

# Single-Ended Class-A Tube Amplifier Design and Construction

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**Abstract**—The design and construction of a single-ended class-A amplifier is presented. By employing the use of tube technology and transformer coupling, a musical sounding amplifier is devised taking advantage of 2<sup>nd</sup> order harmonic distortion and a shortest possible signal path.

**Index Terms**—Class-A, Audio, Electron Tube

## I. INTRODUCTION

MODERN AUDIO AMPLIFIERS are efficient, noise-free, and can be as powerful as needed for any given application. Electron tube technology, despite being outdated, inefficient, and inherently noisy, still manages to provide a tonal quality that some ears find more pleasing, despite its pitfalls.

Setting out to design and eventually construct a tube amplifier provides several challenges and hazards. Scarce (and therefore expensive) component availability, dangerously high power-supply voltages, and large components with specific layout and construction constraints are among these. The main challenge, however, is a lack of available information on the use of this technology.

The design chosen for this project involves a single ended audio amplifier, which consists of a resistive input network, a driver stage, and an output stage to a typical 8 ohm loudspeaker load, all the while, using a minimum of supportive passive components for biasing and coupling duties. Power-supply voltage is provided by dual half-wave diode rectification of 120 VAC stepped up by a magnetic transformer. Although somewhat trivial, this design provides a quality audio amplifier that can be realized at a reasonable cost.

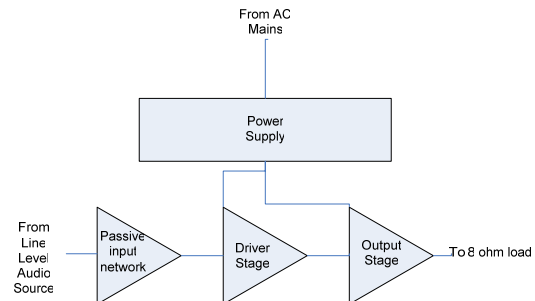


Fig 1. High level block diagram of the amplifier

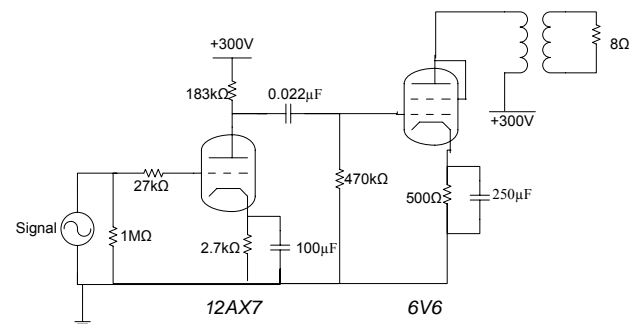


Fig 2. Schematic for the amplifier, omitting power supply

## II. PRE ANALYSIS / DESIGN

### A. The Input Network

The input to the amplifier uses a resistive gamma network.

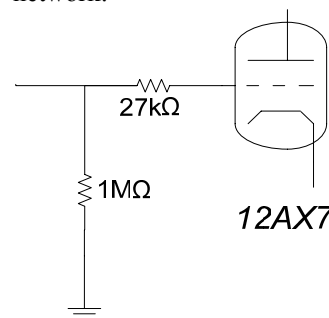


Fig 3. Gamma Network on Input

This configuration serves two major functions. The 1M resistor maintains a path from grid to ground regardless of the state of the input of the amplifier, preventing potential damage to the driver tube caused by source failure[4]. In addition, the Miller capacitance of the 12AX7 is used in conjunction with this network to create a low pass filter designed to prevent HF radio interference from summing with this sensitive stage.

The Miller capacitance of the input stage equated to 151pF, using (1). Note that values for both driver gain ( $G$ ), and capacitance from plate to grid ( $C_{PG}$ ) will be derived in part B.

$$C_M = (G+1)(C_{PG}) \quad (1)$$

Gain of the passive network can be calculated using (2).

$$G = \frac{Z_M}{R_2 + Z_M} \quad (2)$$

Where:

$$Z_M = \frac{1}{2\pi f C_M} \quad (3)$$

Using these formulas, mid-band gain ( $f = 1$  kHz) equates to 0.975, which corresponds to 0.22 dB of attenuation. Commercial radio which begins around 535 kHz is attenuated by 23.34 dB using this design, proving that commercial radio interference is well eliminated. Care must be taken so that the HF attenuation doesn't interfere with the upper end of the audio spectrum, which is discussed in greater detail in B.

### B. The Driver Stage

Design of the driver stage is concerned with voltage amplification as well as linearity in order to provide the output section with a strong and relatively clean signal. The choice of a driver tube is the 12AX7 which is a common small signal tube. Load line analysis was used to determine the behavior of this stage.

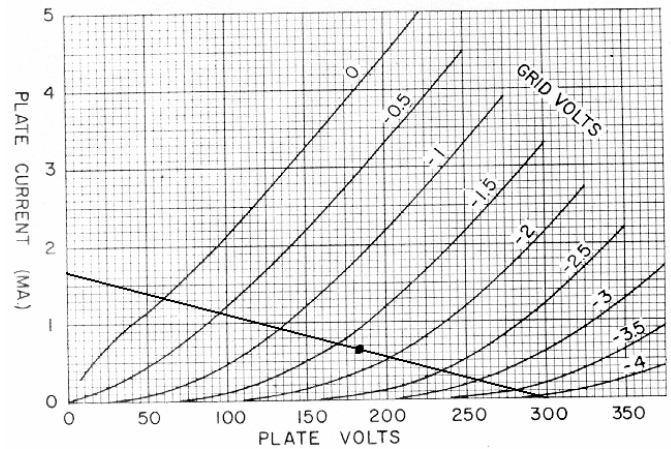


Fig 4. 12AX7 load line associated with driver stage

The load line above is the result of the decision to use a +HT = +300V power supply, recommended by [1], and a 183 kOhm load resistance, which lies within a range recommended by [1] [2] [3].

