Design and Implementation of a Vacuum Tube Overdrive Guitar Pedal (June 2009)

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I. Introduction

Beside the basic setup of electric guitar and amplifier, guitarists have many other ways of altering their overall guitar tone. One option is to add an overdrive pedal in series with the guitar before reaching the input of the amplifier. The principle of an overdrive pedal is to amplify and distort the signal coming from the guitar in such a way that is pleasing to the guitarist's ear. In the case of vacuum tubes, which have pronounced 2nd order harmonic distortion, this results in asymmetrical clipping. Essentially, the idea behind this design was to create the sound of a vacuum tube amplifier – which tends to be expensive – at the cost and size of a pedal – which tends to be inexpensive. To implement the overdrive pedal, hand calculations and PSPICE simulations were used to achieve a theoretical circuit response, followed by the construction of a prototype to test actual performance.

II. Architecture Design

A. Design Specifications

The pedal was designed to accept input signals from electric guitars, and output signals to guitar amplifiers. This requires a high input impedance, to minimize signal loss from the guitar to the pedal, and low output impedance, to minimize signal loss from the pedal to the amplifier. The topology was to provide sufficient internal gain such that the signal distorts, producing 2nd order harmonics. Since the pedal is designed to operate at a high voltage, power constraints were limited to those of the components. Finally, a volume control was necessary to ensure that the input of the guitar amp was not damaged from excessive output voltage from the pedal.

B. Discussion on the chosen architecture

The circuit consists of three stages: two common-cathode amplifiers, and a cathode follower. The first common-cathode stage provides significant gain to the input signal. To produce the desired distortion, a second common-cathode stage, which has a potentiometer at the input to vary the gain, is pushed into the saturation and cutoff regions from the large first stage output voltage, which produces the desired asymmetrical clipping of the signal. The final stage is a cathode follower, which has close to unity gain, to ensure low output impedance so that there is little signal loss when the pedal is connected to a guitar amplifier input.

III. Circuit Design

A. Schematic

Figure 1 represents the topology of the overdrive pedal, V1, V2, V3 being the 12AX7 triodes.

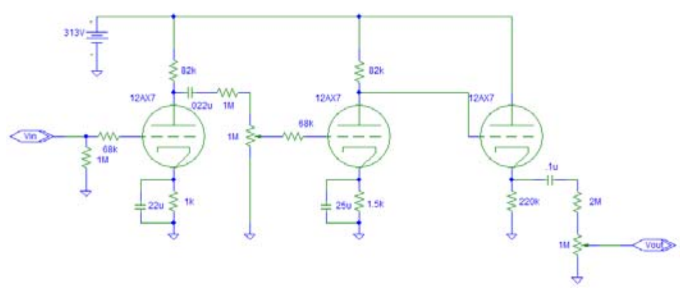

Fig. 1: Complete circuit schematic of the overdrive pedal.

B. Design methodology

Each stage was designed individually, with the assumption that a dc-blocking capacitor between the two common cathode stages wouldn't significantly alter their respective responses. First, load-line analysis techniques were used to determine the operating point of each stage. To minimize the size of the power supply transformer, an initial voltage of 250V was used during the design process, which set the maximum plate voltage for load-line analysis. The first common-cathode stage was designed to amplify the guitar signal with minimal distortion, while the second stage was to provide the clipping for the pedal. To ensure that the entire frequency range of the guitar signal was not attenuated, large cathode bypass and dc-blocking capacitors were used.

C. Simulation results

Figures 2 through 5 exhibit the output characteristics at various gain settings of the overdrive pedal.

