# Not Only Valve Pre-amplifiers Give a Warm Sound

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*11-Feb-2007*

## *Introduction*

This has to be the biggest nonsense that I have ever heard from about the late 1960's onwards; but I am relieved that I hear it from people that do not have the faintest knowledge of analogue electronics. In other words, people that say this do so because they are highly ignorant of the facts about preamplifiers (and/or the early amplifier stages in amplifier systems).

The facts are not entirely simple, but nobody really seems to want to analyse the situation and come up with the facts to make an informed response. (Nothing like the facts to ruin a colourful story!) The problems is where to start, and where to finish, and my initial analysis starts with considering several various types of preamplifiers, then making an equivalent structure so that each can be measured on its characteristics. This then provides a fairly equivalent comparison platform, and this in turn will provide a range of answers that can be the structure for informed opinions.

## *Preamplifier Input Circuitry*

The standard input circuitry for most valve based Guitar Amplifiers has a 1 M ohm load, in parallel with about 15 pF, feeding into a common Cathode (triode valve) amplifier as the first stage, and this usually has between 47 k ohms and 220 k ohms as the plate (anode) load resistor, connecting into a 0.1 uF coupling capacitor into the next stage.

In almost all cases this valve is a 12AX7, 12AU7 or 12AT7, which is a dual triode valve, where the 12 stands for the filament voltage (12 V) – which is a series connected filament with each section able to work from 6 V. The difference with these three valves is the mutual conductance (or gain) of the valves, and mutual conductance is nominally calculated in milliamperes per volt (mA/V). As I best recall it, the 12AX7 had the highest gain and the others had less gain back to the 12AT7 that was low gain (and low noise). The European equivalents were the ECC83, ECC82, and ECC81

These hermatically sealed valves were tremendously popular in the 1950s through to the 1980s: initially because they were the new technology of an all-glass container including the glass base for the pins. This was small, sauvé, and 'sexy', and was a generation beyond the glass bottle with Bakelite pin support. These valves became very commonplace and cheap to manufacture in large quantities and became the defacto standard for almost all valve amplifiers – up to the power stage.

## *Why not Other Technologies*

Bipolar Junction Transistors (BJTs) really did not hit the scene until the mid 1960's and by then valves were entrenched in musos minds as the only suitable amplifier component, and it took engineers some decades to let go of the 'hi-fidelity' mindset (with lashings of negative feedback) – and by then BJTs were 'history' for all the wrong reasons!

Analogue Integrated Circuits (ICs) in the mid 1970's fell into the same hole as BJTs, as these IC demanded lots and lots of negative feedback because their gain without feedback was literally enormous.

Field Effect Transistors (FETs) as preamplifiers cam in by the 1980's were never given a chance primarily because of wide production tolerances (compared to valves, and BJTs). It is rather interesting that valves and FETs have a virtually identical maths structure set, so if anything would emulate valves than FETS would be the number one choice without any question!

The transfer curve for Valves ($V_{gk}/I_a$) and for FETs ($V_{gs}/I_d$) follows a common "squared" shape with an offset that defines the so-called cut-off point where the anode/drain current is effectively minimised to virtually zero. Because this transfer curve follows the "x squared" curve, the signal inherits a significant amount of even harmonic distortion through the first couple of stages as usually these amplifier stages have little if any audio frequency feedback. The larger the signal the greater the even harmonic distortion!

## *How this Distortion is Introduced*

The real reason why musos and audiophiles like valves over other technologies is because almost all valve circuits have a very limited negative feedback arrangement so these amplifiers are prone provide distortion from the front-end stages. The first two stages of most valve amplifiers usually have no feedback, and because these amplifier stages are asymmetric, they produce a range of even harmonics and people find that these even harmonics are pleasant to listen to. The overload characteristic is in most cases very gradual, so valve pre-amplifiers produce a dynamic compression effect, making the output appear much louder than it could be if amplified through an amplifier that has considerable feedback.

