DSP Implementation of a 1961 Fender Champ Amplifier

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Project Summary

This project will use a 32-bit floating-point DSP to generate the distortion characteristics of a 1961 Fender Champ Amplifier at its 12 different volume settings by modeling its nonlinear cascaded layout. Nonlinearities produced from this configuration are thought to be the primary reason for the improved quality of sound. Audio signals either saved to file or generated by a guitar via an A/D interface to the DSP will be passed through C/C++ or assembly language digital filters with different gains. The output from the D/A converter will be either stored to file for analysis in MATLAB or interfaced to a set of speakers to play back the filtered input.

Functional Description

Inputs/Outputs
The system inputs will be an analog audio signal from either a guitar A/D interface or a saved audio file, and a software or hardware based volume selection will regulate the filters' behavior. The output will be an audio signal with similar effects to a tube amplifier. This signal will either be displayed in MATLAB, or the D/A converter output will be interfaced to a set of speakers.

Modes
The system modes will consist of the 12 volume settings similar to those provided with the 12-volume switch on the 1961 Fender Champ. If time permits, other effects or modes can be programmed onto the DSP including echo, reverberation, fuzz, and vibrato.

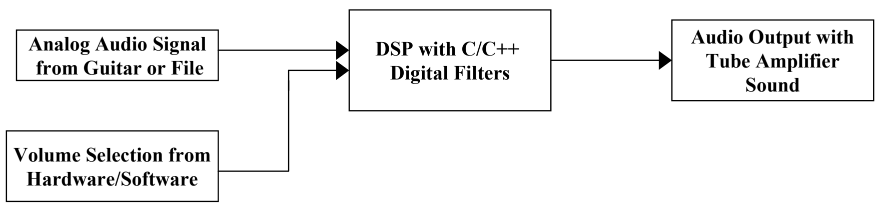


Figure 1: Overall Block Diagram

Methods
One of three methods will be used to obtain the sound of a 1961 Fender Champ:

- One approach will consist of a number of digital filters followed by a summer. The nonlinear model from the summed filter outputs will produce the frequency response of the tube amplifier within the frequency range that can be handled by the DSP. Each input sample will be placed in memory and processed on a sample-by-sample basis as each input becomes available. The result will be a real-time filter with infinite duration once the DSP is initialized. The block diagram of this method can be seen on the next page.

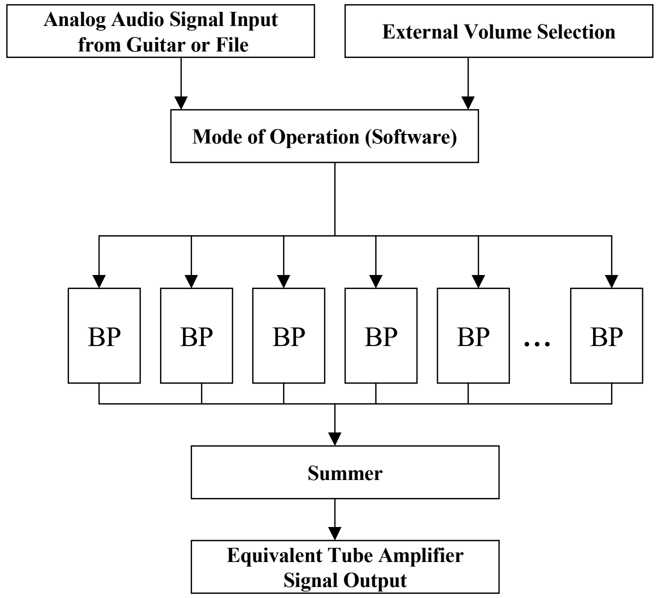


Figure 2: Multiple Bandpass (BP) Digital Filter Approach to Tube Amplifier DSP Model

- Another approach will involve taking the FFT of the input before it is sent to the digital filters for conditioning the amplitude response in the frequency domain. The system will process the input once a memory buffer is filled with new data. The IFFT can then be taken from the summed result of the filtering scheme, and the output will be sent to a D/A converter. This method can be seen below.