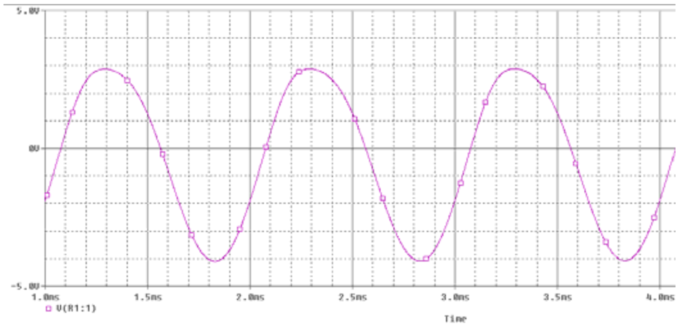

Fig. 2: Output waveform with a 100mV$_{pk\text{-}pk}$ input at 1 kHz with maximum volume and moderate gain

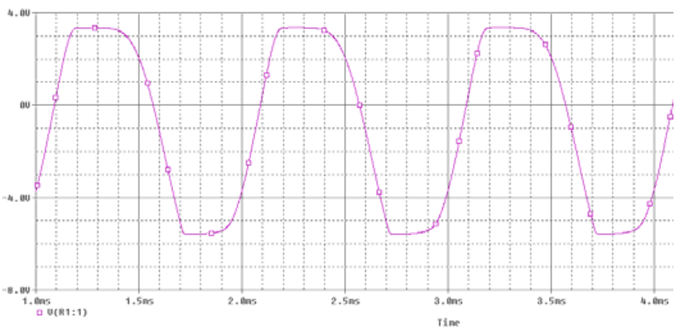

Fig. 3: Output waveform with a 100mV$_{pk\text{-}pk}$ input at 1 kHz with maximum volume and gain

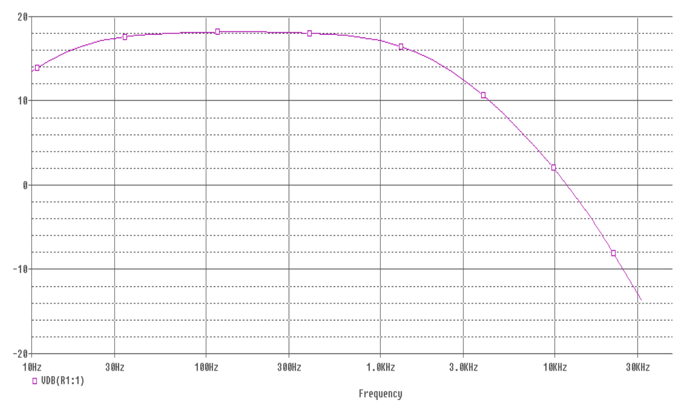

Fig. 4: Frequency response at maximum gain.

As is evident in figures 2 and 3, the pedal can boost the input signal without significant distortion, as well as impose asymmetric clipping. The frequency response seems to have a fairly narrow pass band, especially considering that the frequency spectrum of a guitar extends past the cutoff frequency of the simulated pedal.

IV. Prototype Results

Once the simulations were completed, a prototype pedal was constructed. The first test that was performed on the pedal was verifying DC operating points. The most noticeable difference was the supply voltage: it read 330V. The power transformer that was ordered stated that it had a 120V secondary, but the transformer that arrived actually had a 200V secondary. Due to the difference in power transformer, the pedal was tested with a simple RC power supply network to ensure maximum voltage ratings weren't reached. Although the supply voltage was much larger than expected, the voltages all were under the maximum ratings.

The next test was to ensure that the output voltage was within acceptable limits, so as not to damage the input circuitry of the guitar amp. Using the AC voltage measurement ability of a multimeter, a very large AC voltage was noticed at the output, even without an input signal. Without the use of an oscilloscope, it was assumed that hum and noise in the circuit was being amplified. As shown in figure 1, the output potentiometer is in series with a 2MΩ resistor. This resistor was added to ensure that the maximum output voltage would not damage the input of a guitar amp.