The first valve stage usually acts as a linear preamplifier, and the second stage is usually driven to and sometimes past its limits and in this mode it is the second stage that provides the (pleasant) distortion and overload compression. It is down to the choice of input signal level and the amplification of each stage that determines the amount of 'exertion-based' distortion, and yes it is that simple!

To better understand more precisely 'how' this works, it is necessary to draw on a little applied maths, and some experience. Firstly it is necessary to have a look at the specifications of the various valves, and accurately interpret these figures. This is exciting as it provides the insight into exactly what is going on. Firstly there is what are called 'static' specifications secondly what are called 'dynamic' specifications; and these are good engineering tools and I will leave that to the Engineers, as that is a little deep for most people.

We can get a real appreciation of how these various valves operate by looking at several Typical Operating Conditions and the tables below (which were derived from the Philips Data Manuals) is very telling but needs a little explanation! The amplifier in consideration is a common cathode amplifier with a following amplifier stage having a known grid resistor. The data in bold italics has been derived from the base data.

## *Introducing the dBu Notation*

I have purposely introduced dB notation as a unified measure approach for gains, losses and levels. With 600 ohm based equipment; 0 dBm = 1 mW across 600 ohms and the voltage = 0.7746 Vrms at this state. The term dBu is based on the voltage and not the power level and so 0 dBu = 0.7746 Vrms as the reference level.

As dB notation is logarithmic, the process of addition and subtraction makes amplifier calculations very simple and quick, and this has a close association to our sensation of hearing (or ‘loudness’) perception. Some decades ago a person told me that once I use dB’s I would never go back and he was right for all the right reasons!

| 12AX7 / ECC83 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Static Specs** | | | | | | | |
| Supply Voltage | V | 200 | 200 | 200 | 300 | 300 | 300 |
| Anode Resistor | k ohms | 47 | 100 | 220 | 47 | 100 | 220 |
| Anode Current | mA | 0.86 | 0.65 | 0.36 | 1.55 | 1.11 | 0.63 |
| ***Anode Voltage*** | ***V*** | **160** | **135** | **121** | **227** | **189** | **161** |
| Cathode Resistor | k ohms | 1.5 | 1.8 | 3.3 | 1 | 1.2 | 2.2 |
| ***Grid Bias*** | ***mV*** | **-1,290** | **-1,170** | **-1,188** | **-1,550** | **-1,332** | **-1,386** |
| AC Load Resistor | k ohms | 150 | 330 | 680 | 150 | 330 | 680 |
| **Dynamic Specs** | | | | | | | |
| ***Anode Load*** | ***K ohms*** | **35.8** | **76.7** | **166.2** | **35.8** | **76.7** | **166.2** |
| Output Voltage | V rms | 18 | 20 | 24 | 26 | 30 | 36 |
| ***Output Voltage*** | ***dBu*** | ***27.3*** | ***28.2*** | ***29.8*** | ***30.5*** | ***31.8*** | ***33.3*** |
| Voltage Gain | Vo / Vi | 34 | 50 | 56 | 40 | 57 | 72 |
| ***Voltage Gain*** | ***dB*** | ***30.6*** | ***34.0*** | ***35.0*** | ***32.0*** | ***35.1*** | ***37.1*** |
| ***Input Voltage*** | ***mV rms*** | **529** | **400** | **429** | **650** | **526** | **500** |
| ***Input Voltage*** | ***dBu*** | **-3.3** | **-5.7** | **-5.1** | **-1.5** | **-3.4** | **-3.8** |
| ***Input Voltage*** | ***mVpeak*** | **749** | **566** | **606** | **919** | **744** | **707** |
| Total Distortion | % | 8.5 | 4.8 | 4.6 | 5 | 2.7 | 2.6 |
| ***Total Distortion*** | ***dB*** | **-21.4** | **-26.4** | **-26.7** | **-26.0** | **-31.4** | **-31.7** |

The rows in plain font were taken straight from the Philips manual and the Bold / Italic rows were derived from these data. There are six situations covered here one set of three using a 200 V source and the second three using a 300 V source. The difference is that the load and bias conditions are changed.