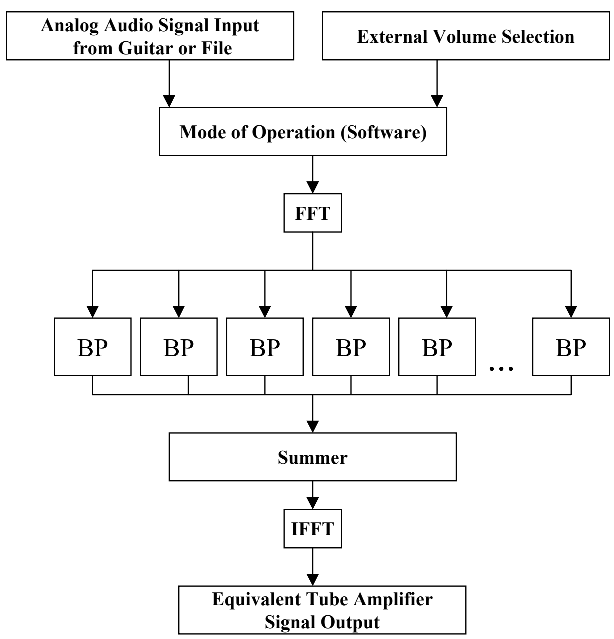


Figure 3: FFT Filter Network Approach to Implement a Bandpass (BP) Filter Bank for Tube Amplifier DSP Model

- The final approach to the digital filtering algorithm is multirate signal processing where the frequency response is broken into several subbands using a multistage lowpass (LP) and highpass (HP) filtering network [1]. This first stage is defined as the Analysis Filter Bank. The final output is then reconstructed by decoding the encoded frequency bands, up-sampling the response, and summing both filtered results to be up sampled by another stage. This final network is the Synthesis Filter Bank. Thus, this method can provide the means for modeling the Champ's nonlinear network while processing a wide range of frequencies from the guitar input with lower order filter designs. Again, filter gains will be controlled according to the volume selection from the user. This optimum method can be seen in the figure below.

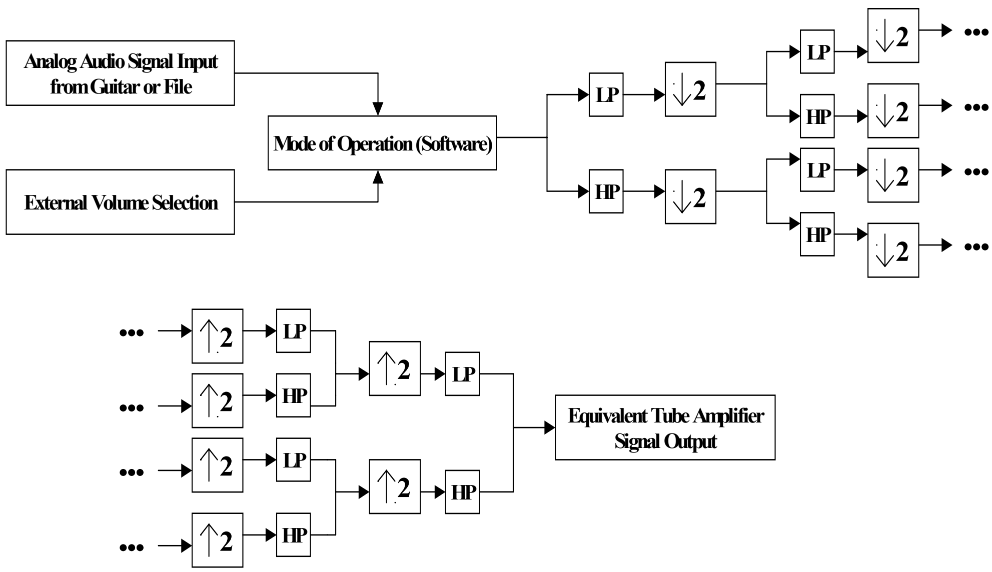
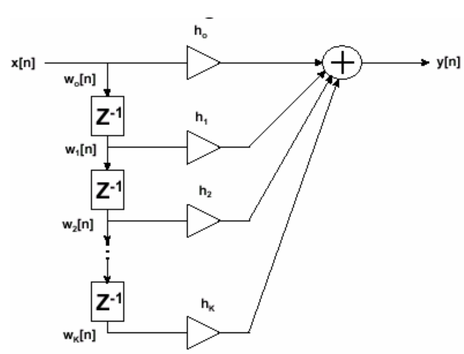


Figure 4: Multirate Signal Processing Approach to Tube Amplifier DSP Model

The digital filtering algorithm to model the nonlinearities of the tube amplifier will be performed with FIR filter designs. If the algorithm's noise floor is greater than the 16-bit input's noise floor, the FIR models will provide the best magnitude response in addition to a linear phase response.



$$y[n] = \sum_{k=0}^{\infty} h[k]x[n-k]$$

Figure 5: FIR Digital Filter Algorithm

Previous Work

Patents

Two patents have the same objective as this project, but both DSP algorithms do not involve any of the approaches discussed in the previous sections. Also, neither patent intends to specifically model the 1961 Fender Champ. The patents are listed below.

