Tube Amplification Guitar Pedal

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1 Background

Before the age of semiconductors, for the purpose of signal amplification, Vacuum Tube Triodes were used. These got replaced by transistors eventually due to the uncertainity in behaviour of these tubes and the variation induced by the surroundings of the Tube. Nevertheless, a good amount transistor circuit design ideas originate from our experience with these Tubes that preceded them: Class-A and Class-AB amplifiers especially.

Although these Tubes are deprecated in most electronics applications, these are particularly sought after in the Music world. The iconic "distortion" sound that guitarists use til-date is but an artefact of amplification using such tubes. The classic amplifier heads used in the 80s and 90s were all using tubes and rectifiers to process the signal that comes out of a guitar, and are considered the peak of guitar signal processing even today.

Even though amplifier simulations model this distortion from the tubes well, there is still some scope to try out using actual tubes to do the same. Moreover, with the amount of transparency that has been achieved today with solid state or digital amplifiers and nearly-flat response speakers, the iconic "distortion" sound could potentially be captured in a guitar pedal that adds a pre-amplification audio effect instead of a full-size amplifier head. Hence we try to build a Guitar Pedal with a Tube Amplifier with knobs controlling key parameters that affect the response.

2 Schematic Design

We divide the schematic into 5 sections for convenience:

1. Input Stage
2. Tube Amplification Stages
3. Tone Control
4. Output Stage
5. Power Regulation

2.1 Input Stage

The Input Stage includes a fuse and a non-inverting Op-Amp amplifier. The fuse is essentially a measure to protect the guitar from any large surge of current in case the experimentation in the pedal main amplification stages causes one. The non-inverting amplifier with a potentiometer in the feedback path lets us control the input volume that is being fed into the grid of the first tube amplification stage thus giving us more control on over-driving the tube or not. Moreover a non-inverting amplifier is chosen so that the amount of current drawn from the guitar pickup itself is minimized.

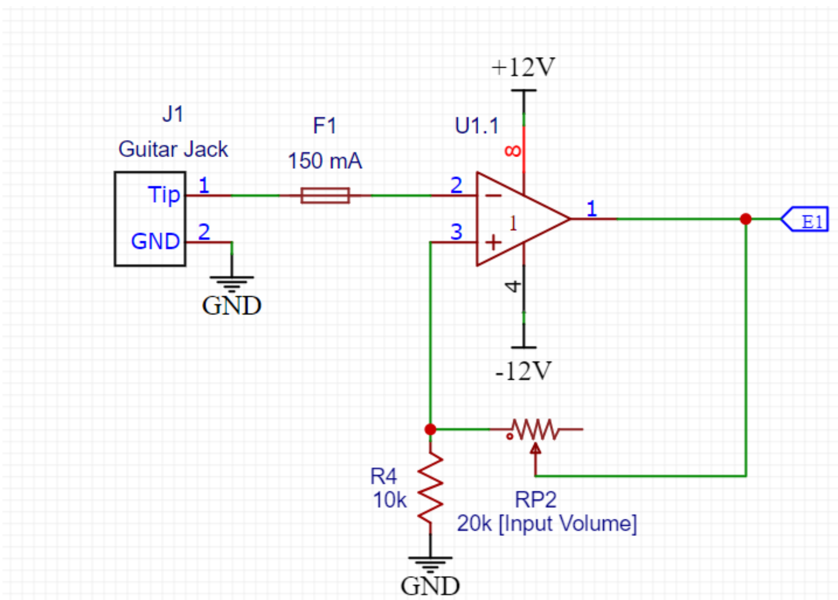

Figure 1: Schematic - Input Stage

As for the values of used, we estimate that 150mA is a safe amount of current to flow (even though not much should flow because we have connect it such that not much current will flow). The non-inverting amplifier's R1 and RP2 values are chosen to emulate the typical range of the output impedance of guitar pickups ($5\text{k}\Omega - 25\text{k}\Omega$). Moreover, R4 is chosen to allow an input volume control from $1\times$ to $3\times$

2.2 Tube Amplification Stages

Let us motivate how a tube works a little before diving in. The tube's cathode is heated with the rated voltage to initiate electron generation. The relative voltage between the anode and cathode drives current flow. This is controlled using the potential at the grid that comes in between the cathode & anode, which resists the flow from cathode across itself before it reaches the anode.

