DIGITAL AUDIO SYSTEMS: WRITTEN REVIEW 2
DIGITAL TUBE SIMULATION MODELS

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1. INTRODUCTION

With the rapid rise of digital technology in the music and audio engineering industries over the past two decades, tubes based equipment has become known as a thing of the past. The tone and quality created when using analogue tube equipment is still as popular as ever in higher end audio situations. There has been some considerable headway made with digital tube simulations, however until variables such as different types of triodes and the miller effect are taken into account, exact replications will not be fully achieved. The main reason for digital tube simulations is for the application of digitally replicating digital guitar amps, which over the past 50 years have been argued to have a 'fatter, warmer, cleaner, softer, more detailed' sound.

1.1. Tube Guitar Amplifiers 'Fat' Sound

Long standing argument by audiophiles, guitar enthusiasts and audio engineers is the question of 'why do tube amplifiers have fat sound while solid state amplifiers don't?' Although it may seem to be a purist versus modern technology enthusiasts argument there's a lot of science evidence and proof behind why tube amps and equipment can be 'described as "warm", "clean", "soft", "fat", "detailed", "euphoric", "life like", "vivid" or some times labeled as "tube sound"' and the list goes on. The sound of these amps comes from the specific breakdown of the electronics within the 'tubes themselves', which will be discussed further in this report. Tubes or valves have been used in guitar amplifiers as far back as 1946 in some of the early fender guitar amplifiers.

1.2. Nonlinear Valve Application

The characteristics that, the presence of valves gives to equipment continues further than guitar amplifiers. Many pieces of equipment such as: high end hi-fi systems 'guitar stomp boxes, equalizers, dynamic processors, power amplifiers, valve microphones, compressors, limiters and compressors for vocal recording' contain triode tubes. One of the most 'iconic' studio vocal recording microphones is the 'Neumann U47 tube microphone' which contains a 'Telefunken VF-14M pentode vacuum tube' which is a 'steel tube which was originally built for the German army and used in field radios during World War II'. Amazingly 'no noticeable research or development has been made on' valve amplifiers since the 70's. Many mastering engineers still prefer to use tube based equipment and continue to run stereo digital files through 'analogue equipment. They mainly use tube compressors, equalizers and pre-amplifiers' in their mastering chain to take the stereo mix 'out of the box' or in common terms 'out of the computer' or digital format, before converting it back to digital 44100 at the end of the mastering chain.

2. VACUUM TUBES

This section of the paper, the basics of tubes and their inner workings and characteristics will be discussed.

2.1. Diodes

A 'vacuum diode' is the simplest type of tube. Vacuum diodes work 'where two electrodes, anode and cathode' are all mounted within a 'vacuum cylinder'.

Cathode (is heated) = K
Anode (or plate) = A (collects electrons)

2.2. Current in tubes

NB: While the anode is cold it cannot emit electrons; once it is heated, current flow is possible.

'The electrons then leave the hot cathode with random velocities'. In order to suppress the current flow at this point a negative voltage is applied here. 'The formula for the current flow through diode '*I'* is as follows':

$$I = I_0 \cdot e^{\frac{V}{E_T}}$$

[Equation 1: Current flow through diode *I*]

Current flow can be increased through the diodes with the introduction of positive voltage, once the positive voltage is added the 'emitted electrons' are 'pulled' toward the anode. This process increases the flow of current. The 'emitted' electrons are drawn toward the 'hot' cathode forming 'the space charge' ('a cloud of negative charges'). When the voltage passes a certain point '**current saturation'** occurs. The various heat exchanges within tubes is a major factor in creating its sound when used for amplification.

2.3. Triodes

Triodes are types of tubes directly relevant to this report. Triode tubes introduce an 'extra third electrode' in close proximity to the *'cathode'*. This extra electrode creates the 'grid'.