- <u>Tube Modeling Programmable Digital Guitar Amplification System</u>
  - U.S. Patent 5,789,689 – August 4, 1998
  - Employs a sampling rate conversion algorithm to model the nonlinear transfer function of the tube circuitry.

- <u>Electric instrument amplifier</u>
  - U.S. Patent 6,350,943 – February 26, 2002
  - Employs a sampling rate conversion algorithm to model the nonlinear transfer function of the tube circuitry.
  - Includes a tube configuration and a solid-state power circuit on the D/A output of the DSP board.

Standards

The only applicable standards to this project include the means to program the linear guitar effects following the nonlinear tube modeling stage. Several resources are available to implement these features if the main portion of the project is completed.

Laboratory Materials

Datasheet
All necessary information for operation of this design can be referenced from the Texas Instruments manual. Any user of this project result will not want or need to read any datasheets, but will want to begin to play music with the device.

Equipment List
All required components for the guitar interface to the DSP board's A/D converter and for the speaker interface to the D/A converter are available, leaving no parts to be ordered.

Laboratory Research

In order to develop the most accurate DSP model of the 1961 Fender Champ's sound, several experiments had to be performed in the laboratory to gain a thorough understanding the amplifier's behavior for various inputs. Most test inputs to the Champ were sinusoidal with the exception of one set of data taken from a 1952 Fender Telecaster. Frequencies chosen for the sinusoids were available from guitar note frequency chart seen below [3].

Guitar Note Frequencies

Chromatic Scale 12 half-notes per octave				Diatonic Scales (Major) (7 notes per octave)					Frequency Hz.	12th Root of 2 (2.000000128)
Piano octaves	Guitar octaves	Note # Key of E	Guitar String	Key of E	Key of G	Key of A	Key of C	Key of D	A octaves	A octaves
E	E	1	# 6	do (1)					329.63	1.0594631
F	F	2							349.23	1.0594631
F#	F#	3		re (2)					369.99	1.0594631
G	G	4		mi (3)	do (1)				392.00	1.0594631
G#	G#	5							415.30	1.0594631
A	A	6	# 5	fa (4)	re (2)	do (1)			440	1.0594631
A#	A#	7			mi (3)				466.16	1.0594631
B	B	8		so (5)		re (2)			493.88	1.0594631
C	C	9		la (6)	fa (4)	mi (3)	do (1)		523.25	1.0594631
C#	C#	10							554.37	1.0594631
D	D	11	# 4	ti (7)	so (5)	fa (4)	re (2)	do (1)	587.33	1.0594631
D#	D#	12			la (6)		mi (3)		622.25	1.0594631
E	E	1		do (1)		so (5)		re (2)	659.26	1.0594631
F	F	2			ti (7)	la (6)	fa (4)	mi (3)	698.46	1.0594631
F#	F#	3		re (2)					739.99	1.0594631
G	G	4	# 3	mi (3)	do (1)	ti (7)	so (5)	fa (4)	783.99	1.0594631
G#	G#	5					la (6)		830.61	1.0594631
A	A	6		fa (4)	re (2)	do (1)		so (5)	880.00	1.0594631
A#	A#	7			mi (3)		ti (7)	la (6)	932.33	1.0594631
B	B	8	# 2	so (5)		re (2)			987.77	1.0594631
C	C	9		la (6)	fa (4)	mi (3)	do (1)	ti (7)	1,046.50	1.0594631
C#	C#	10							1,108.73	1.0594631
D	D	11		ti (7)	so (5)	fa (4)	re (2)	do (1)	1,174.66	1.0594631
D#	D#	12			la (6)		mi (3)		1,244.51	1.0594631
E	E	1	# 1	do (1)		so (5)		re (2)	1,318.51	1.0594631
F	F	2			ti (7)	la (6)	fa (4)	mi (3)	1,396.91	1.0594631
F#	F#	3		re (2)					1,479.98	1.0594631
G	G	4		mi (3)	do (1)	ti (7)	so (5)	fa (4)	1,567.98	1.0594631
G#	G#	5					la (6)		1,661.22	1.0594631
A	A	6		fa (4)	re (2)	do (1)		so (5)	1,760.00	1.0594631
A#	A#	7			mi (3)		ti (7)	la (6)	1,864.66	1.0594631
B	B	8		so (5)		re (2)			1,975.53	1.0594631
C	C	9		la (6)	fa (4)	mi (3)	do (1)	ti (7)	2,093.00	1.0594631
C#	C#	10							2,217.46	1.0594631
D	D	11		ti (7)	so (5)	fa (4)	re (2)	do (1)	2,349.32	1.0594631
D#	D#	12	(fret#)		la (6)		mi (3)		2,489.02	1.0594631
E	E	1	1(12th)	do (1)		so (5)		re (2)	2,637.02	1.0594631
F	F	2	1(13th)		ti (7)	la (6)	fa (4)	mi (3)	2,793.83	1.0594631
F#	F#	3	1(14th)	re (2)					2,959.96	1.0594631
G	G	4	1(15th)	mi (3)	do (1)	ti (7)	so (5)	fa (4)	3,135.96	1.0594631
G#	G#	5	1(16th)				la (6)		3,322.44	1.0594631
A	A	6	1(17th)	fa (4)	re (2)	do (1)		so (5)	3,520.00	1.0594631
A#	A#	7	1(18th)		mi (3)		ti (7)	la (6)	3,729.31	1.0594631
B	B	8	1(19th)	so (5)		re (2)			3,951.07	1.0594631
C	C	9	1(20th)	la (6)	fa (4)	mi (3)	do (1)	ti (7)	4,186.01	1.0594631
	C#	10	1(21th)						4,434.92	1.0594631
	D	11	1(22th)	ti (7)	so (5)	fa (4)	re (2)	do (1)	4,698.64	1.0594631