The operating point of this stage was chosen to be as follows:

$$\begin{aligned} V_{GK} &= -1.7 \text{ V} \\ V_{P(\text{quiescent})} &= 185 \text{ V} \\ I_{P(\text{quiescent})} &= 0.65 \text{ mA} \end{aligned}$$

This bias point yields a large voltage swing between saturation (near  $V_{GK} = 0\text{V}$ ) and cutoff (near  $V_P = +\text{HT}$ ), and also maintains operation in the most linear portion of the plate characteristic curves.

Further load line analysis yields small signal parameters:

$$\begin{aligned} r_p &\sim 71.43 \\ \mu &\sim 100 \\ g_m &\sim 1.4 \end{aligned}$$

Cathode bias sets the operation point. Relying on the theory in [2], cathode resistance was calculated using (4) to be equal to 2.62 kOhm, which is approximated in the actual design by a 2.7 kOhm resistor.

$$R_K = \frac{V_{GK}}{I_P} \quad (4)$$

Bypassing  $R_K$  with a capacitor allows for more AC gain, as well as LF filtering. (5) yields an effective cathode resistance ( $r'_K$ ) of 1.3 kOhm. Using (6),  $C_k$  is calculate to 122  $\mu\text{F}$  which is approximated in the actual design by a 100  $\mu\text{F}$  capacitor providing a -3dB cutoff at 1.22Hz, which is well below the audio frequency spectrum.

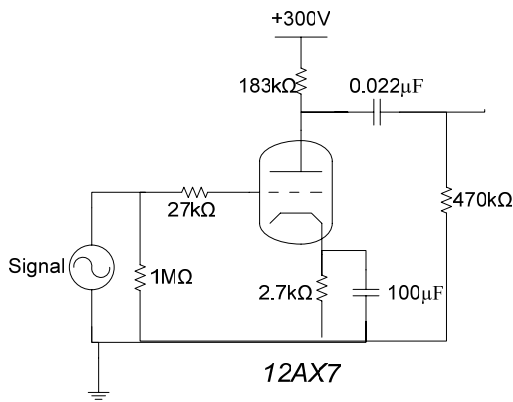
$$r'_K = \frac{R_L + r_p}{\mu + 1} \parallel R_K \quad (5)$$

$$C_K = \frac{1}{2\pi f r'_K} \quad (6)$$

Gain of this stage is calculated to be about 72 using equation (7) from [2].

$$G = \mu \frac{R_L}{R_L + r_p} \quad (7)$$

To calculate the LF cutoff point of the entire driver stage, the input circuit to the next stage must be taken into consideration.



**Fig 5. Entire driver section including following input network**

Choosing a common coupling capacitance value of .022 μF [1], and grid leak resistance of 470 kOhm, which is just below the 500 ohm maximum grid resistance for the 6V6 published in [1], LF cutoff is calculated using (8) to be 13.87 Hz.

$$f_{-3dB} = \frac{1}{2\pi C_C R_{eq}} \quad (8)$$

Where

$$R_{eq} = r_p \parallel R_L + R_{G(nextstage)} \quad (9)$$

$C_C$  is the .022 μF coupling capacitor.

HF cutoff is the product of the input circuit discussed in A in conjunction with the driver stage Miller capacitance.

As calculated above,  $C_M$  is equal to 151 pF. Using (10), HF cutoff is calculated to about 39 kHz.

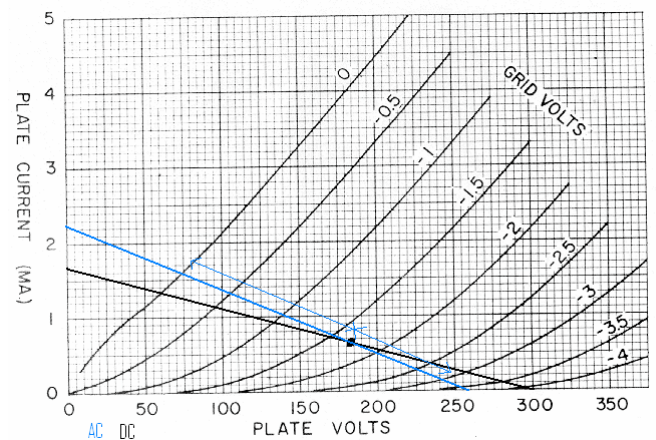
$$f_{-3dB} = \frac{1}{2\pi C_M R_2} \quad (10)$$

Where

$R_2 = 27 \text{ kOhm}$  “grid stopper” resistor

A wide frequency response design in the driver excludes frequency degradation to unpredictable factors such as output transformer response and stray wiring capacitance.

The headroom, defined as the maximum signal swing before distortion, of this stage can be calculated using an AC load line [4]. At audio frequencies, the load of interest is the 183 kOhm load resistance in parallel with the 470 kOhm input impedance of the following stage, which equals 132 k.



**Fig 6. AC load line (in blue)**

Cutoff can be assumed to be the point where plate current equals about 0.1 mA. Saturation is reached at  $V_{GK} = 0 \text{ V}$ , whereas cutoff is reached at  $V_{GK} = -3 \text{ V}$ , meaning that our bias point of  $V_{GK} = -1.7 \text{ V}$  is closer to cutoff than saturation, and so cutoff is the limiting factor concerning headroom. Assuming a symmetrical input voltage, undistorted headroom is therefore 2.6 V<sub>pp</sub>.

