SDMAY18-39: Vacuum Tube Audio Amplifier Emulation

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1) Introduction

1.1 Acknowledgements

Dr. Randall Geiger and Dr. Degang Chen have served as technical advisors on this project – they have acted to guide us in direction and motivated us in our pursuit of understanding of the project's scope. Dr. Geiger and Dr. Chen acted to fuel our ambition and turn our curiosities into reality. This acknowledgement is intended to serve as our expression of gratitude to our advisors, without whom project progress would surely have suffered.

1.2 Overview

The purpose of this project was to research and design an emulator for modeling sounds associated with vacuum tube audio amplifiers. This software-based emulator took voltage data from audio signals, passed as the input argument of the model, and output the original audio signal enhanced with the nonlinear characteristics of vacuum tube amplifiers, specifically Pentode devices.

1.3 Problem and Project Statement

In the audio amplification world, particularly with respect to electric guitar signal amplification, musicians have historically chosen to use amplifiers driven by vacuum tube technology. Up until around the 1970s, vacuum tubes dominated the audio market, and many of the 'classic' rock albums that listeners hold in high esteem are recordings of vacuum-tube driven amplifiers. The sonic footprint these albums left on the modern musician is considerable, and many guitarists refuse to perform with amplifiers driven by tube alternatives – the dominant alternative being the BJT solid state amplifier – solely because of the 'classic' tones associated with vacuum tubes.

There are significant advantages to utilizing solid state technology for guitar amplification. Solid state devices are significantly more power efficient than vacuum tubes, and the physical footprint of BJTs are magnitudes of order less than that of vacuum tubes. Additionally, solid state technology is far more resilient to abuse – both physical and electrical – than tubes. Perhaps most importantly, BJTs are significantly less expensive than vacuum tubes.

Despite the advances made in BJT technology (in efforts to model the tube amplifier) and the considerable financial benefit to producing solid state amplifiers on a commercial scale, solid state technology still, for the most part, is undervalued to vacuum tubes amongst professional musicians. The team believes this is largely due to a failure to properly address the sonic aesthetics surrounding vacuum tube amplifiers.

The team believes that, if the key musical parameters around the tube amplifier are quantitatively observed, a tube 'effect' can be modelled and reproduced. In the proposed solution, the team designed an emulator that could impose vacuum tube amplifier characteristics onto input audio signal. The solution offers a tunable model over a range of frequencies and amplitudes. After proper data manipulations are made to the input file, the user can generate a model output with the desired emulation signal.

1.4 Purpose

The main purpose of this project is to develop the knowledge of what it takes to synthesize tube amplifiers output and attempt to digitally emulate the sound. Additionally, because of the accessibility to model parameters, weighting on model coefficients can be easily implemented to achieve the users desired output.

1.5 Expected End Product and Other Deliverables

The main deliverable is the statistically and algorithmically verified tube emulation model. The model encompasses a family of input frequencies and amplitudes and faithfully reconstructs signals that are true to the behavior of a pentode tube amplifier.

Additionally, the "open-hood" structure of the model permits the user to tune emulation coefficients to their particular needs. In this way, the model offers much more than a traditional tube amplifier, as it does not only replicate the preferred characteristic of the device, but also permits the user to customize and shape the output beyond what a tube amplifier would provide.

1.6 Intended Users and Uses

Any musicians or musical technicians who wish to impose desirable traits onto their audio profiles would be interested in our model. By running their properly formatted audio thru the emulation profile, a highly preferred output can be provided and modified until their musical needs are met. These users need a mild technical background to effectively utilize some of the emulator's features – in particular, some pre-requisite knowledge of basic MATLAB and statistics can be beneficial, and the manual adjustment of weighted coefficients can be an involved and technical process.

It is important to note that the emulator and subsequent tuning of coefficients is not a real-time process. The scope and timing constraints surrounding the project's development permitted us to accurately construct an emulation profile, but did not allow for its realization in real-time or on a portable unit (such as a microcontroller). However, musicians with technical training and capabilities should have no problem obtaining their desired effects with the product as it stands. More time and resources are needed to bring the product into a more accessible and ergonomic form factor.

1.7 Assumptions and Limitations

Assumptions

The emulator shall be used with any input signal frequency within the range of the audio band. Additionally, the emulator will be used on a PC using MATLAB code to run and remodel the signal until the desired output is achieved.