(1)=Tonic (5)=Dominant
(4)=Sub-dominant (7)=Seventh

Each horizontal line = 1 half-note = 1 fret
Chromatic Scale = Each half-note is 5.95% higher in frequency than the previous note.

Figure 6: Guitar Note Frequencies

PSPICE Simulations

First, PSPICE Transient Analysis simulations were completed for –20V to 60V sinusoidal inputs at 1 (kHz) to tube amplifier configurations for the 12AX7 triode and 6V6GT pentode tubes included in the 1961 Fender Champ design. The simulation results can be seen below and on the following page.

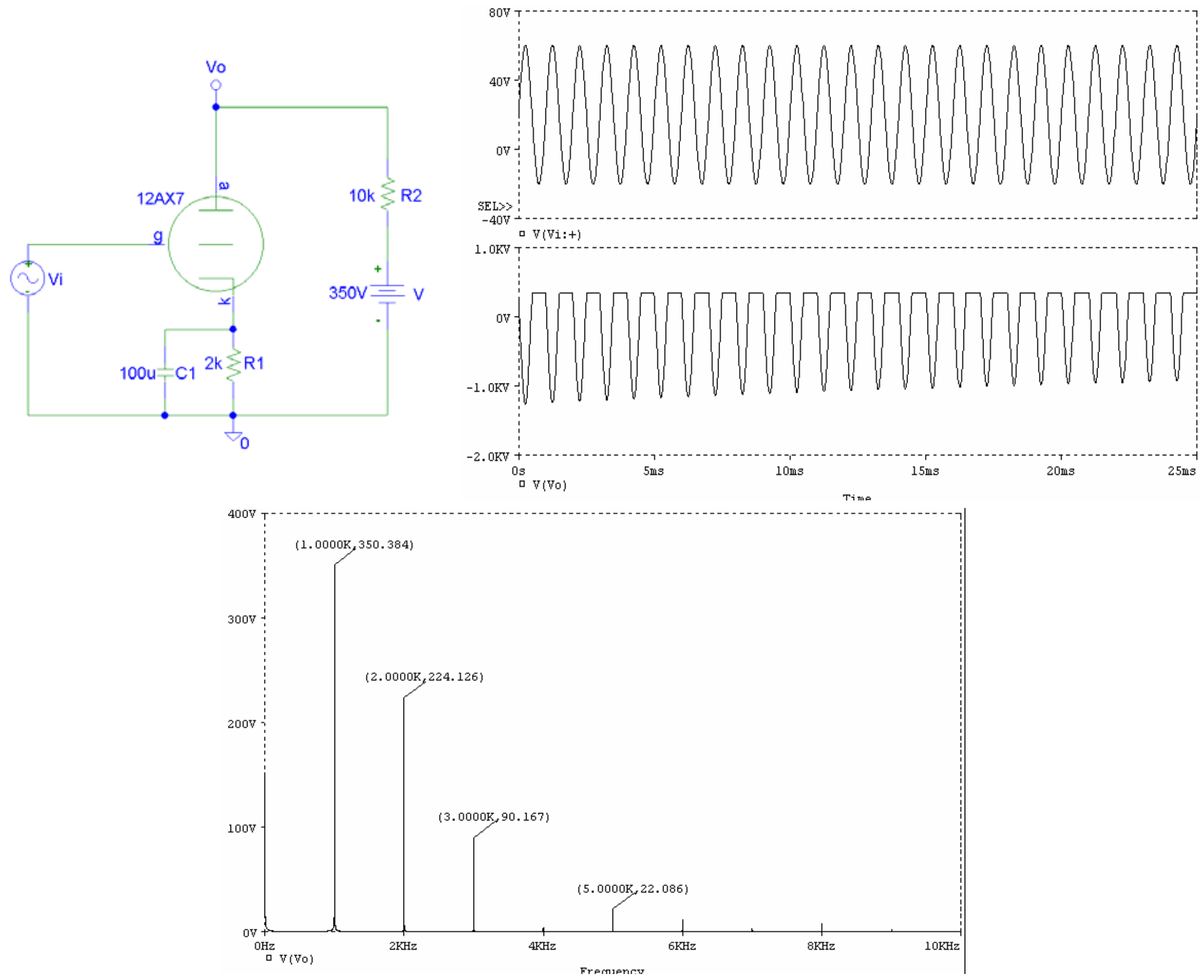


Figure 7: 12AX7 Triode PSPICE Transient Analysis Simulation Results