C. The Output Stage

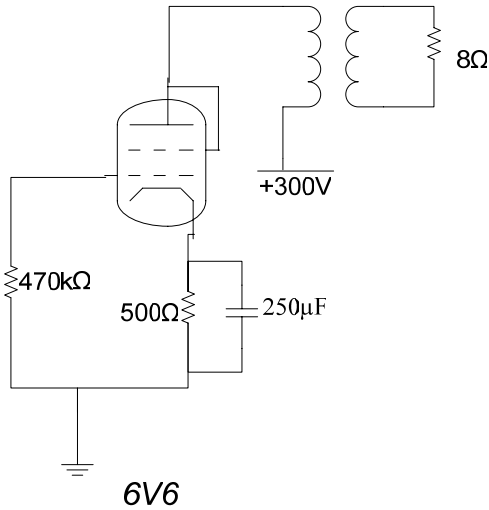


Fig 7. Output stage

The major factor involving the design of this single ended output stage is matching an available output tube to an available output transformer (OT), which can provide the proper impedance matching. Using typical operating parameters laid out in [1], the 6V6 power tube, operating in triode mode, has an ideal load impedance of 5k Ohm, and generates about 4.5 watts of power. An OT was used, handling 8 watts and providing impedance matching from a 5k primary to an 8 ohm secondary, which is a common loudspeaker impedance.

Bias for this stage is set purely based on typical operation specs set in [1], due to the fact that load line analysis is not intuitively applicable. The reason for this, being that the inductive load of the output transformer doesn't have any DC resistance with which a proper load line can be constructed. A 500 ohm cathode resistance closely approximates the ideal  $R_k$  of 490 ohms published in [1]. Using an available bypass capacitance of 250  $\mu$ F provides a low frequency cutoff below 10 Hz.

D. Power-Supply

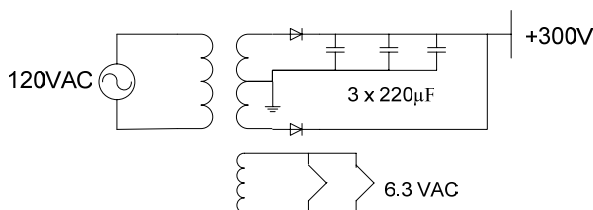


Fig 8. Power supply section

The amplifier uses a simple linear power supply to develop 300VDC. Heater voltages are supplied directly from the 6.3VAC taps on the secondary of the power transformer. The other secondary windings, rated at 380VAC with a center tap, are used for the DC supply. Each half of the 380VAC winding is rectified separately during the positive<sup>1</sup> half wave cycle only, using the center tap as the common. In this configuration, the output voltage of the power supply is halved, while the current capacity of the transformer is doubled, since each half-coil only has a 50% duty cycle. Following rectification, a bank of capacitors is used to filter AC ripple. A filter design utilizing a choke in series with the supply was briefly considered, but modern, low-cost high voltage electrolytic capacitors offer a simpler and more economical solution. To calculate the minimum amount of capacitance needed in the filter section, the following equation was used:

$$C = (I_L / \Delta V) * k * 1,000 \mu F \quad (11)$$

... where

$I_L$  = Load current

$\Delta V$  = peak-peak ripple voltage

$k$  = 6 for 120Hz or 7 for 100Hz ripple frequency

This simplified equation for filter capacitance as a function of ripple voltage and load current uses a linear approximation of RC voltage decay. A linear approximation is acceptable because the ripple voltage magnitude is very small compared to the supply voltage magnitude, and in this region the exponential decay will be most closely linear.

For a ripple voltage of 2V peak to peak, a maximum load current of 100ma, and full wave rectification<sup>2</sup>, approximately 300uF of capacitance is needed. Our design uses three electrolytic capacitors rated at 220uF each to achieve 660uF of filter capacitance. This was chosen based on parts available and to keep the filter capacitance value large enough at the low end of the capacitors' wide tolerance.

Our measured value of supply ripple was 0.2V, which is reasonable considering that the equation used was an approximation. The end goal is that the ripple voltage be insignificant in magnitude with respect to the supply voltage.

<sup>1</sup> With respect to the center tap

<sup>2</sup> The output of the rectification stage is effectively full wave because two half cycles are rectified every cycle

### E. Pspice

Spice simulations are a valuable tool that aid in the design of tube amplifiers. Using [6] as a guideline, the following models were used in Spice simulation. Note that a 6L6 model was used in place of a 6V6 because it was readily available. These tubes are comparable, with many common parameters.

```
.SUBCKT T12AX7 P G K
E1 2 0 VALUE={V(P,K)+83.5*V(G,K)}
R1 2 0 1K
GP P K
VALUE={1.73U*(PWR(V(2),1.5)+PWR(S(V(2),1.5))/2)}
CGP G P 1.7P
CGK G K 1.6P
CPK P K 0.4P
.ENDS
```

```
.SUBCKT T6L6 P S G K
ESP 2 0 VALUE={V(P,K)+19.3*V(S,K)+154*V(G,K)}
E1 3 2 VALUE =
{0.539U*(PWR(V(2),1.5)+PWR(S(V(2),1.5))/2)}
R1 3 0 1K
GK S K VALUE = {V(3,2)}
GP P S VALUE = {0.95*V(3,2)}
CGP G P 0.6P
CGK G K 5P
CGS G S 5P
CPK P K 6.5P
.ENDS
```

In addition to tube models, an accurate model for an output transformer was also modeled. Pspice models its generic transformer in terms of primary and secondary inductances,  $L_1$  and  $L_2$ , as in (12).

$$L_1 = \left( \frac{N_1}{N_2} \right)^2 L_2 \quad (12)$$

where

$$\left( \frac{N_1}{N_2} \right) = \sqrt{\frac{R_{in}}{R_L}} \quad (13)$$

Simulation results support hand calculations and bias points are as expected. See appendix A. for simulation results.