*To better understand the derived Static Specifications:*
Anode Voltage = Supply Voltage – Anode Resistor * Anode Current
Grid Bias = Cathode Resistor * Anode Current

*To better understand the derived Dynamic Specifications:*
Anode Load = Anode Resistor // Following Grid Resistance
Output Level (dBu) = 20 Log (Output Voltage / 0.7746)
Input Voltage (mVrms) = 1000 * Output Voltage / Voltage Gain
Voltage Gain (dB) = 20 Log (Voltage Gain)
Input Voltage (mVpeak) = Input Voltage (mVrms) * 1.414
Total Distortion (dB) = 20 Log (Total Distortion (%) / 100)

That was pretty basic secondary school maths, and now we have a table of data that can be column related like never before!

There is a lot of variation in the 12AX7 table. The prime reason is that most valves are inherently non-linear, and the 12AX7 fits this criterion well. Under these varying load and quiescent anode current conditions, the Voltage Gain varies by about 6 dB, and this implies that both the dynamic Anode Impedance and the mutual conductance (change in resultant anode current for change in grid / cathode voltage) are both anode voltage and anode current dependent. This then goes a long way to explain the (large signal) distortion varies between -22 and -31 dB, and is highly dependent on the anode load.

It would be interesting to better understand the distortion in terms of output level, gain, and input level. Mathematically we know that the distortion is even-harmonic because the amplifier is asymmetrical in design – and it is this that gives the ‘warm timbre’ to the sounds. It is just a matter of how ‘warm’ the sound needs to be!

Before going down that path it is worth looking at a brother to the 12AX7 the 12AU7 and the same table as above is filled out for the 12AU7 (with data from the Philips data manuals).

| 12AU7 / ECC82 | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Static Specs** | | | | | | | |
| Supply Voltage | V | 200 | 200 | 200 | 300 | 300 | 300 |
| Anode Resistor | k ohms | 47 | 100 | 220 | 47 | 100 | 220 |
| Anode Current | mA | 2.41 | 1.3 | 0.66 | 3.65 | 1.97 | 1.16 |
| ***Anode Voltage*** | ***V*** | **87** | **70** | **55** | **128** | **103** | **45** |
| Cathode Resistor | k ohms | 1.2 | 2.2 | 3.9 | 1.2 | 2.2 | 3.9 |
| ***Grid Bias*** | ***mV*** | **-2,892** | **-2,860** | **-2,574** | **-4,380** | **-4,334** | **-4,524** |
| Following Grid Resistance | k ohms | 150 | 330 | 680 | 150 | 330 | 680 |
| **Dynamic Specs** | | | | | | | |
| ***Anode Load*** | ***k ohms*** | **35.8** | **76.7** | **166.2** | **35.8** | **76.7** | **166.2** |
| Output Voltage | V rms | 26 | 25 | 22 | 43 | 41 | 36 |
| ***Output Voltage*** | ***dBu*** | ***30.5*** | ***30.2*** | ***29.1*** | ***34.9*** | ***34.5*** | ***33.3*** |
| Voltage Gain | Vo / Vi | 13.5 | 14 | 14.5 | 13.5 | 14 | 14.5 |
| ***Voltage Gain*** | ***dB*** | ***22.6*** | ***22.9*** | ***23.2*** | ***22.6*** | ***22.9*** | ***23.2*** |
| ***Input Voltage*** | ***mV rms*** | **1,926** | **1,786** | **1,517** | **3,185** | **2,929** | **2,483** |
| ***Input Voltage*** | ***dBu*** | **7.9** | **7.3** | **5.8** | **12.3** | **11.6** | **10.1** |
| ***Input Voltage*** | ***mVpeak*** | **2,723** | **2,525** | **2,145** | **4,504** | **4,141** | **3,511** |
| Total Distortion | % | 6.1 | 5.6 | 4.4 | 6.5 | 6.1 | 5 |
| ***Total Distortion*** | ***dB*** | **-24.3** | **-25.0** | **-27.1** | **-23.7** | **-24.3** | **-26.0** |

Now this is a very different (triode) valve, and even under a wide range of operating conditions the Voltage Gain is highly consistent at about 22.9 dB and the large-signal distortion is fairly tight in the –24 dB to –27 dB range.