The tube amp stage consists of two **Class-A Amplifiers** (See the figure below). The tube's three terminals are biased to a DC point of operation by setting the resistances and V_A. The point of operation is decided against the characteristic in the data-sheet based on the desired small signal behaviour.

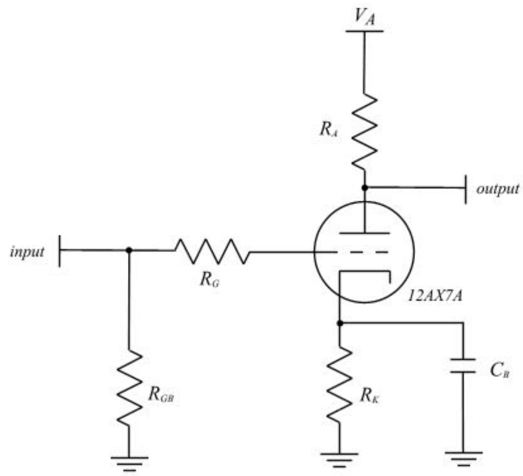

Figure 2: Class-A Tube Amplifier

Going in an orderly fashion from left to right: R_{GB} must be a high resistance that makes the input impedance large ("Hi-Z") and sets the grid's DC point at $0V$. R_G is used to damp oscillations higher than 20kHz. To explain this, we think about what happens once we amplify the AC small signal, the amplified output will cause miller effect making the parasitic capacitance C_{GA} between grid and anode in the tube a large capacitance with which R_G interacts to give a dominant pole in the system. R_K is used to bias the Cathode. R_A is used to bias the Anode and control the small signal gain. We'll discuss the exact calculation of these two resistances soon. C_B is essentially a decoupling capacitor (Infact, we'll benefit from having several different valued capacitors in parallel combination in-place of C_B).