Limitations

The emulator currently only supports inputs in which only one tone is played at a time. These single tones are where we have collected significant data to train the model to an adequate least-squares regression fit. Consequently, this means there is more work to be done in order to input mutli-tone signals or full songs to be emulated. Additionally, as mentioned above, the emulator functions as a post-processing sound profile enhancement, and not as a real-time device.

2) Specifications and Analysis

2.1 Proposed Design

The team has developed a device that emulates the non-linear characteristics of a vacuum tube amplifier. The device is intended to serve as a processing tool for input signals. The device will combine the use of signal manipulation and modeling a nonlinear system to achieve the tube signal profile

Functional Requirements

- Model signal accurately produces the output signal of a tube-amplifier
- Model signal has a statistically accurate signal in the time domain of the tube output signal
- Model signal is a consistent spectral profile of harmonic frequencies compared to the tube output signal

Non-Functional Requirements

- Ease of use, and understanding in using the modelling software
- Clarity of software generated signal

2.2 Design Analysis

Overview

The most important requirement of the project is the device's ability to emulate a tube amplifier. The focus of the team, as all other aspects of the project depend on the tube emulation. The team has done multiple tests on three amplifiers: a solid state amplifier and a vacuum tube amplifier with an in-unit speaker and customization. The tests consisted of acquiring coherently sampled data from both amplifier outputs and signal inputs. A frequency-domain analysis was then performed on the data. Determining the frequency responses of the amplifiers was instrumental in developing model parameters for the emulator. Once sufficient data was collected, the team began designing the emulator profile in software. Further detail on what testing was performed can be found in the results section.

Methodology Assessment

The overall methods of this design process can be broken down into several categories of technical overviews, each with their own strengths and weakness:

1. Frequency-Domain Analysis
   The underlying strength of acquiring spectral response of amplifier data was that the inherent differences between the two types of devices could more easily be observed. However, relying on developing an emulator that operates on spectral data is impractical because of difficulties associated with implementing a FFT based program.

2. Transient Analysis
   Transient based analyses of audio devices make it difficult to determine behavioral differences. However, if a robust method can be obtained, it is easier to implement this

method in a fit-processing program.

3. Method for Data Recording
   In the current environment, a 24bit, 192ksps ADC is being used to acquire amplifier data. These are excellent specifications for capturing all relevant frequency components for audio signals. However, once the measurements are converted into digital data, they must be compressed using the mp3 format. This results in some degradation in effective resolution since the mp3 format is a lossy compression.

   To supplement this data, a basic home-audio tube amplifier was fed a sinusoidal input from a signal generator, and high resolution data captures of both the input and output stage of the amplifier were taken. The data sets obtained with this test-bench greatly informed the tuning of the model, and therefore directly impacted the performance of the emulator (i.e. yielded excellent goodness-of-fit)

2.3 Previous Work and Literature

In the professional audio industry (especially guitar) it is still widely known that the best performance comes from vacuum tube amplifiers. However, several well-known audio equipment manufacturers (e.g. Dunlop, Electroharmonix, Ibanez etc.) have worked to create products that achieve tube-like sound from solid state components. Unfortunately, these devices tend to be limited five to a 1 pedal -1 function design and fail to deliver tube-like sounds for all signal types/combinations. Recently, the company Korg has created a product called the “NuTube” that is advertised as a “solid state /vacuum tube hybrid”, implying that it is a unique semiconductor device that has both features to it. The device may provide reasonable competition with the produced product. In terms of research, some effort has been made to identify the factors behind why people still prefer tube amplifiers over solid state.

