Vacuum Tube Audio Amplifier Emulation

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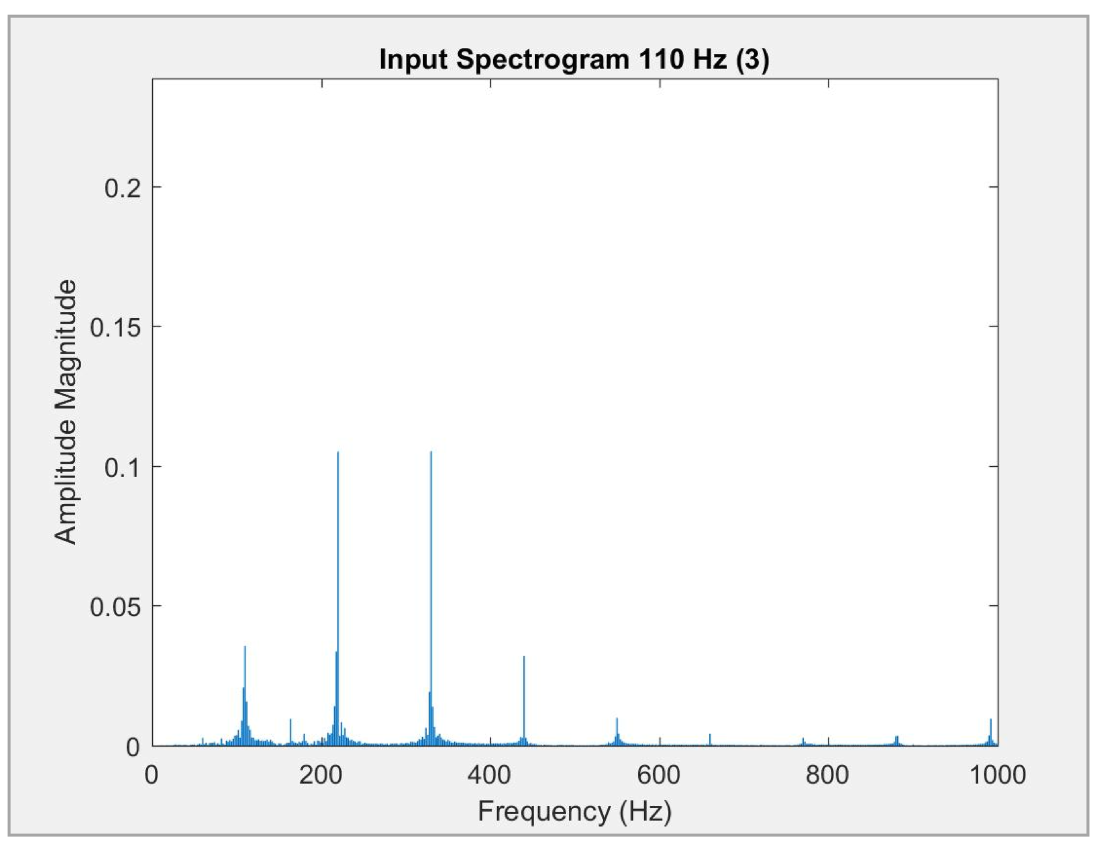
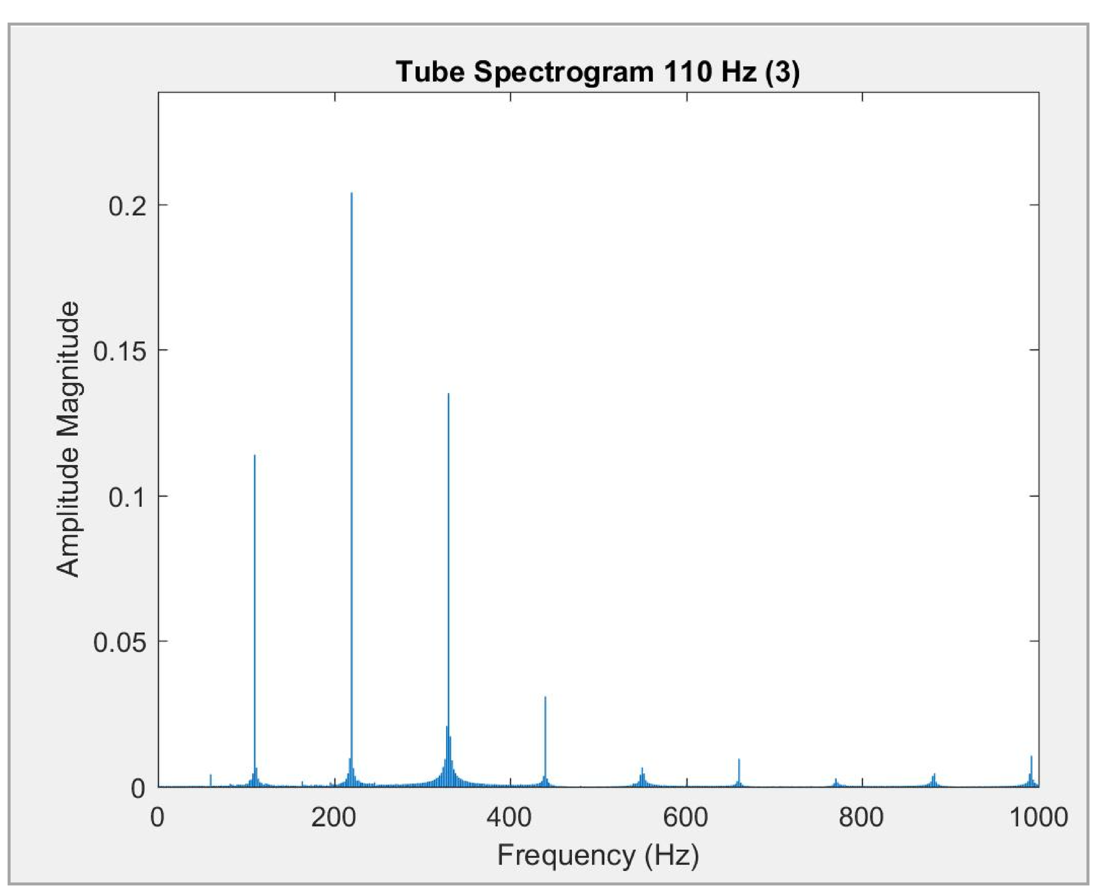
Introduction

