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. This stage is connected with a dual switch to bypass it when we choose to. This stage is to be used **1.** When we are still prototyping and testing the tube stage of the circuit just so that any human error won't affect the Guitar's electronics or **2.** When we need more control on the Input Volume that is being fed into the Tube Amplification Stage. In cases when this stage is not absolutely necessary, we bypass it so as to cut down on the noise introduced by this stage.

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. This is followed by biasing the signal to a DC value of 6V so that we can use the Op-Amp with just our 12V and GND lines as the power lines. 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.

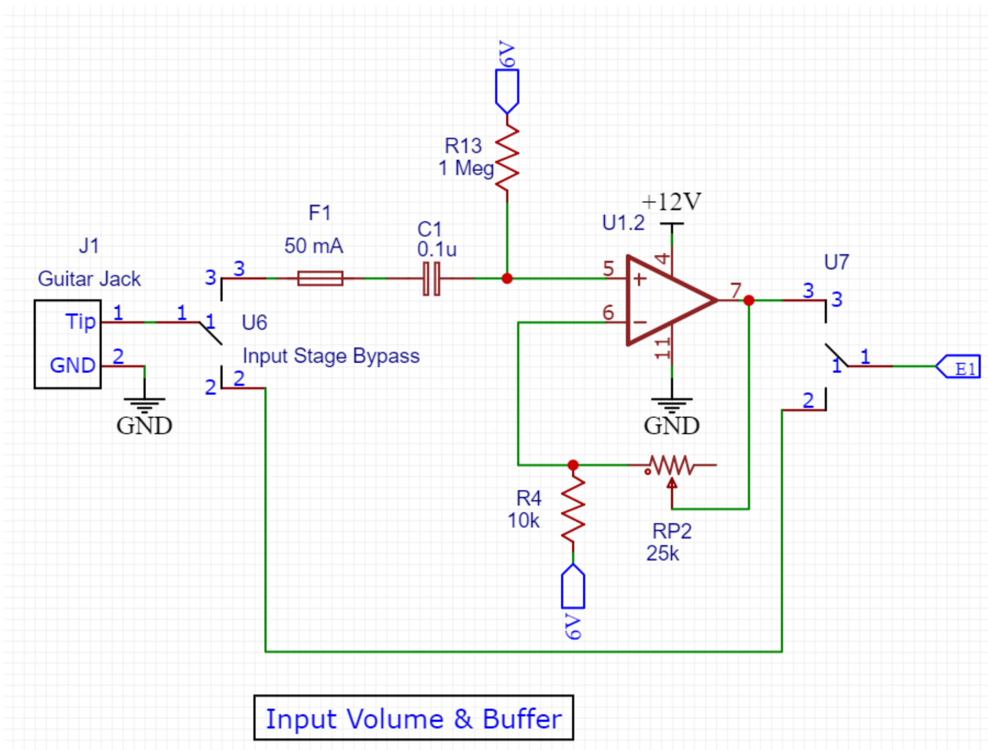

Figure 1: Schematic - Input Stage

As for the values used, we assume that 50mA 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. Note here that Guitar Signal can be anywhere from $100mV - 1V$.

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.

2.2.1 Class - A Amplifiers

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.

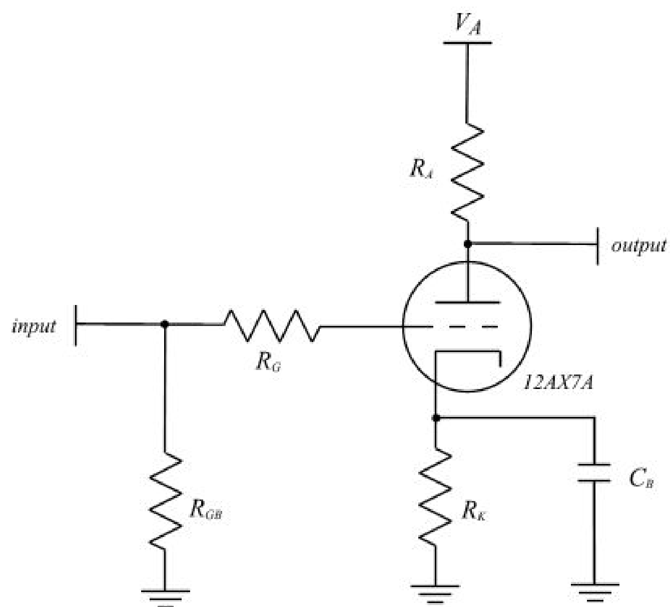

Figure 2: Class-A Tube Amplifier

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).