3) Testing and Implementation

3.1 Hardware and Software

Testing Hardware

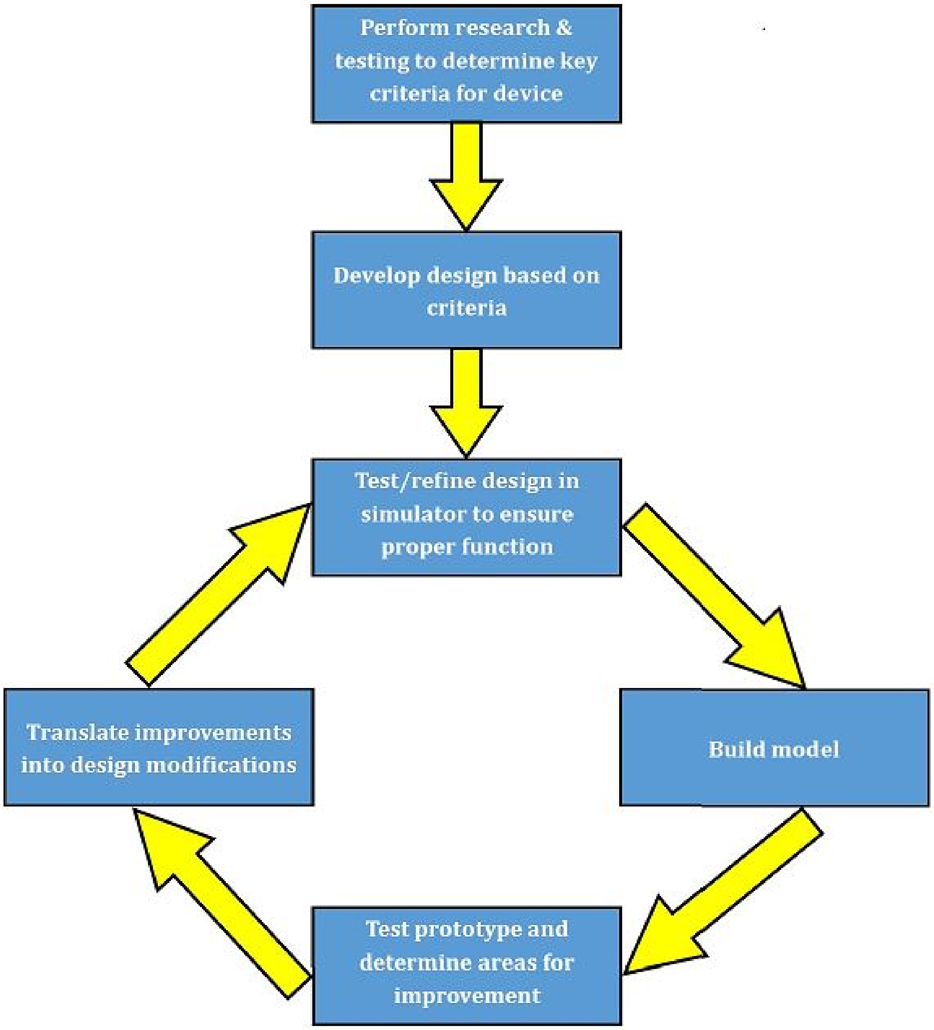
Two distinctly separate testing configurations were used for the duration of this project. The first configuration revolved primarily around the capture of real musical outputs from standard guitar amplifiers. In this test-bench, both a solid-state guitar amplifier and a vacuum tube amplifier were fed various signals from an electric guitar. The outputs of both amplifier, in addition to the unamplified input guitar signal were captured on oscilloscopes for analysis. Time-domain and FFT analysis of these captures greatly informed the direction of the project. The inspiration for the key parameter in our model (the tuning and least-squared regression of harmonics) was derived from this initial test bench. Although this method of data recording and processing was far too convoluted to develop the emulation profile off of, it served the critical function of providing quantitative insights into the differences between linear amplification (solid-state) and the preferred non-linear (tube-derived) flavor. In summary, this initial test bench was used to inform further investigation using its successor, the test bench described below.

The second testing configuration, as alluded to above, connects much more directly with our model derivation. Using the home-audio tube amplifier discussed above (which provided much easier access to I/O points), a simple function-generator derived sinusoid in the audio band was fed into the input stage of our tube audio amplifier. The output signal was then tapped off of the output stage of the device and burned across a high-power 8 ohm resistor. This resistor acted to simulate the load impedance of a traditional audio speaker, without coupling in the reactive noise and un-idealities into our measurement. Oscilloscope probes were then used to capture several cycles of both the input sinusoid and the output signal from the amplifier's gain-stage. These data captures were the dominant method for training our model algorithm, and yielded an emulation profile with highly accurate performance (average r-squared > 0.95) across a wide range of input amplitudes and frequencies.

Testing Software

MATLAB was used for the analysis each signal - input, tube output and models the output signals. Specifically, the team applied temporal analysis using least-squares fit regression to compare the waveform in the time domain. In the spectral domain, a spectrogram using Fourier analysis and coherent sampling was used to analyze the harmonic frequencies between signals. Additionally, transient analyses was used to ensure no unexpected distortion is created through the tube emulation device.