Grid = G

As discussed in section 2.2, the voltage applied to the electrodes increases or decreases the flow of current within the tube. With 'excess current flow' grid distortion can occur, which can be desirable for the application of guitar amplifiers. The 'ratio' between, 'grid current, anode current' and 'voltage' is taken into high consideration with the design of triode tubes. The equation below, taken from 'Spangenberg's' publishing shows this ratio relationship:

$$\frac{I_a}{I_g} = \delta\sqrt{\frac{V_a}{V_g}}, \qquad \frac{V_a}{V_g} > 0.8, \;\; V_g > 0$$

The three electrodes within a triode tube are given the following names:

-Anode
-Cathode
-Gate (or Grid)

The inner workings of a standard 'three-electrode vacuum tube' or 'triode tube' is shown below. Where *F*, *G* and *P* represent the three electrodes, *Eg* is the 'alternating voltage', '*Rp* is the resistance component', *Xp* the reactance component'. Also included in the diagram is the three 'capacities between the 3 electrodes', these capacitors are represented by C_1, C_2 and C_3 respectively. See Fig 2.1. These elements carry over to tube simulation relationships.

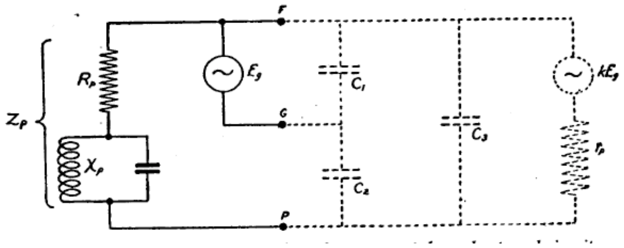
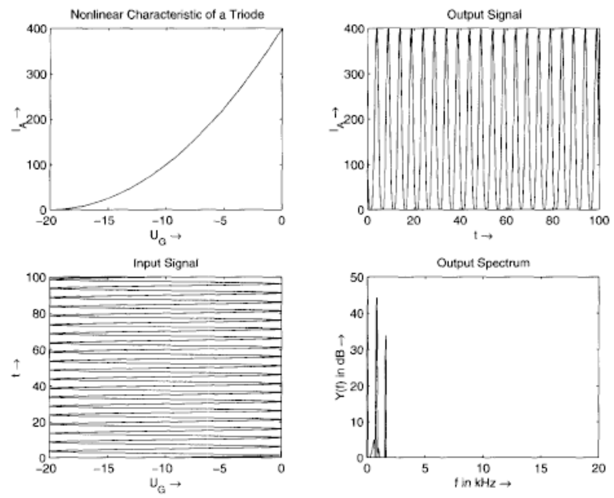


Fig: Diagrammatic representation of a three electrode vacuum tube and external circuits. (Take from: *Department of Commerce, Scientific Papers, Bureau Of Standards, S. W. STRATTON, Director, 1919-20*)

When these three elements of the triode are working in harmony the 'warm, soft, fat, sound' can ben achieved. As discussed in Smith's DAFx text (Chapter 5) it is 'the nonlinear transfer function for anode current verses input gate voltage of the triode' this relationship is show in the figure below. 'The input signals are shown by 'the gate voltage Ug' which delivers anode output current IA = f(Ug) which is show in the output signals below:



The characteristic curve of a nonlinear triode IA = f(Ug). ('The output spectrum consists of the fundamental input frequency and a second harmonic generated by the quadric curve of a triode') (Udo Zolzer, 2002)

3. DIGITAL TUBE SIMULATION

3.1. Digital Audio

Over the past decade or so digital audio systems have made their stamp on the audio industry stretching right through to instruments, synths, audio production programs (eg. pro tools, logic, cubase) taking over and flooding the industry. This influx of new technology on the rise has in a lot of way left analogue equipment such a 'Tube Amplifiers' to be 'thing of the past', or collectors item unfortunately. Analogue equipment is unfortunately generally known as being old, expensive and high maintenance to the next generation of musicians and engineers.

3.2. Tube Simulation.

The leading digital tube simulation calculations are taken from 'Norman Koren's', 'SPICE model' created as 'an electronic circuit simulation program', developed at 'The University of California at Berkeley'. The majority of the leading proposed tube simulation VST's or Programs are based on the spice model. Almost all digital tube simulations are based on a modified version of the 'Child-Langmuir equation'. Another earlier leading model is a model by 'Leach'.