- Vacuum tube amplifiers are preferred over solid state amplifiers by many musicians.
- The unique sound produced by vacuum tube amplifiers is largely due to the non-linear distortion of the tube itself.
- The project aims to develop a model to artificially add the desirable tonal qualities of the vacuum tube to music played through a solid-state amplifier.





Our Initial Observations:

The model was derived based upon observations of the vacuum tube's unique spectral 'fingerprint'. The plots above reveal this 'fingerprint' to be the generation of harmonics.

Design

Fundamental Concept

- We wish to develop a computational model that accurately represents vacuum-tube behavior
- The model alters the audio input to simulate the nonlinear distortions of the tube amp

Functional Requirements

- Ability to emulate the spectral characteristics of a vacuum tube amplifier
- Robust software model to be used over multiple signals at different frequencies and amplitudes
- Model signal statistically emulates the tube amplifier's temporal output signal

Non-Functional Requirements

- Software should provide ease of weighting model parameters to enhance output signal

Operating Environment Constraints and Engineering Standards

- Model supports single tone signals within the range of the audible frequencies and amplitudes as input signals
- Software model developed using MATLAB
- Employed IEEE standards

Model Development

A given signal is modelled as the first five harmonic frequencies derived from the following equation.

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

Each model coefficient was found by solved using non-linear least squares regression via numerical algorithm (Gauss-Newton):