Figure 1: Flow Chart of Overall Process



3.3 Functional Requirements

Tube Amplifier Emulation

The ability to emulate the positive characteristics of a vacuum tube amplifier was considered to be the fundamental requirement for the proposed device, as the sound profile resulting from vacuum tube amplification continues to be the leading preference in the professional audio industry. The ability to capture that profile and implement it in a solid state (i.e. semiconductor) setting will drive the marketability of the device, as well as serve as a novel approach to audio design.

Final Module – Software Model

The module was implemented on a PC. It takes in an audio file and converts it a tube sounding audio file. The generic model equation used in the software is seen below. The input signal is modeled to the first five harmonic frequencies of the input signal. The model, therefore, consists of 11 parameters: a DC constant, and five pairs of amplitudes and phase shifts corresponding to each harmonic. This initial model is then adjusted and remodeled to have all amplitudes to be positive values and phase shifts in the range of [-pi, pi].

$$M(t) = C_0 + \sum_{k=1}^{N} \alpha_k \sin(k\omega t + \phi_k)$$

3.4 Non-Functional Testing

The emulator was evaluated for its usability and ease of changing parameters. Parameters are easily modified by simply changing the extracted parameter coefficients to tune to the designed output signal. E.g. if you wanted an emphasized second harmonic, the user will simply add a relative sized constant to the second harmonic amplitude parameter.

3.5 Results

Here, the unique nature of overdriven vacuum tube devices was explored. Additionally, a novel approach was established for developing a statistical method for rendering the audio characteristics of a vacuum-tube amplifier without needing the physical vacuum-tube device. Furthermore, it was shown that all regressions on the model have a goodness of fit of at least $R^2 = 0.95$. Supplemental investigation of the results of the project are required to develop an "interpolating" model that encompasses the entirety of the audio band and full array of input amplitude possibilities. Below, we present what we consider to be the best argument in terms of our emulator's validity, in the form of the following figures:

Figure 2: R-Squared Distribution for Entire Family of Fits (~100 Separate Data Collections)

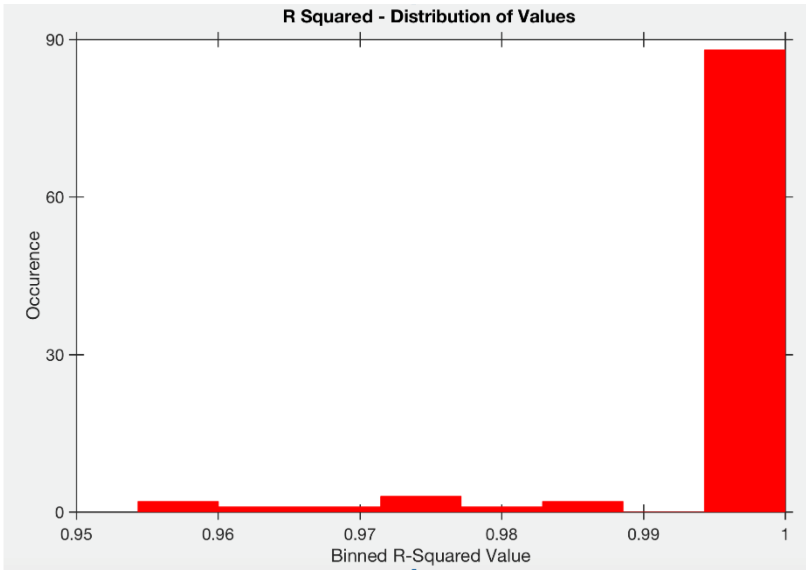
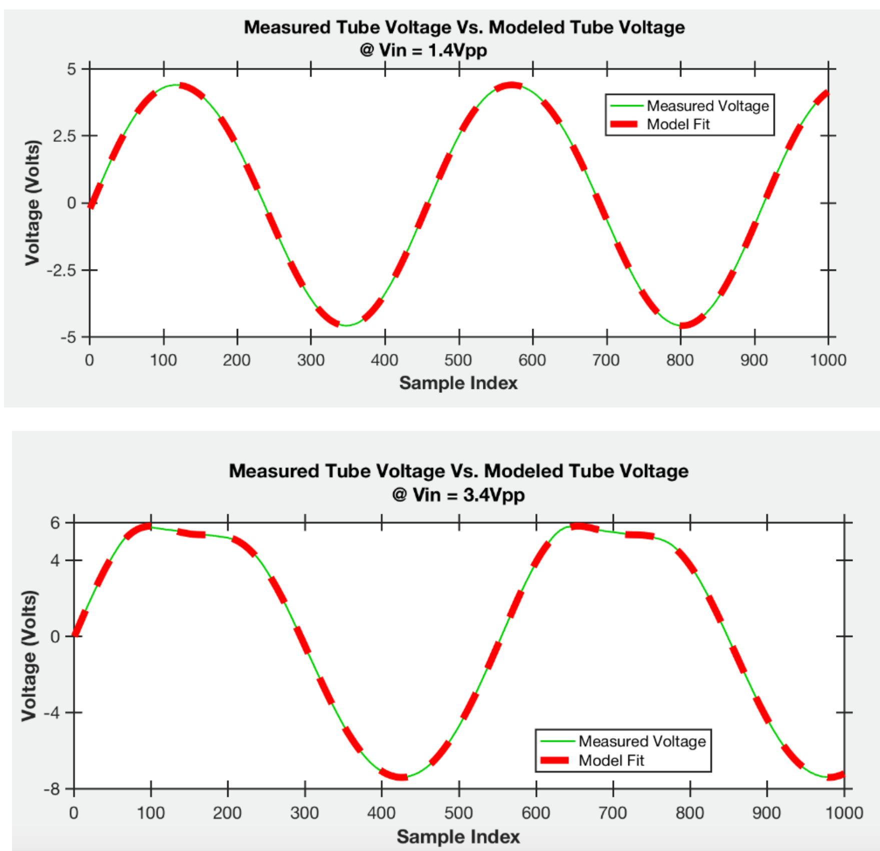