### III. CONSTRUCTION

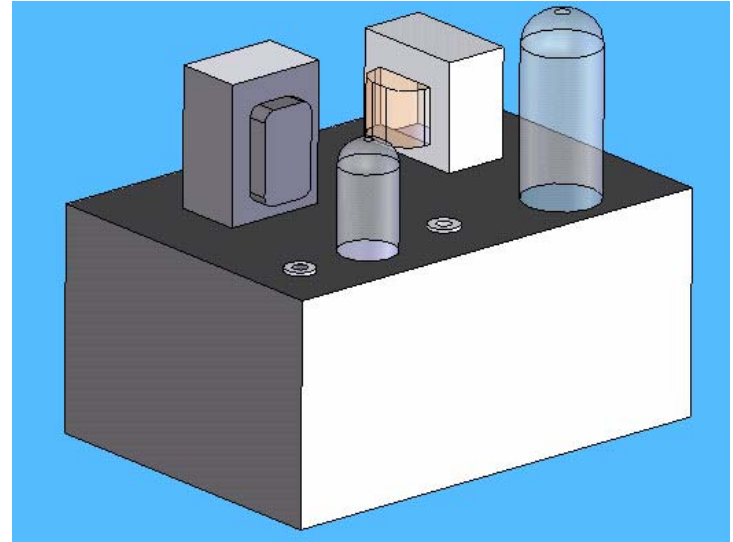
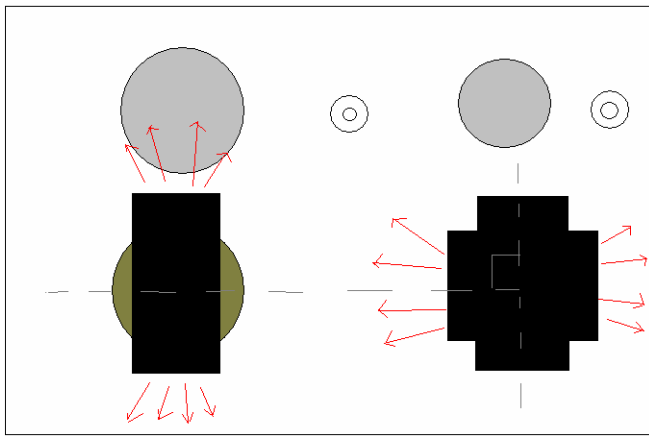


Fig 9. Amplifier fully assembled



Several construction issues were considered in the building of this amplifier. High power supply voltages, large and leaky inductive components, and high temperatures are among these considerations

A 6x5" aluminum chassis from Radioshack was used to populate with the electronics and hardware necessary. Major components were laid out as such:



**Fig 10. Bird's eye view of the amplifier chassis**

Magnetic flux is expelled from the transformers as shown by the red arrows above. By placing the output transformer (OT) and power transformer (PT) at opposite ends of the chassis, and rotating their axes 90° from one another, induction noise from PT to OT is reduced about 27 dB [3]. Although this configuration sees flux from the OT directed at the 6V6, PT flux interference into the sensitive preamp stage tube is avoided. Beneath the chassis hum reduction is further achieved by winding all pairs of wire containing AC (filament heater wires, PT primary, and secondary wiring to the diode rectifier).

Due to the 300V power supply voltages used, components were carefully chosen to withstand peak conditions. Cathode capacitors were rated to withstand the maximum voltage experienced under extreme input conditions. Coupling capacitors were rated to handle the entire power supply voltage. Cement power resistors connect the output tube cathode to ground.

Connections were made using lead-free solder and a minimum of cloth insulated wire. Excess wire was trimmed from the circuit, and wires were attempted to cross each other at 90° if possible in the interest of eliminating cross-talk.

Safe and noiseless grounding is realized using separate ground connections for the driver circuit and output circuit which join at a third “master” ground connection mounted to the chassis. This master ground is where the mains ground and PT center tap are connected. Power switching is controlled with a SPST “heavy duty” switch in line with the mains hot wire. A 3 amp fuse is also in line with the mains neutral wire for safety.

Chassis work was accomplished with help from the UW physics lab, supplemented by lots of “pretty” drilling, grinding, and electrical taping done in the basement.

IV. TESTING

Testing was accomplished using a digital oscilloscope, signal generator, DC multi-meter, and an 8-ohm loudspeaker.

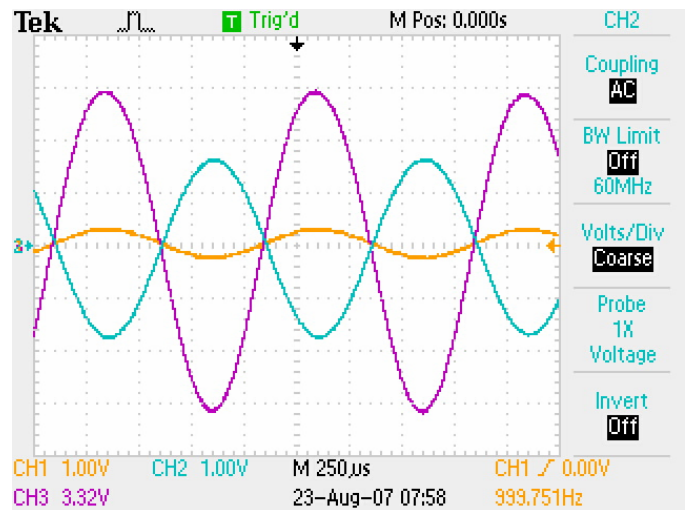
**Table 1. Measured points of operation**

	$V_{GK}(V)$	$V_p(V)$	$I_p(mA)$
Driver Stage	-1.7	180	0.58
Output Stage	-35	300	9.62

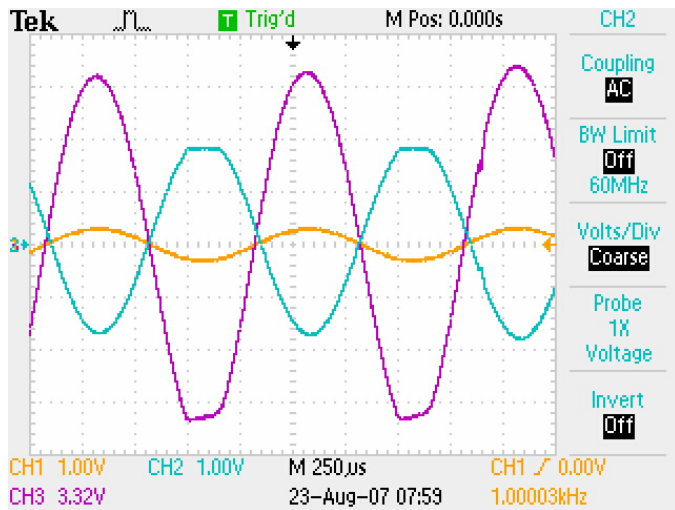
**Table 2. Driver stage AC Test Parameters**