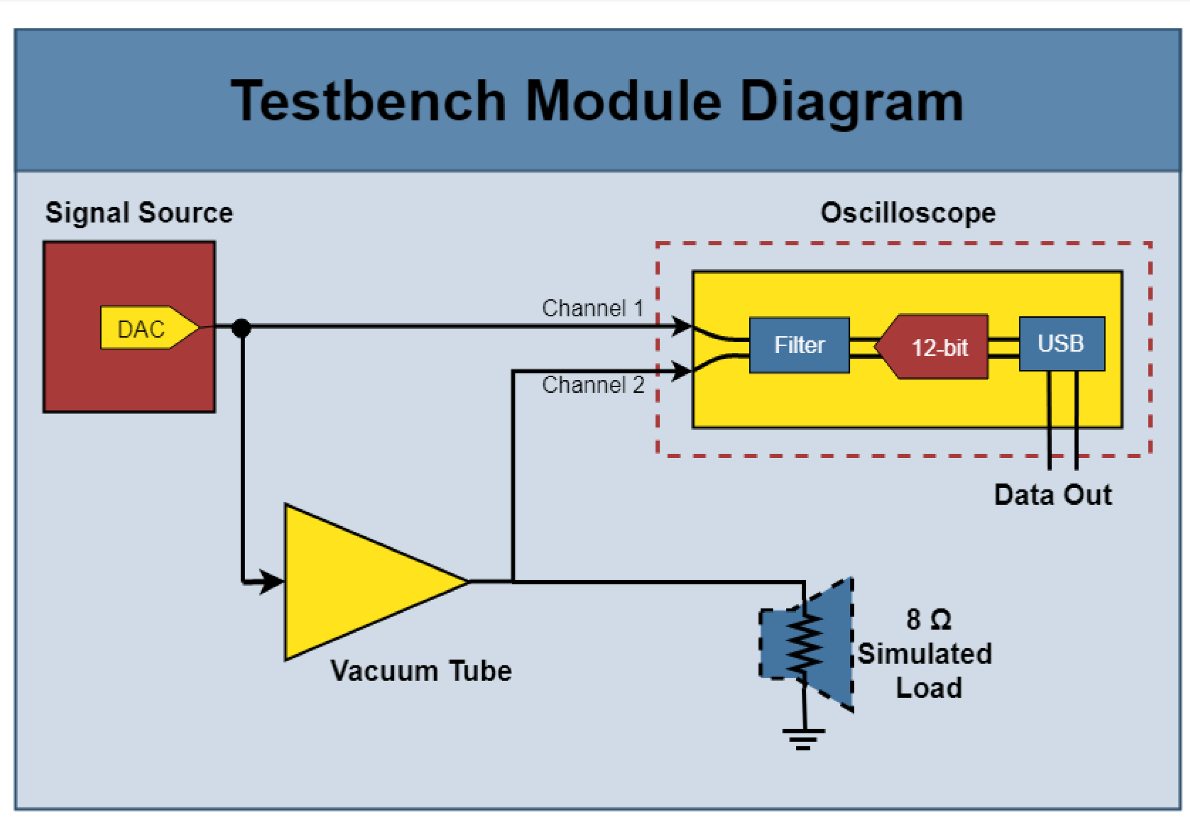
$$\alpha_k \approx \alpha_k^{i+1} = \alpha_k^i + \Delta\alpha_k$$

$$\Rightarrow M(v_{in}^i, \alpha) \approx M^i(v_{in}^i, \alpha) + \sum_k \frac{\partial f(v_{in}, \alpha)}{\partial \alpha}(\beta_k - \beta_k^i)$$

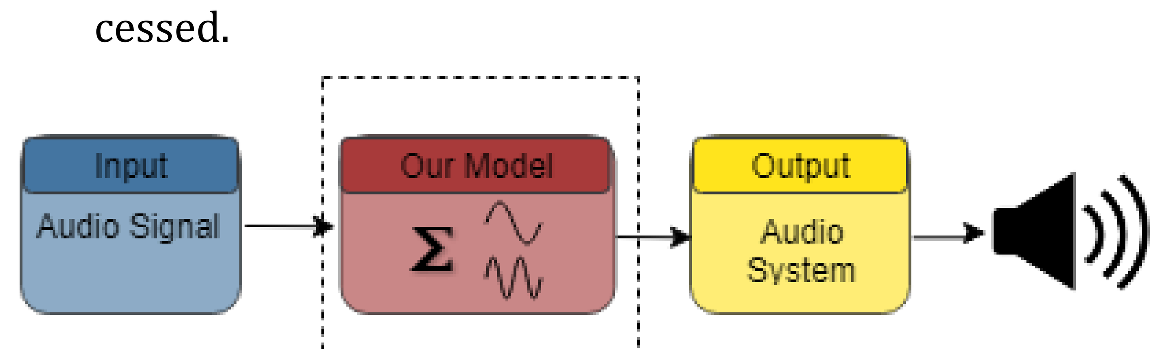
Modeling Pseudocode:

```
for each data_signal {
    Sync Data to a Consistent Start Point
    Initial_Parameters = Initial Least Fit Squares Modeling
    Adjust Amplitude Parameters to be Positive
    Adjust Phase Shift Parameters to be within [-π, π]
    Final_Parameters = Remodel using Least Fit Squares
}
```

Data Acquisition



- Data acquisition goal is to gather voltage data at various frequencies and amplitudes.
- The data is used to develop non-linear regressions.
- High fidelity sinusoidal signal (THD <-60dB) source is used as the input to the tube amplifier device
  - Signal amplitude and frequency are systematically changed to yield a family of static X-Y (transfer) characteristics
  - Vacuum tubes exhibit unique behavior when overdriven to "clipping" state
- Linear-load is used to simulate speaker impedance
- Data is acquired using an oscilloscope with particular settings:
  - LPF set to limit input bandwidth to 20MHz
  - High-resolution mode sets input ADC to 12bits of ENOB
- Data is stored into stack memory that can interface with standard USB storage devices
  - Collected data is formatted into column separated vector (.CSV) files and exported into software to be processed.