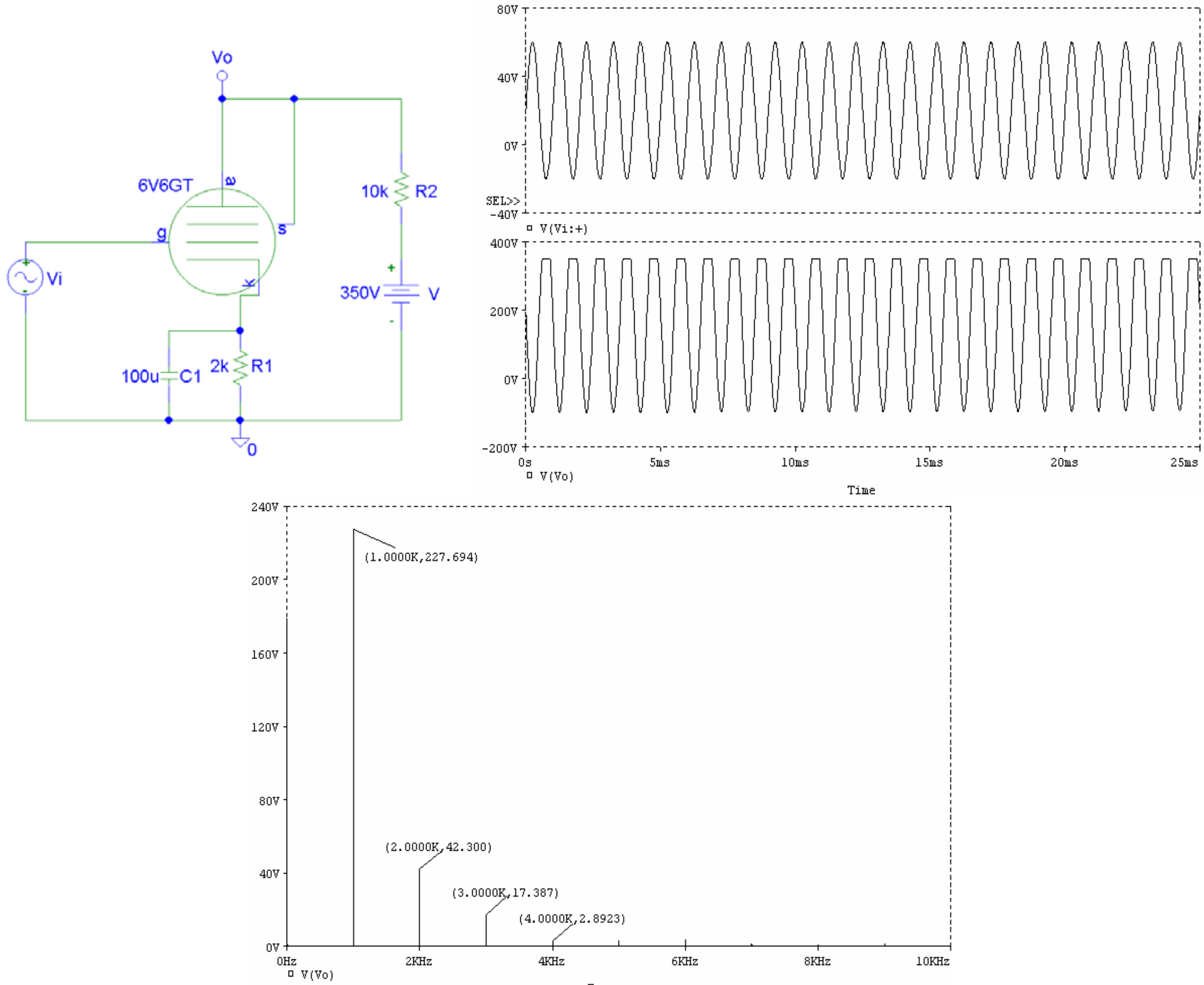


Figure 8: 6V6GT Pentode PSPICE Transient Analysis Simulation Results

From the simulation plots in **Figure 7** and **Figure 8**, both tube amplifier configurations produced the expected output of a dominant first harmonic component, a second harmonic with approximately half the amplitude of the first harmonic amplitude, and successive harmonic components [1].

16-bit Digital Audio Data from 1961 Fender Champ Output

Following the simulations, the amplifier was taken to the Acoustics Laboratory to measure the output from the speaker. Inputs to the amplifier included one guitar input and 1Vp sinusoids at twelve