After inserting the large resistor at the output, the pedal was tested with a guitar. A solid-state bass guitar amplifier was used during testing. Since this type of amplifier is designed to have little to no distortion in the output signal, the "true" tone of the pedal was heard. The sound while playing through the pedal was surprisingly close to the intended sound, which was the overdrive and distortion of a complete tube guitar amplifier. Unlike simulations, however, distortion seemed to occur earlier in the gain control than expected. To alleviate this problem, a 1MΩ resistor was added in series with the gain control potentiometer to attenuate the input signal of the second stage further. After this resistor was added, a greater range of overdrive was available.

One problem was present throughout the entire testing process: hum. Figure 5 shows a screenshot of the output voltage with no input signal.

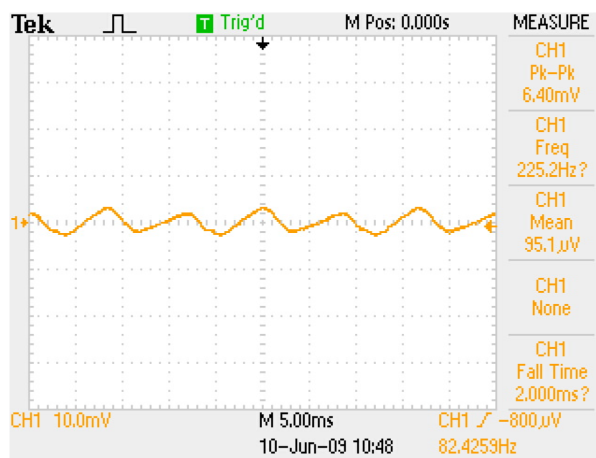

Fig. 5: Output voltage without input signal after minimizing hum

The waveform is very recognizable as power supply ripple. Although the image shows conflicting frequencies, it was found that the frequency of the signal was 120Hz. The first step involved adding more capacitance to the power supply circuit. This attenuated the ripple very mildly, so a complete rewiring of the circuit was carried out. The "star-ground" method – having a single ground point to connect each leg of the circuit to – was used to try to avoid ground interference, all signal carrying wires were minimized, and the heater supply wires were wound very tightly to avoid electromagnetic interference. Once again, the ripple was very noticeable at the output. The final step was to convert the AC heater voltage supply to DC. This turned out to be the major hum contributor, and the change greatly reduced the audible hum. Although hum was still present, it was at a much more tolerable level.

After making the stated changes to the pedal, the DC, frequency, and transient responses were measured. Table 1 displays the DC operating points of the three triodes, as well as the heater and high voltage supplies.

Table 1: DC operating voltages

	Voltage (V)
Anode (V1)	205
Cathode (V1)	1.284
Anode (V2)	224.7
Cathode (V2)	1.513
Anode (V3)	311
Cathode (V3)	225.6
B+ Supply	311
Heater Supply	6.06

After the addition of extra capacitance to the power supply circuitry, the voltage dropped slightly to 311V. This was acceptable for the design, and had little to no audible affect. Also, the heater supply voltage did not quite reach the value of 6.3V, which is the operating voltage given by the 12AX7 datasheet.

Figures 6 through 8 show the output signal with a 1 kHz sine wave at the input. The pedal was set for maximum gain and volume, and the input voltage was varied to display the differing amounts of clipping that can occur.

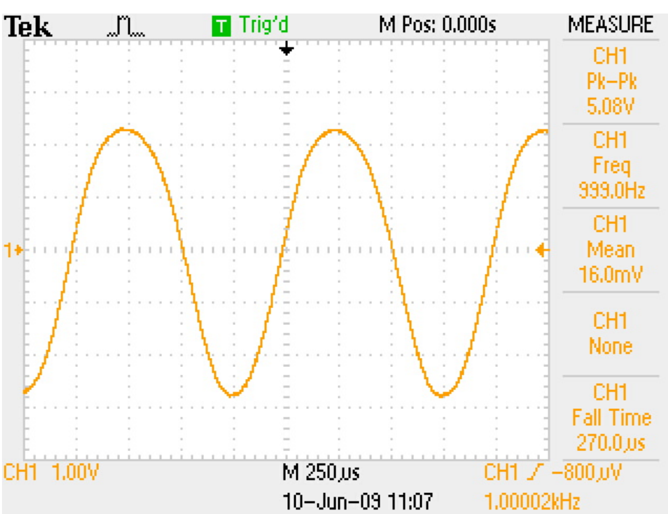

Fig. 6: Output waveform with a 100mV$_{pk-pk}$ input at 1 kHz with maximum volume and gain