Let us calculate these above resistances and capacitances setting the value of $V_a = 140V$ as our starting point. Then let us add potentiometers to allow for small tweaks. Note that we will be doing two stages of this and the second stage is just the first stage without the additional input handling, hence we use the same values for both. Also we can set $R_{GB} = 1Meg$; $C_B = 33\mu$ for both cases since these just need to be arbitrarily large.

2.2.2 The Distorted Tone

Below is the I_p vs V_G plot of the 12AT7 Tube where I_p stands for the current through R_A towards the Anode and V_G is the potential at the grid. We are looking at this particular characteristic because V_G is going to be our input and I_p is going to determine the potential drop across R_A to result in our output.

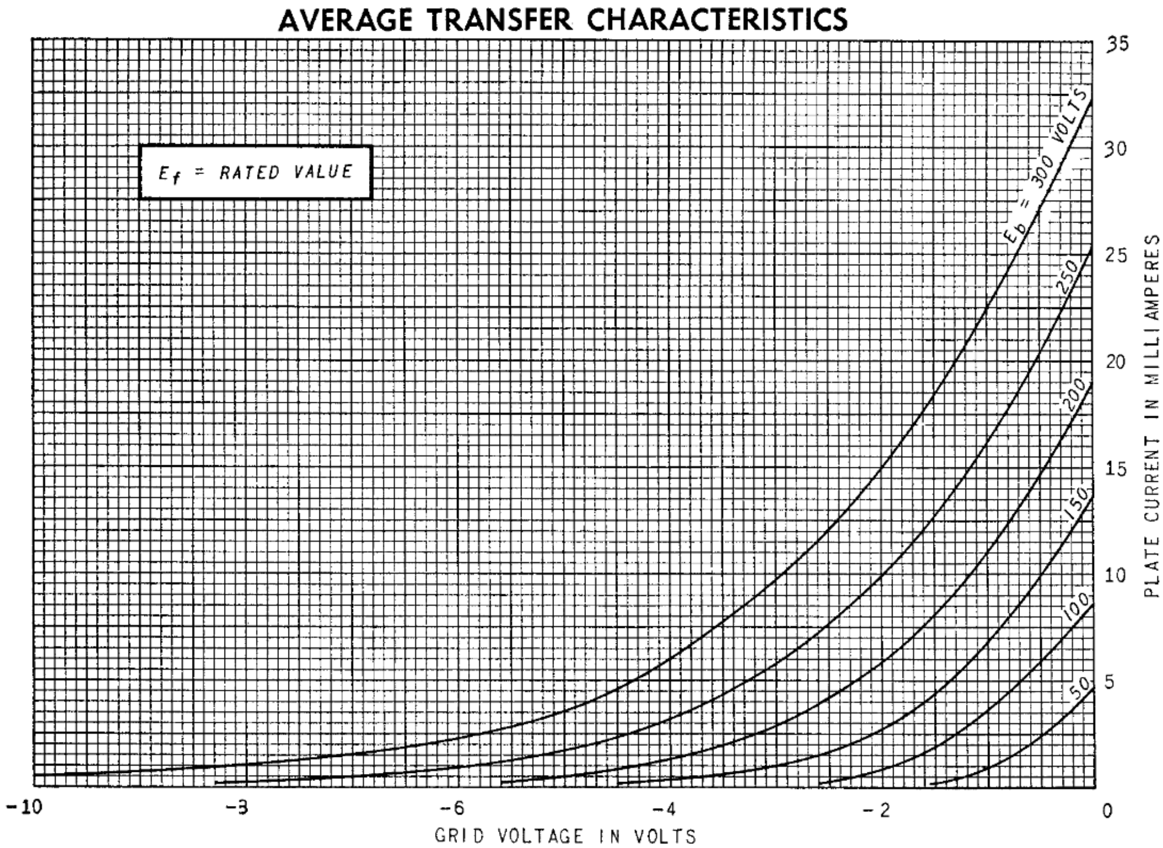

Figure 3: 12AT7 Plate Current vs Grid Voltage Characteristic

We need to operate at the most non-linear region of this characteristic. This causes the V_{out} vs V_{in} characteristic to be non-linear which generate harmonics to the given Input. This is the bread-and-butter of distortion. These harmonics make the Guitar sound fuller by occupying a larger and thicker area of the frequency spectrum.