of the frequencies listed in **Figure 6**. The 1 (V) amplitude was chosen since guitar strings produce waves with amplitudes as high as 1 (V). Cool-Edit software recorded the amplifier output at three of the Champ's different volumes through a microphone connected to a 16-bit A/D converter. This data was saved in '.wav' format and read into an array in MATLAB with the 'wavread ()' command. The sampling frequency was set to 44.1 (kHz), the standard sampling rate for audio stored on compact disks. Some sample plots from this investigation are on the next page.

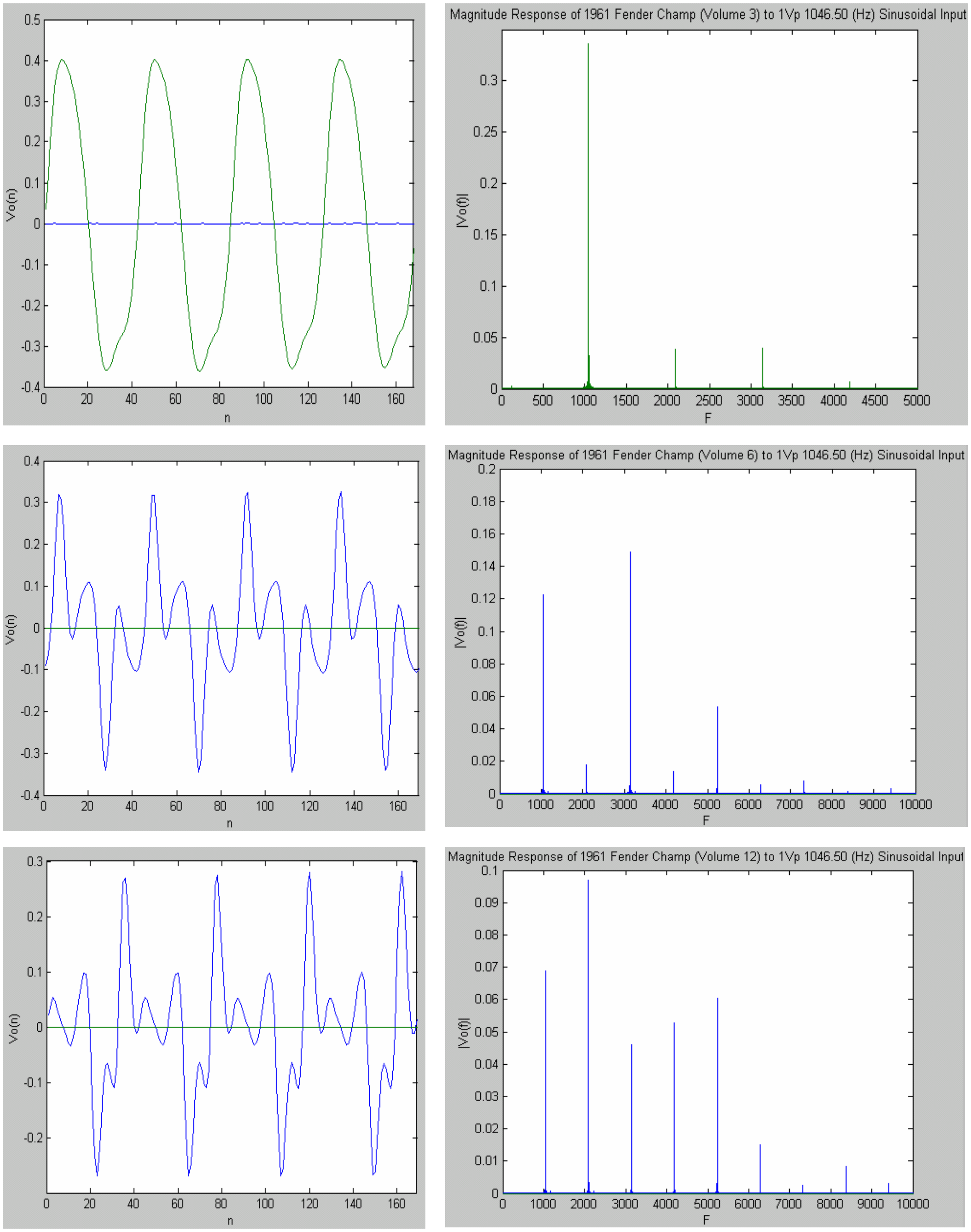
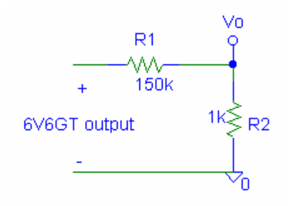