Both Koren and Leach's model's 'model the triode as two current sources which are a function of the voltages *Vpk and Vgk* ':

Ip = Lp(Vgk, Vpk)
Ig = Lg(Vgk, Vpk)

Where *Lp* and *Lg* are nonlinear functions.

3.3. Tube Simulation Equations: Leach Model

The 'Leach Model' is a derivative of the 'Child-langmuire Law'.

'For current: *Ig*, the Leach Model formula is expressed as the following equations:

$$L_p = \begin{cases} K(\mu V_{gk} + V_{pk})^{3/2} & \text{if } (\mu V_{gk} + V_{pk}) > 0 \\ \rho & \text{else} \end{cases}$$

$$L_g = \begin{cases} 0 & \text{if } V_{gk} < V_\gamma \\ \frac{V_{gk} - V\gamma}{R_{gk}} & \text{else} \end{cases}$$

3.4. Tube Simulation Equations: Koren Model

The Koren Model is in-fact 'derived from the Leach model' it is also a 'phenomenological' model, taking into account 'the behavior of physical phenomena using parameters not derived from fundamental physics'. This model has limitation when it comes to 'solid state amplification' how ever excels in the replication of 'real world' output results.

This model is designed in a way that 'plate current, *Ip > 0 I* when ever plate voltage *Vpk > 0'*. 'The expression of the *Lp* function' is as follows:

$$E_1 = \frac{V_{pk}}{K_p} \ln \left[1 + \exp \left(K_p \left(\frac{1}{\mu} + \frac{V_{gk}}{\sqrt{K_{vb} + V_{pk}^2}} \right) \right) \right]$$

$$L_p = \frac{E_1^{E_x}}{K_g} (1 + \text{sgn}(E_1))$$

[Equations taken from: 2009, AES Convention Paper 7929, Ivan Cohen, and Thomas Heilie]

3.5 Miller Effect

The '**Miller Effect'** is an effect observed by John M Miller in the early 1920's. It is usually left out of consideration in Tube Amplifier Simulation's. The effect states that: 'The effective input impedance of an amplifier depends on the impedance connected from input to output of the amplifier.' 'The apparent scaling of this impedance often dominates the input impedance and frequency response for the amplifier'.

4. REALISTIC TUBE MODELS

4.1 Real life models:

There 3 main 'standard models' of triode tubes:
-12AX7
-12AU7
-12AT7

4.2 Measurement comparison

The different models of tubes aren't generally taken into consideration within tube simulations. In order to correctly simulate specific amplifiers, the model of the tube and the miller effect will need to be taken into account.

Measurements were taken comparing 'measurements from a RSD 12AX7 triode' and measurements using the Anode current using Langmuir Childs formula. Comparison measurements show below: (take from: 2011, Audio Engineering Society Convention Paper 8507 – Kristjan Dempwolf, Martin Holters, and Udo Zolzer)

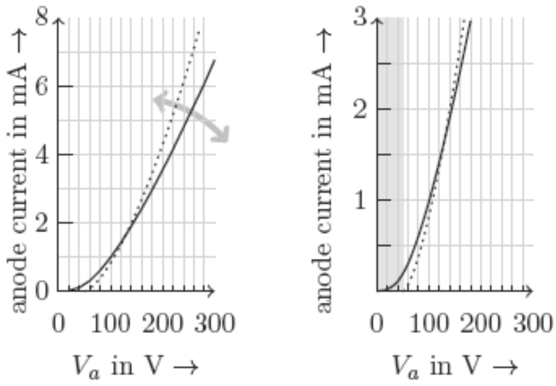


Fig 4.2: Anode current calculated with Langmuir-Childs formula (dotted line) and measurements from a RSD 12AX7 triode (solid line) in a qualitative plot. (2011, Kristjan Dempwolf, Martin Holters, and Udo Zolzer)

5. DISCUSSION

Although the majority of tube models are based on the Leach and Koren's SPICE models there have been some considerable advances in the recent years. In order to obtain optimal 'real world' triode tube results, factors and variables such as the tube model within the plug-in will need to be taken into consideration, along with the miller effect.

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