Because the Voltage Gain is highly consistent, then the dynamic Anode Impedance must be comparatively low, and the distortion must be generated from the Grid – Cathode, and Anode –Cathode voltages having non-linear relationships.

So what we are seeing here is that when we use large signal analysis techniques we begin to understand that there is a considerable amount of (even harmonic) distortion that happens particularly in the second stage. In most situations small signal analysis is done and this totally misses out on the issue that distortion is a major factor to contend with in most amplifier designs, and the analysis rules are deceptively different to manage.

The first key is the Total Distortion, measured in dB and you really need an insight into how dB measurements are universally consistent – especially compared to distortion measured in percentage.

There seems to be two Total Distortion groupings based on Supply Voltage; with 200 V: –26.4 dB and –26.7 dB, and with 300 V: -31.4 dB and –31.7 dB, and there is a direct correlation with the Grid – Cathode bias. Notice now that the Input Voltage Levels match this grouping and that explains why the two other Total Distortion levels of –21.4 dB and –26.0 dB will not correlate to their ‘families’.

As the Anode Load is increased (decrease in resistance, and greater current flow in the Following Load Resistance), the Total Distortion tends to increase, and the lesser the quiescent Anode Current, the higher the Voltage Gain. Virtually nothing has a linear relationship and to make it more confusing, as valves are used, they age, and their emissions (current liberated from the cathode) drops, so this becomes a vendors market where the buyers will believe almost anything

In both Supply Voltage cases, the Grid / Cathode circuit is biased slightly higher than the other two, and this is one reason why the correlation here is poor.

The lower the Anode Load the higher the Total Distortion; but it is not linear! One of the more common valve biasing strategies is to run the valve on 100 V or sometimes less so that the distortion is even more pronounced!

## *Not Using Valves*

The diehards will continue to push for valves but with newer technologies – valves may not be practical.

We know that the voltage can be dropped and FETs can be literally plugged in place of valves. This strategy opens up many doors and places valves in the departure lounge as far as pre-amplifiers are concerned.

Bipolar Junction Transistors (BJTs) also have an exponential Vbe/Ic ratio and this ratio can be used to great advantage to get a large signal distortion that closely resembles that fro a valve. The problem with transistors is that they usually require some form of direct current feedback to stabilise the quiescent current in the stages. If this is done in feedback and the feedback for the audio path is sufficiently filtered, then these work exceptionally well.

Analogue Integrated Circuits (ICs) usually are structured as (mathematical) operational amplifiers, and are often called “op-amps” because of that. These ICs usually have a tremendously large gain so that errors in the amplification maths are virtually eliminated as the error is an inverse proportion of the gain with feedback divided by the open circuit gain.

There are two relatively easy ways to use op-amps. The analogue way is to introduce a non-linear feedback path and consequently the output is a direct inverse of the feedback non-linearity. The digital way is to introduce a non-linear analogue – digital conversion and through that conversion produce a digital stream that is clocked and deliberately distorted by a known amount.

The digital approach is now being taken to another level where the signal is originally converted in a linear fashion and then put through a digital processor that can introduce a pre-determined amount of distortion, and/or echo / reverberation, and / or alter the spectrum just as bass / treble controls did with analogue signals.

## *Conclusion*

Even harmonics give that nice smooth sound that musos and audiophiles love to hear and will pay dearly for a valve front-end amplifier. The same (or even better) sound can be created from FETs, BJTs and Op-Amps at a fraction of the cost.