Figure 3: Below we visually demonstrate the "goodness of fit" of the model, comparted to the measured tube data



In Summary, our emulator delivers along the following figures of merit:

I.) The tube amplifier model achieves an audio profile that is unique and preferred by musicians.

II.) The model accurately tracks real vacuum-tube amplifier characteristics.

III.) The model produces the desired audio profile negating the need for a tube amplifier.

3.6 Issues and Challenges

Timeline with Respect to Project Definition

Over the course of this project, the biggest challenge was instilled by the fact that this project was defined by the team-members. The implication resulted in the project continually changing from month to month requiring us to make changes in requirements, design, test, and data. With additional time and project scope, the model could have be more robust and be able generalize over the entire frequency range.

Unclear Expectations/Outcomes

It is important to note that this project was considered to be a research-based one. With all research, many ideas turn out to be a learning experience, yet an unsuccessful path from the project direction. We as a team struggled to define the requirements of the project, and was driven by many forces in unexpected directions, which often was an inhibitor of the project.

4) Closing Material

4.1 Conclusion

The proposed emulator attempts to construct an audio profile that meets the demands of professional musicians, without compromising on cost or ease of use. The design includes quantifying and reconstructing the positive textures surrounding vacuum tube amplification on a modular small signal platform (pre-gain). The versatility of the platform allow the product to operate universally when it comes to user-defined tube emulation - negating the need for musician to spend thousands of dollars on top of the line equipment.

Appendix

Alternative Version of Tube Emulator Design: Physical Sound Effect Device

Description of Device

For the early portion of the development process the team intended to develop a physical device that could emulate a vacuum tube amplifier along with other analog and digital sound effects. The effects module would be intended for use in conjunction with an amplifier, resulting in a higher quality output sound that emulates the smooth and warm tones commonly associated with tube amplifiers. Additionally, the module would have included several other common sound effects that could be selected and adjusted to suit the musician's desires. The finished effects module would have included several analog effects circuits along with a microcontroller to run all digital effects, and its own power supply and input and output ports. This was intended to be packaged in a painted and decaled aluminum enclosure with all of the necessary adjustment knobs and switches mounted on the top panel for ease of access.

Reason Version was Scrapped

The goal to build a physical sound effects module was redefined in the second semester of the senior design project in order to divert resources to emulating the vacuum tube amplifier. Using a software-based sound processing model allowed for more a complex analysis of the tube amplifier distortion, and allowed sound processing in an environment free from real-time processing constraints. This allowed a much more accurate and complex emulation model to be developed.

It was determined that a more in-depth analysis and emulation of vacuum tube distortions was preferable to a physical device that merely mimicked the sound effect devices already produced by the commercial audio industry. The software version of our project uses in-depth analysis to produce an effect not currently available by the audio industry today