Figure 9: Fender Champ Output in 16-bit Digital Audio Data for 1Vp 1046.50 (Hz) Sinusoid at Volumes 3, 6, and 9

From this investigation, lower frequency inputs exhibited a distorted output with an increased 'ringing' effect as frequency increased to ~1000 (Hz). At 1046.50 (Hz), the 'ringing' seen on the output of the Champ reached its peak such that a 3rd and 2nd harmonic component were both higher than the first harmonic as seen in **Figure 9**. This output was not expected, but assumed to be due to a resonance effect from the amplifier's output transformer. Higher frequencies above ~2000 (Hz) did not exhibit a significant amount of harmonic distortion.

Output of 1961 Fender Champ at Single-Ended Power Tube Stage
To verify the unexpected results in Figure 9 were contributed by the output transformer's frequency response characteristics, the output of the Champ at the single-ended power tube stage before the transformer was measured on an oscilloscope. Since tube circuits are characterized by high output voltages, a voltage divider connected to the 6V6GT output of the Fender Champ allowed the oscilloscope to measure the output at lower amplitudes.



Vo = (R2/(R1+R2))*6V6GT output = 0.00662*6V6GT output

Figure 10: Voltage Divider to Measure Output of Single-Ended Power Stage

This 'Vo' measurement was saved and opened in MATLAB to view the frequency response. The test input for this exercise was a 1Vp 1046.50 (Hz) sinusoid as in **Figure 9** since the worst frequency response was exhibited for this particular frequency. The output for volume 12 on the amplifier can be seen below.

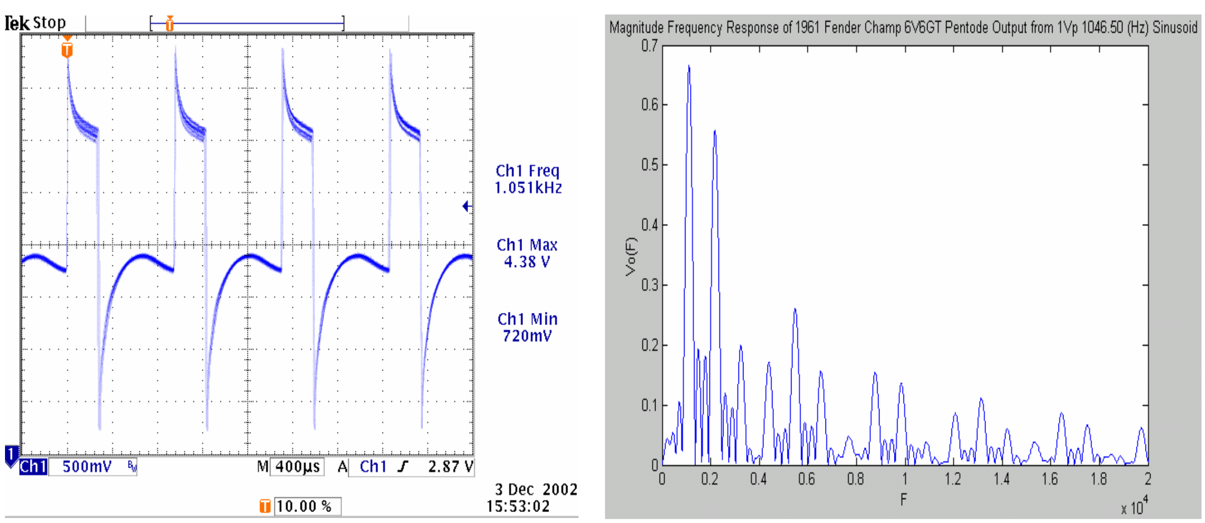


Figure 11: Output at Single-Ended Power Tube Stage of 1961 Fender Champ at Volume 12 for a 1Vp, 1046.50 (Hz) Sinusoidal Input

