spend a lot of time listening to sine waves. OK, some of us nut cases might…
- IMD is easily heard on a sine wave, so…
- We will start with a sine wave

Music

- So now we'll try some music…
- I was surprised that some types of music that I expected to be less… annoying… with IMD added were not as easy to distinguish as I thought
- If it's bad enough obviously you can hear it on anything

That's it…

- Questions?
- Comments?