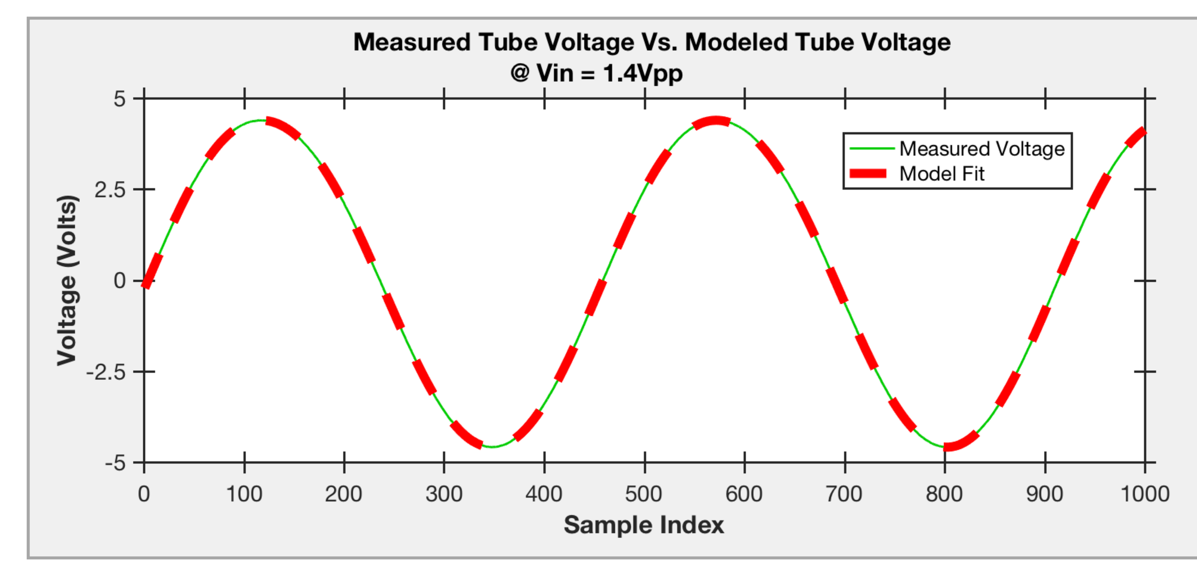
Validation

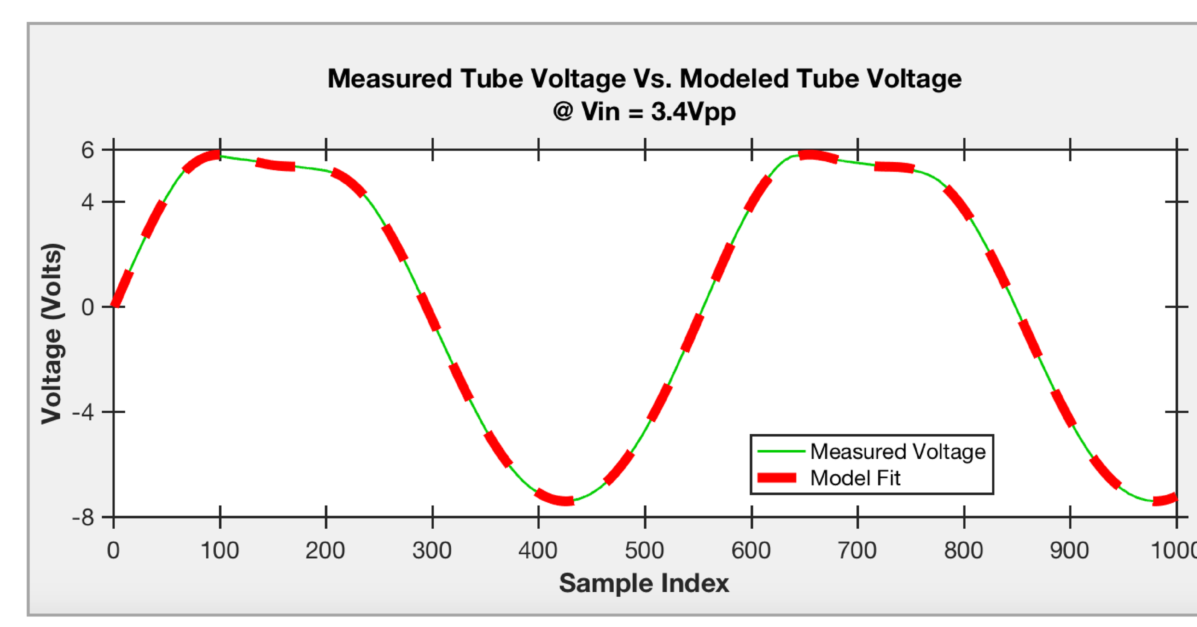
Figures of Merit:

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

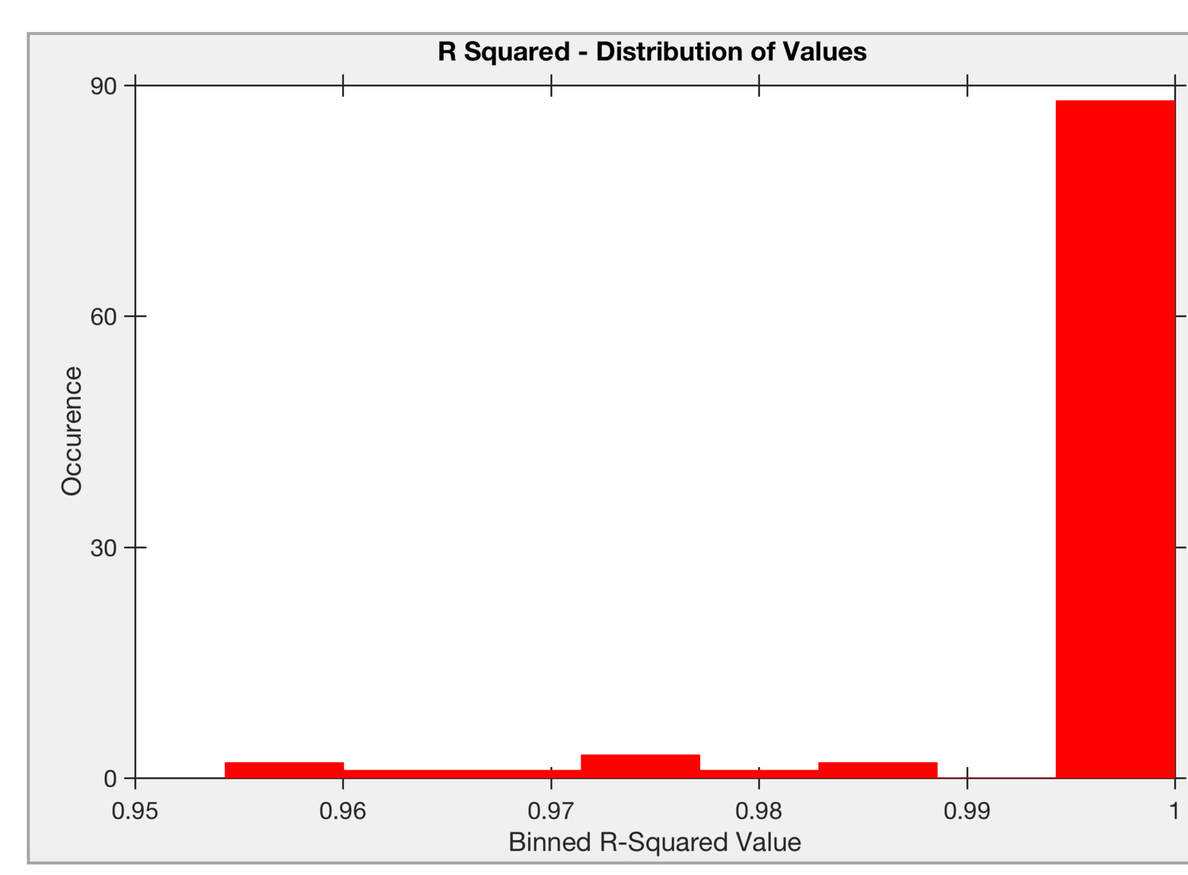
II.) The model accurately tracks real vacuum-tube amplifier characteristics

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





The plots above demonstrate the "goodness of fit" of the model, comparted to the measured tube data



The histogram above demonstrates the distribution of the coefficient of determination ,R-squared for all collected data.

Results

- The unique nature of overdriven vacuum tube devices was explored
- 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
- It was shown that all regressions in the model have a goodness of fit of at least $R^2 = 0.95$
- Further investigation of the results of the project are needed to develop an 'interpolating' model the encompasses all frequencies and amplitudes