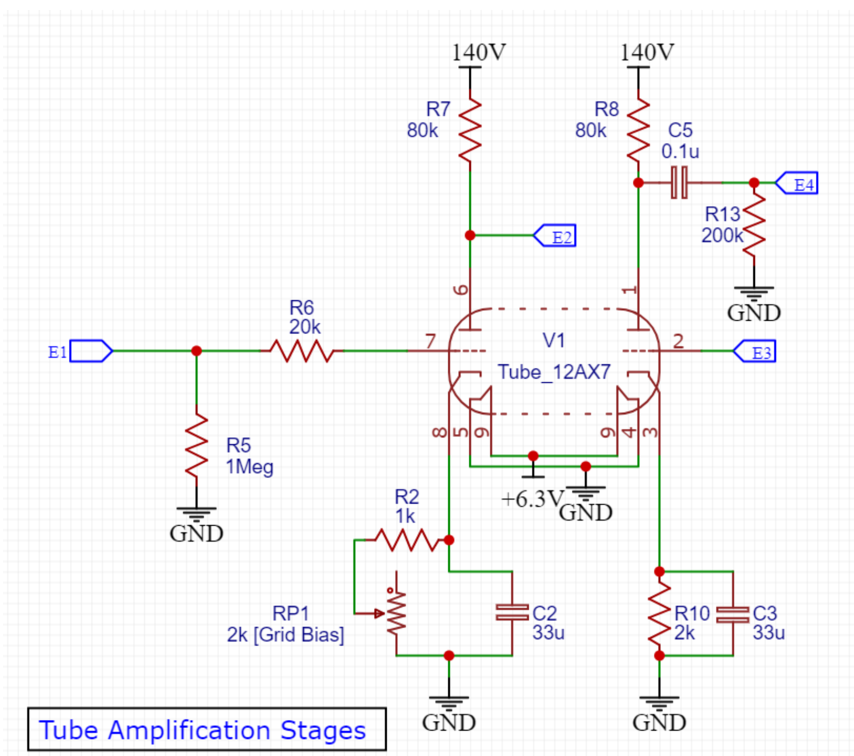

Figure 3: Schematic - Tube Amp Stage

As for calculating and arriving at the values used in the above schematic: note that the second stage is just the first stage without the input handling, hence we use the same values for both. From the above discussion, we may choose any large resistance and capacitance in place of R_{GB} and C_B. R_G too just needs to be not too large so that the f_{-3dB} is still above 20kHz. To start with, we may just choose $R_{GB} = 1Meg$, $R_G = 20k$ and $C_B = 33\mu$. To calculate R_A, V_A and R_K, let us first look at the data-sheet of our 12AX7.