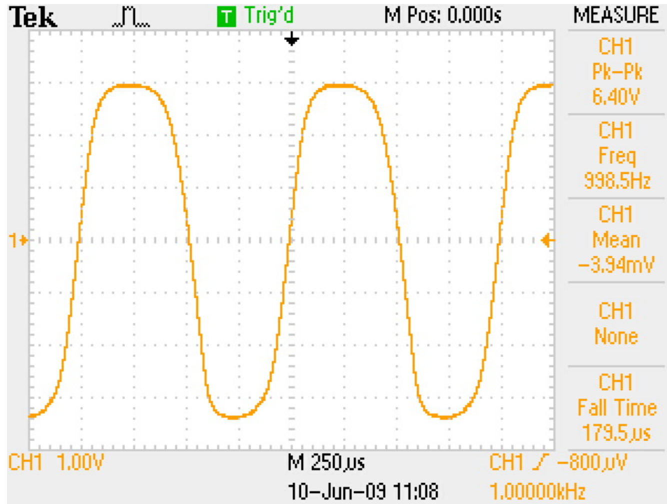

Fig. 7: Output waveform with a 200mV$_{pk-pk}$ input at 1 kHz with maximum volume and gain

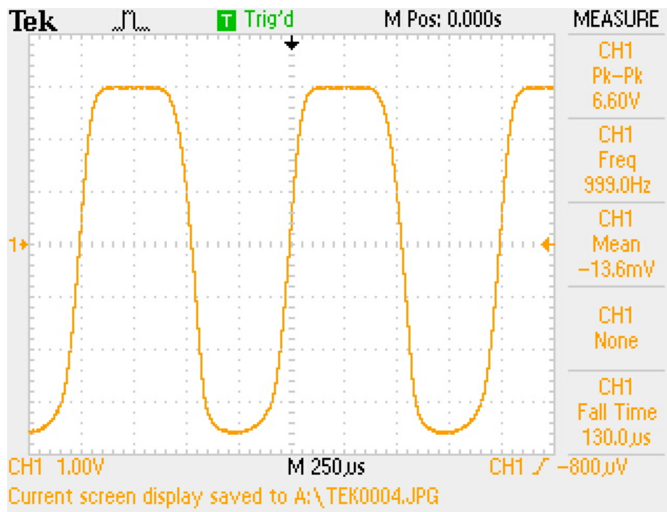

Fig. 8: Output waveform with a 300mV$_{pk-pk}$ input at 1 kHz with maximum volume and gain

As expected, when the input voltage was increased, so did the amount of clipping.

To measure the frequency response of the pedal, the input signal was returned to 100mV$_{p-p}$, and the output was measured as the frequency was swept. Figure 9 depicts the measured response.

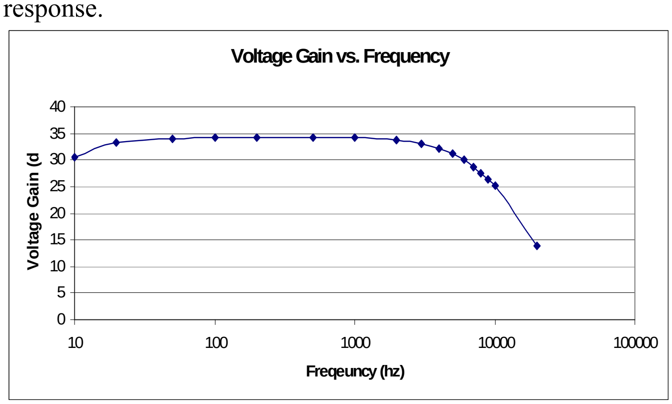

Fig. 9: Output waveform with a 300mV$_{pk-pk}$ input at 1 kHz with maximum volume and gain