From the frequency domain plot in **Figure 11**, one can see that there is a dominant 1st harmonic component as expected from the tube output. The transformer removes all harmonics above 10 and also alters the frequency response of the Fender Champ.

Output of 1961 Fender Champ for 1952 Fender Telecaster Input

The output of the Fender Champ from a guitar input can be seen below and was taken so that later data from the DSP implementation could be correlated with the previous results.

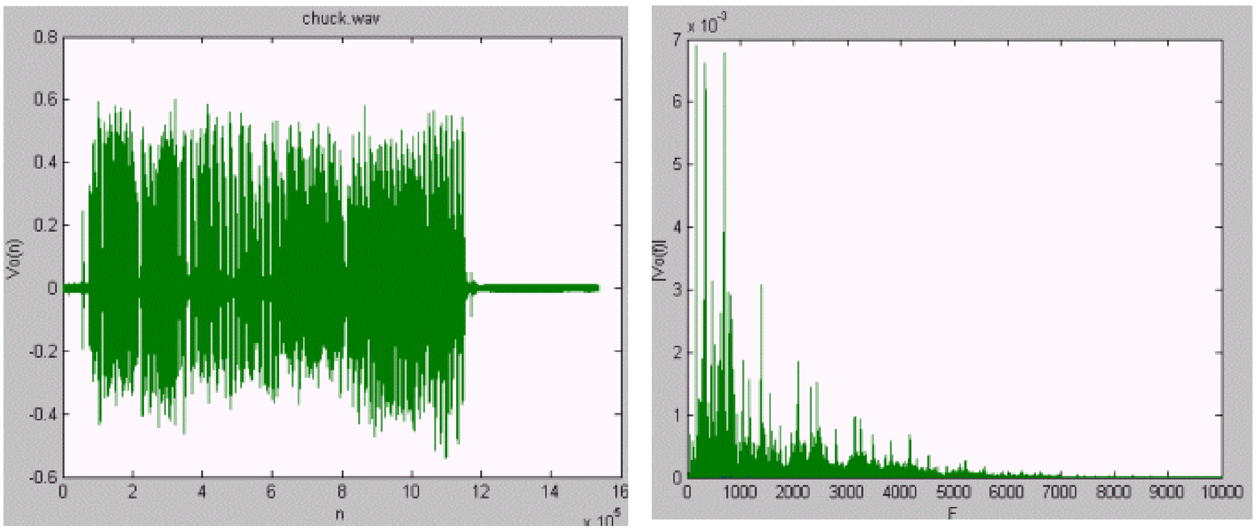


Figure 12: Fender Champ Output from a 1952 Telecaster Input

Conclusion

From all the laboratory data, a nonlinear transfer characteristic can be developed in conjunction with the data available for the 12AX7 and 6V6GT tube data sheets.

Schedule

Laboratory Week #'s	Task
1-4	Complete and simulate model of Fender Champ in MATLAB from obtained 12AX7 and 6V6GT tube data sheets
5-8	Complete software to program the actual DSP board and interface the appropriate hardware to the A/D converter and the D/A converter
9-12	Extra time allotted to complete weeks' 1-4 and 5-8 tasks
13-14	Senior 2003 Expo Preparation
15-16	Senior Project Presentation

References

[1] Barbour, Eric. "The Cool Sound of Tubes." Ed., Michael J. Riezenman. IEEE Spectrum August 1998. 1998. Google. IEEE. 12 pp. Google. 11 Oct 2002. <http://www.spectrum.ieee.org/select/0898/tube.html>.

[2] Digital Signal Processing: Principles, Algorithms, and Applications. John G. Proakis, Dimitris G. Manolakis. Third Edition. Upper Saddle River, New Jersey: Prentice Hall, 1996 pp. 832-834.

[3] Guitar Note Frequencies. Google. 11 Nov 2002. <http://home.pacbell.net/vaughn44/m3.music.notes.6.pdf>