AC Parameter	Value
mid-band gain	62.1
point of non-linear distortion	$V_{in} = 0.29 V_{pp}$
HF cutoff	17 kHz
LF cutoff	22.6 Hz

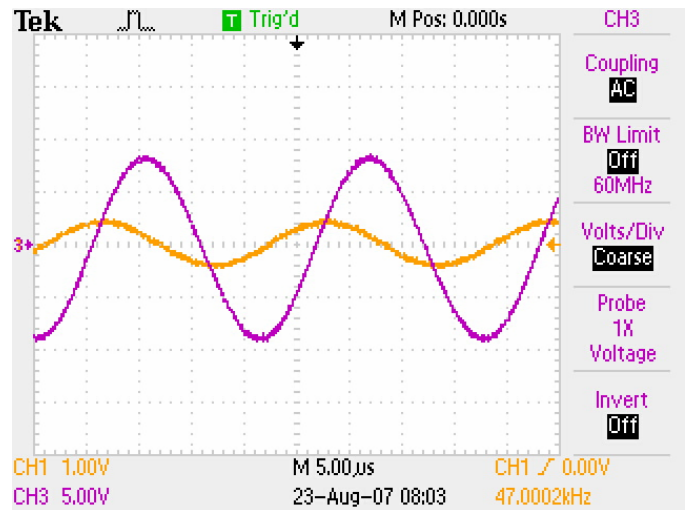
Note that the assumption of driver cutoff at  $i_p = 0.1$  mA, proved a false assumption. Based on our AC load line, clipping at  $0.29 V_{pp}$  corresponds to  $i_p = 0.6$  mA. The onset of cutoff clipping is much more gradual than distortion by tube saturation [4], making identification of a point of cutoff difficult.



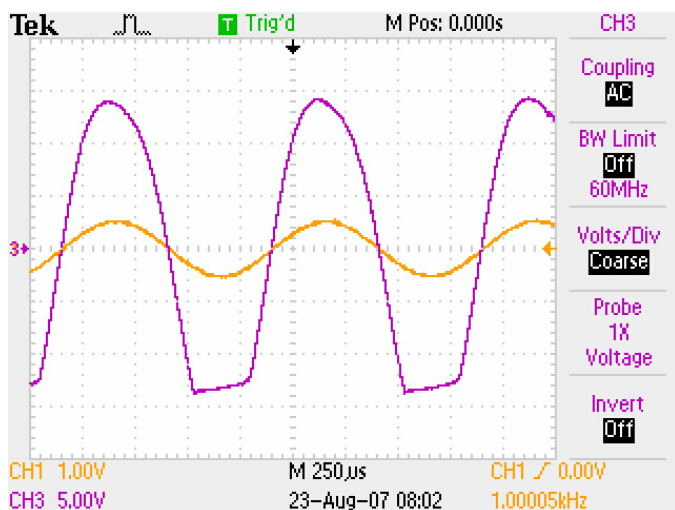
**Fig 11. Maximum signal before distortion. Input signal-yellow, 6V6 grid – blue (probe x10), 6V6 anode – purple (probe x10)**



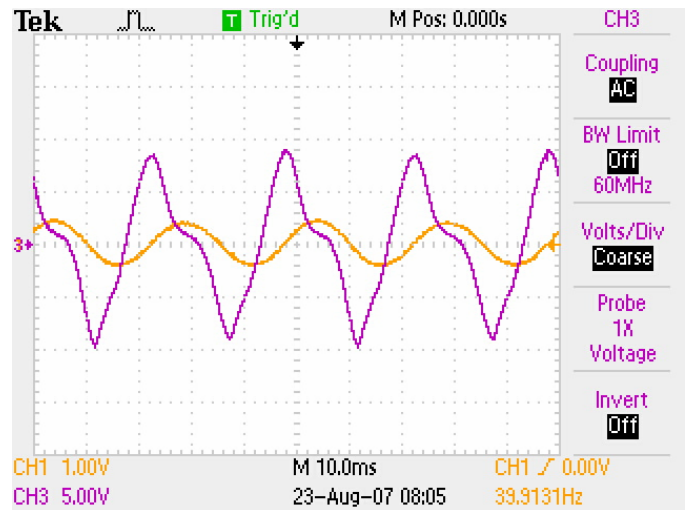
**Fig 12. Initial driver clipping at  $V_{in} = 0.29V_{pp}$ . Notice the clipping in the driver(blue) is reflected in the output of the amplifier(purple).**



**Fig 14. Entire Amplifier HF cutoff at 47 kHz (before OT). Note that purple waveform is reduced by a factor of  $1/\sqrt{2}$  from fig 11.**



**Fig 13. Onset of output tube distortion. The positive peak begins to look misshapen at  $V_{in} = 0.5V_{pp}$ .**



**Fig 15. Entire Amplifier LF cutoff at 40 Hz (before OT)**

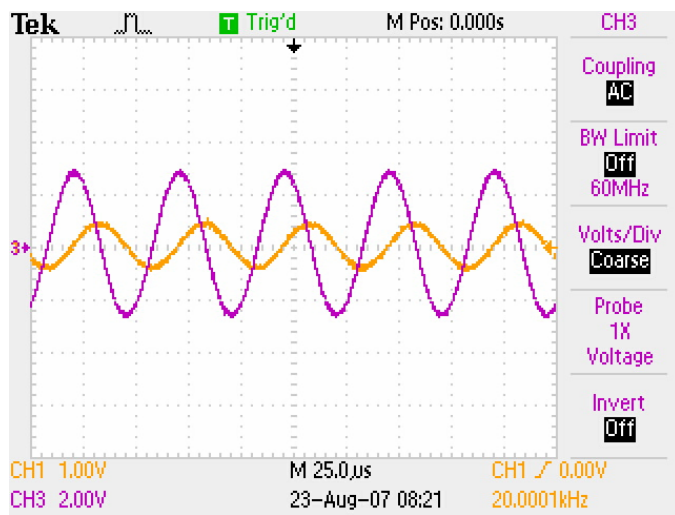


Fig 16. Entire Amplifier HF cutoff at 20 Hz (after OT)