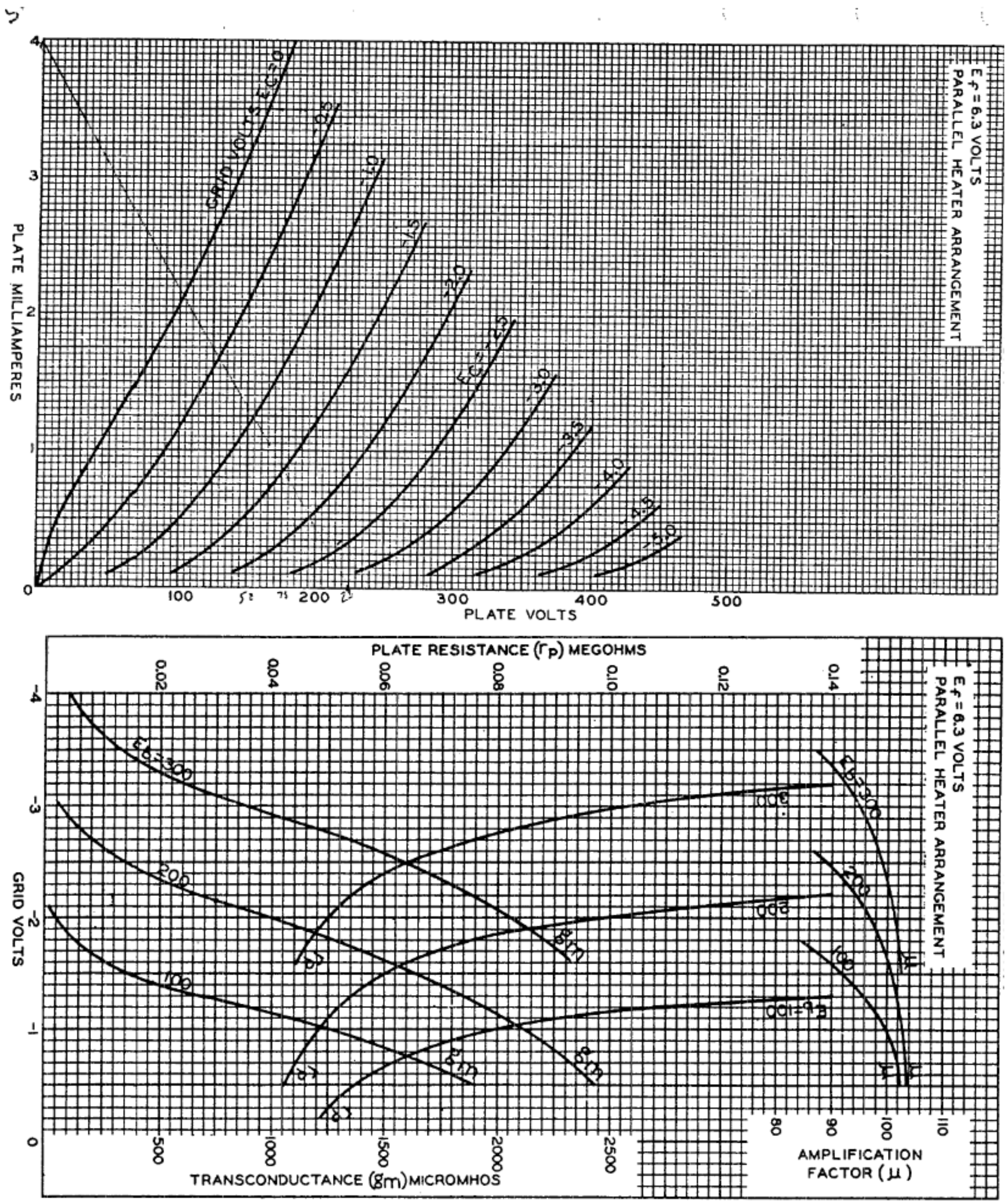

Figure 4: 12AX7 Characteristics

Let us begin with setting Plate Voltage (Anode - Cathode) = $100V$ because of being the safest value with concrete data to work with. Similarly the grid bias could be chosen to be $-1V$. To not restrict the possibilities of trying slightly different characteristics like the ones on the the first graph, we can add a potentiometer to control grid bias upto a variation of $\pm 0.5V$ while keeping all other calculations according to 1V. For the third constraint on our system of 3 parameters, we need to define small signal gain A_v. The small signal equation for the Tube Class-A Amplifier is:

$$i_p = \left(-\frac{v_{\text{out}}}{R_A}\right) = g_m v_{\text{in}} + \left(-\frac{v_{\text{out}}}{r_p}\right)$$

$$\implies A_v = g_m \left(R_A \mid\mid r_p\right)$$

According to the first graph, for $100V$ DC plate voltage and $-1V$ DC grid voltage, we will have a plate current of $0.5mA$. Which implies that:

$$R_A \left(\frac{0.5}{1000}\right) = V_A - 100$$

And also implies that

$$R_K \left(\frac{0.5}{1000}\right) = 1$$

According to the second graph, we have $g_m = 1250 \cdot 10^{-6}\ \Omega^{-1}$ and $r_p = 80k\Omega$.

$$A_v = 1.25 \cdot (R_{\text{A in k}\Omega} \mid\mid 80)$$

Clearly, there is a trade-off between the maximum A_v we can push for and the minimum V_A we can bring down the make the pedal safer against human errors, but let us settle for the following:

$$\boxed{R_A = 80k\Omega}\ \boxed{V_A = 140V}\ \boxed{R_K = 2k\Omega}$$

If we manage to get a V_A that is not exactly $140V$, we can change R_A accordingly. We can allow a trimpot setup to let $R_K = 1k\Omega$ to $3k\Omega$

2.3 Tone Control

For tone control we aim to have one knob that takes the response form a bass-heavy to a high-presence. To achieve this with only passive elements, a decent amount of hit-and-miss was used by simulating different ideas and values in LTSpice. This was achieved:

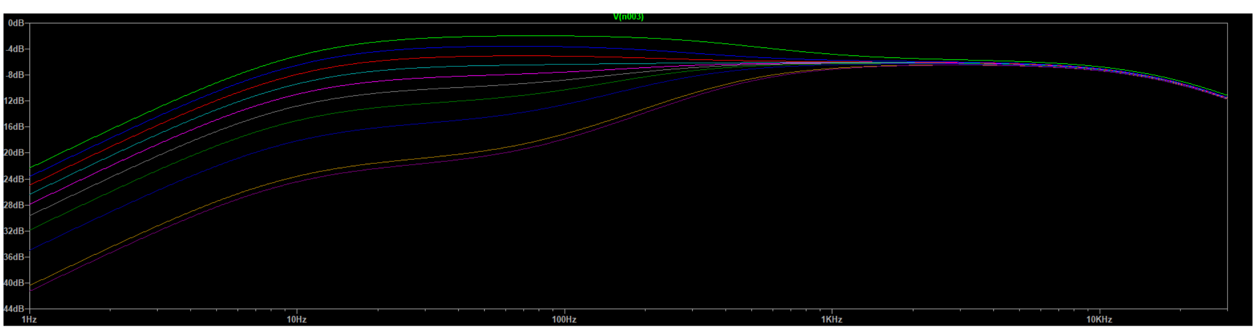

Figure 5: Tone Control Response

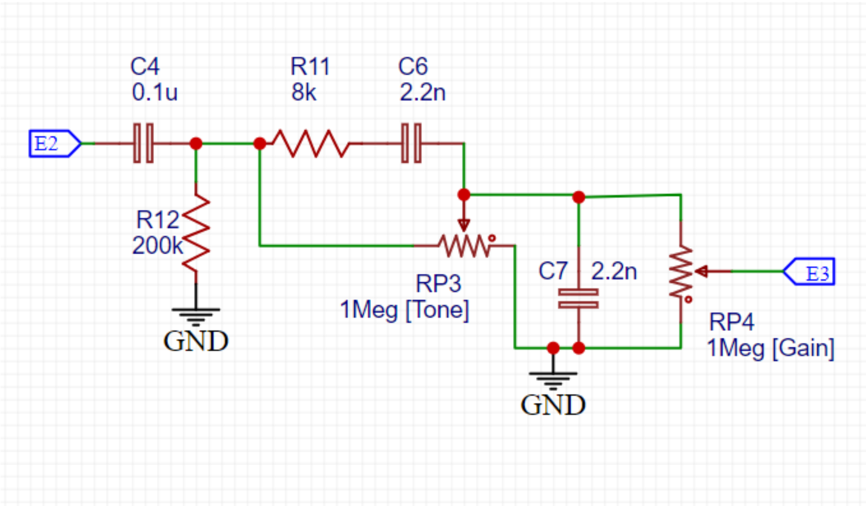

Figure 6: Schematic - Tone Control

2.4 Output Stage

By the time we reach here we have possibly amplifies our signal by a gain factor of 250 or so, which is possibly not what a digital practice amplifier or any home speaker is designed to take, unlike having another power amplification stage. This we include a master volume stage that can be tweaked to have gain factors up to $\frac{10}{250}$. The amplifier is protected with a fuse too.

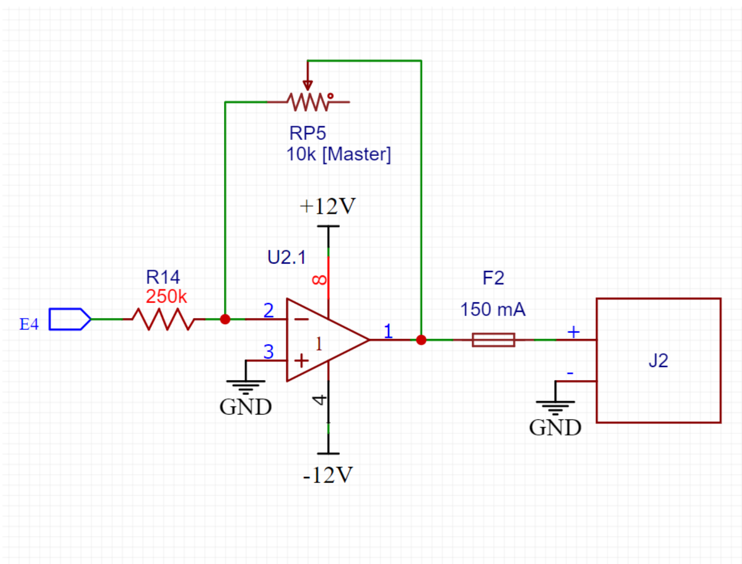

Figure 7: Schematic - Output Stage

2.5 Power Regulation

12V, -12V, 140V, 6.3V are all the four power lines required in the pedal. Since tubes consume a lot of energy, taking these off from 9V batteries is infeasible, hence we are left with options to either use transformers with AC or use DC adapters and then use DC-DC converter. Since the latter is a more handier option, we'll proceed with it.

3 Methodology & Practical Implementation

4 Results