When compared to the simulated frequency response shown in figure 4, there were two distinct differences. First, the pass band magnitude was greater for the prototype, even though the simulated circuit had the same components and supply voltage. Also, the actual cutoff frequency was much higher for the prototype – about 5 kHz – as opposed to the simulated cutoff of about 2 kHz. This difference is most likely due to the fact that the simulations are based on models that don't completely match the characteristics of a real 12AX7.

Finally, the power consumption of the pedal was calculated. To do this, the current through each triode was determined by measuring the voltage across the each plate resistor. The sum of these currents was multiplied by the power supply voltage to get the first portion of the power consumption. The rest of the power is dissipated through the heaters of the tubes. Not being sure how to measure the current through the heaters, the nominal value of 300mA per tube was used from the datasheet as an estimate, and multiplied by 6.06V, the measured DC voltage across the heaters. Summing the values, the power dissipation is found to be:

$$P = P_{circuit} + P_{heaters}$$

$$P = (311V * 3.61mA) + (6.06V * 600mA) = 4.76W$$

V. Conclusion

Although the prototype circuit had differing frequency and DC responses, it sounded remarkably close to the anticipated overdrive effect. The power supply ended up providing a much higher voltage than the circuit was designed for, so perhaps a future implementation of the pedal would use a different power transformer for a reduced supply voltage. This will alter the operating points of the circuit, but the overall tonal effect is harder to determine. Also, the use of a smaller transformer will allow for a more compact enclosure for the pedal, making it much more portable.

As of now the only controls for the pedal are gain and volume, but the addition of a tone control section would allow for a greater range in sounds. There are many different tone control topologies, each with their own unique shaping characteristics, so several circuits could be tested to find the best sounding match to the existing pedal.

Finally, a low power vacuum tube pedal would be interesting to pursue. It would not require the large supply voltages of the current pedal, and would also be much smaller with the lack of a sizeable transformer. The main drawback is that vacuum tubes aren't supposed to be operated at low voltages, so the design process would deal much more with breadboard prototyping and less on design equations.

References

[1] Kuehnel, Richard. *Vacuum Tube Circuit Design: Guitar Amplifier Preamps*, Pentode Press, Seattle, 2007.

[2] Jones, Morgan. *Valve Amplifiers, 3rd Edition.* Great Britian, Elsevier Ltd. 2003.

Appendix

Table 2: Part List and Cost

Part	Qty	Cost Per Part	Total
Hammond 263AX Transformer	1	50.89	50.89
GBU1010 Bridge Rectifier	2	1.59	3.18
450v Electrolytic Capacitor	3	2.50	7.50
35V Electrolytic Capacitor	1	5.49	5.49
25V Electrolytic Capacitor	2	0.20	0.40
2W Carbon Film Resistor	1	0.20	0.20
5W Power Resistor	1	0.50	0.50
1/2W Carbon Comp Resistor	8	0.35	2.80
1/2W Carbon Film Resistor	3	0.10	0.30
12AX7WA Dual Triode	2	8.00	16.00
Audio Taper Potentiometer	2	2.00	4.00
Switchcraft 1/4" Jack	2	2.50	5.00
DPDT Switch	1	3.00	3.00
SPDT Switch	1	4.00	4.00
7-Pin Terminal Strip	2	1.00	2.00
9-Pin Ceramic Tube Socket	2	5.00	10.00
Panel-Mount Fuse Holder	1	2.00	2.00
Totals	**35**		**117.26**