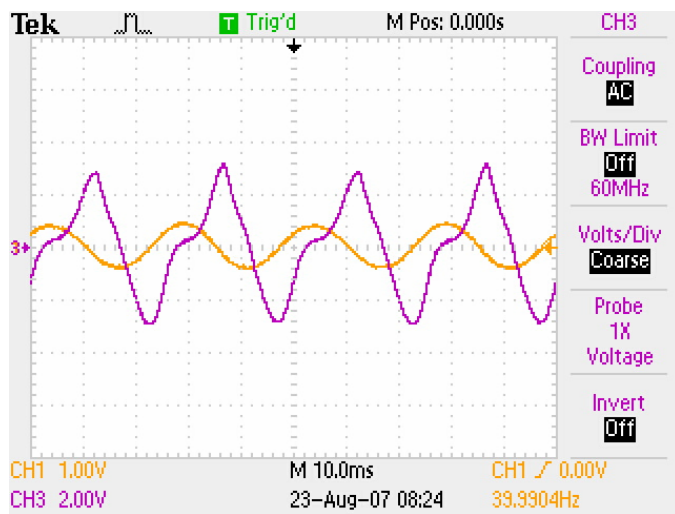


Fig 17. Entire Amplifier LF cutoff at 40 Hz (after OT)



APPENDIX

A. Spice results

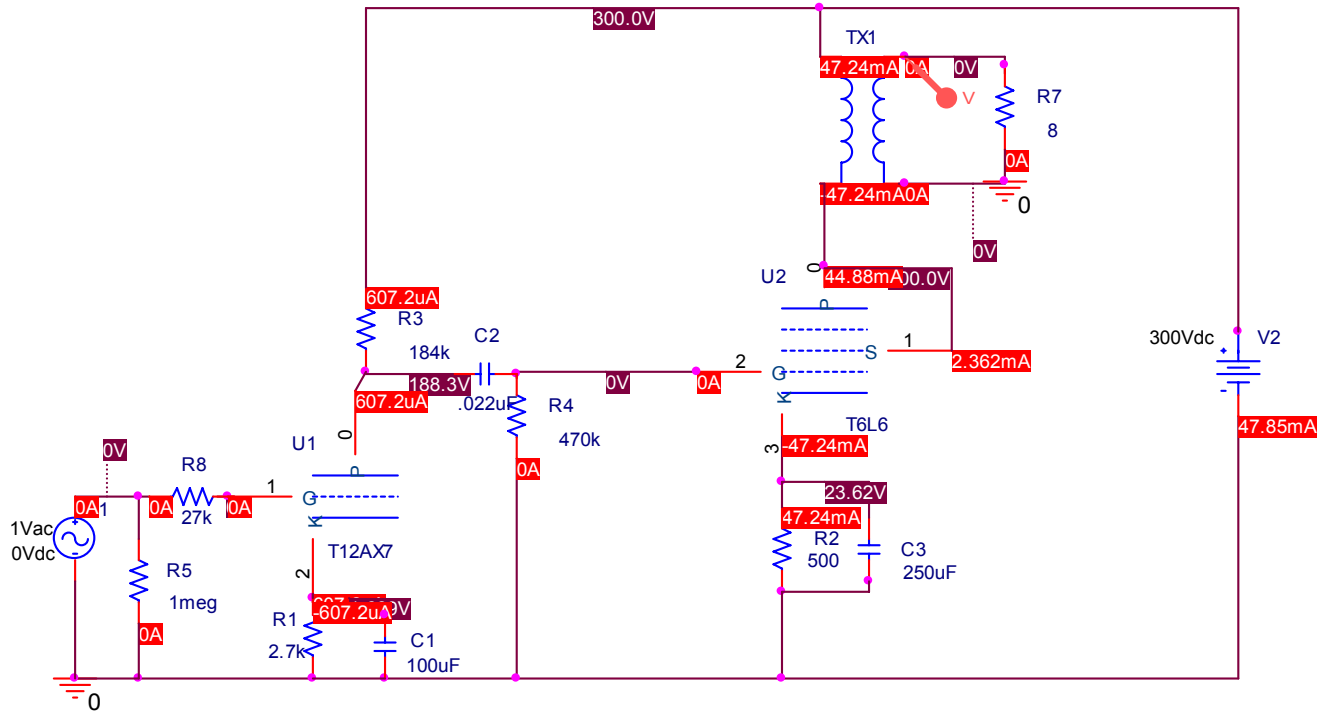


Fig A1. Spice simulation results of DC transient analysis

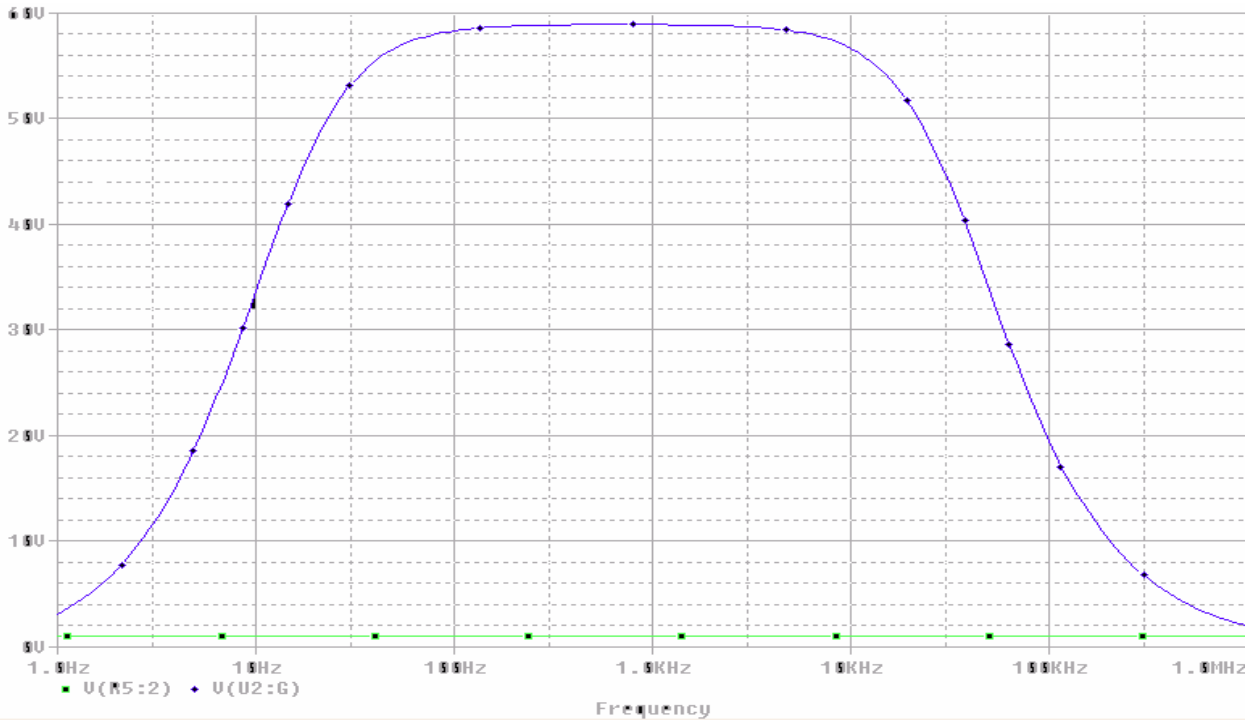


Fig A2. AC simulation verifying 1<sup>st</sup> stage voltage gain (blue) around 60. Note input signal (green) is 1 volt AC.

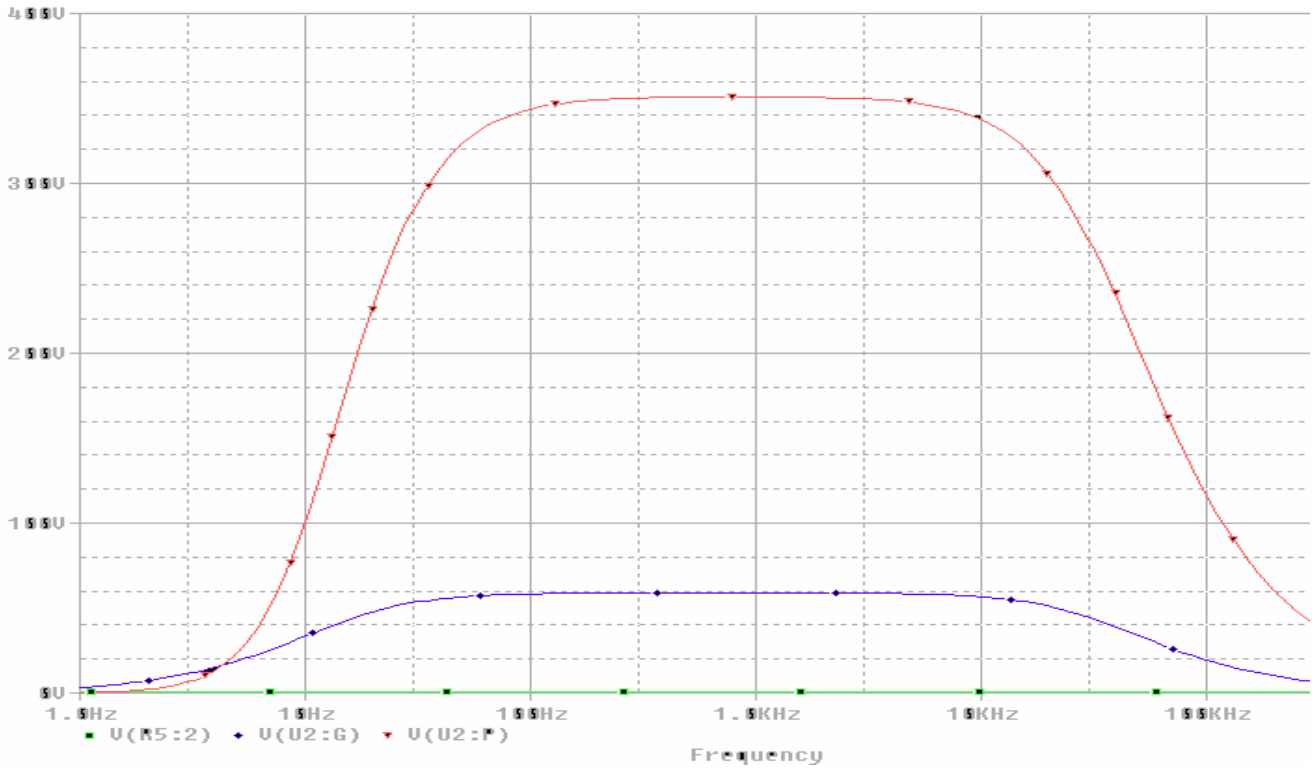


Fig A3. AC simulation of entire amp, pre-transformer. Mid-band gain around 350 from about 20 Hz to 20 kHz.

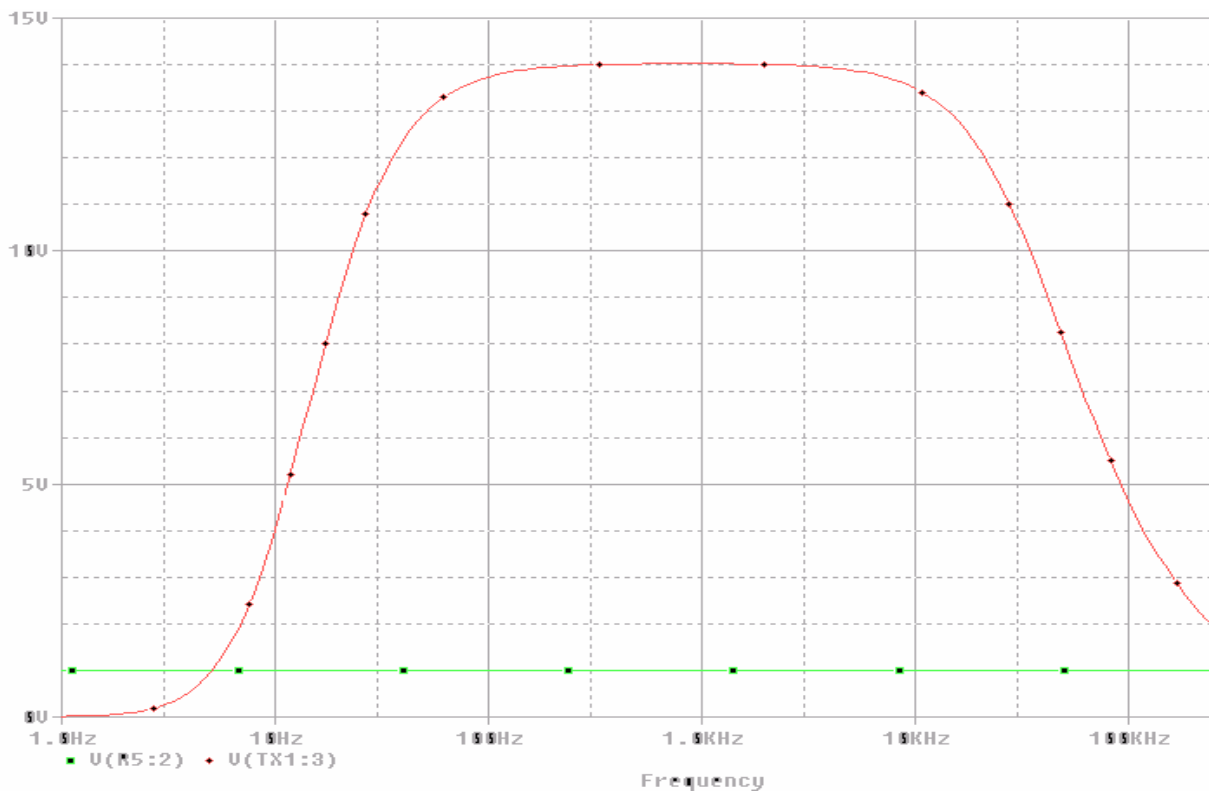
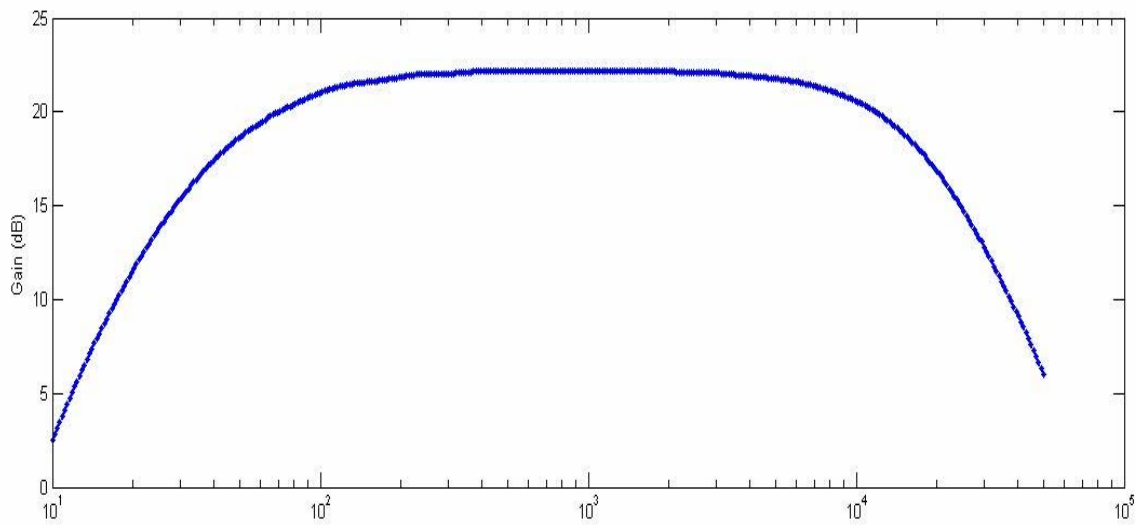


Fig A4. AC simulated analysis displaying post-OT voltage(red).



**Fig A5. Measured frequency response post-OT verifying simulation results. The measured gain was 22dB, compared to the simulated gain of 22.9dB.**

#### REFERENCES

- [1] RCA TUBE MANUAL
- [2] Jones, Morgan, "Valve Amplifiers" 2<sup>nd</sup> Edition", Newnes, Oxford, UK, 1999.
- [3] Jones, Morgan, "Building Valve Amplifiers", Newnes, Oxford, UK, 2004.
- [4] Kuehnel, Richard, "Guitar Amplifier Preamps", Pentode Press, 2007
- [5] Tremaine, Howard M., "Audio Cyclopedia" 2<sup>nd</sup> Edition, Howard W. Sams & Co., 1959.
- [6] Leach Jr., W. Marshall, "SPICE Models for Vacuum-Tube Amplifiers", AES Paper, 1994.