To the best of our ability, we can estimate non-linearity by drawing circles through 3 consecutive points and comparing the curvature. Below are 3 circles 'c', 'd' and 'e' drawn through 3 consecutive data points on the 100V curve to estimate the 2nd order deviations at -2V, -1.5V and -1V respectively. Clearly 'd' has the most deviation, hence we choose the operating point of **100V and -1.5V**

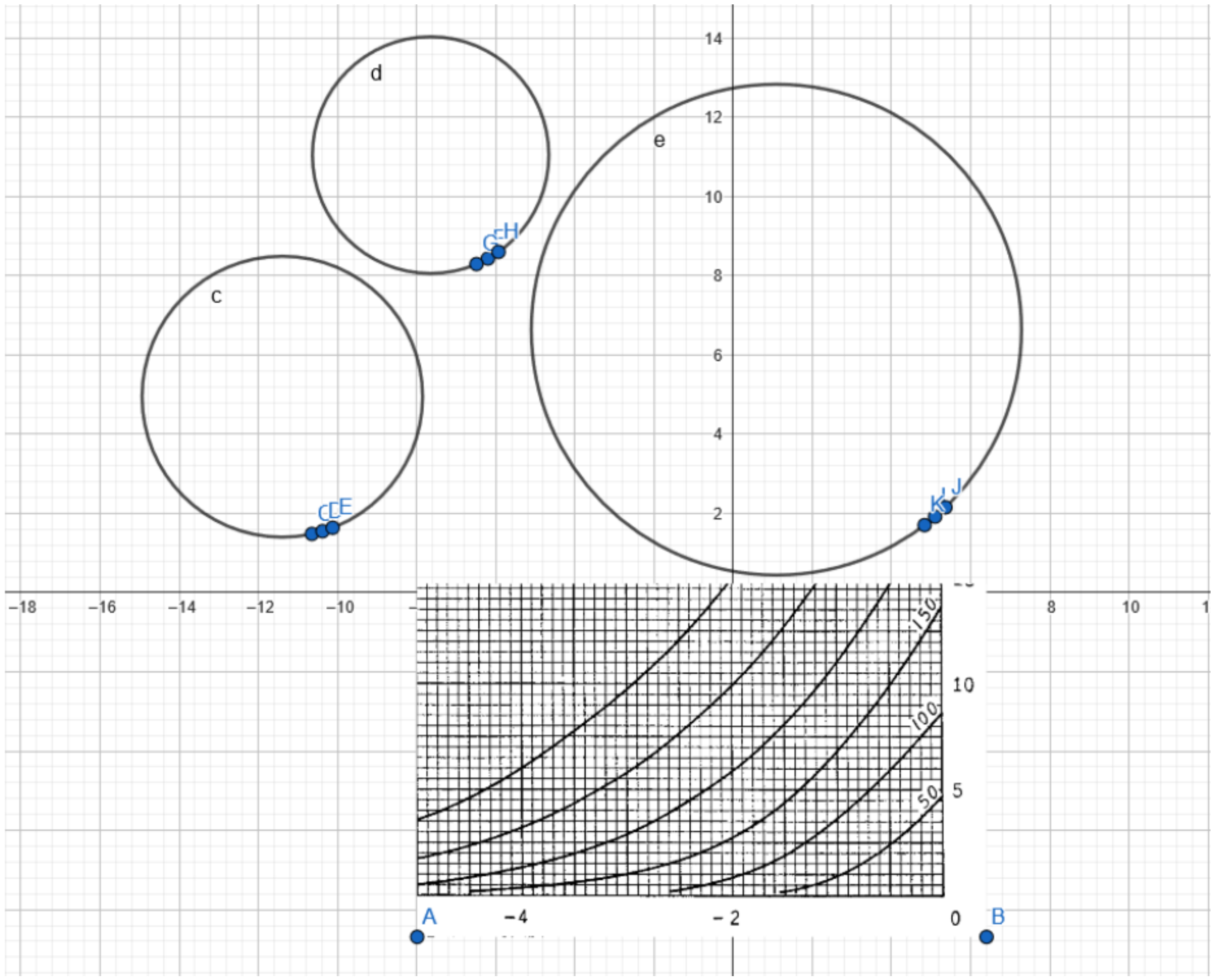

Figure 4: Comparing Curvatures

2.2.3 Calculations

So far we've decided the operating point to be $V_A = 140V$, $V_p = 100V$ and $V_G = -1.5V$. Now we can refer to the same characteristic above and find out that $I_p = 2mA$. For choosing R_A:

$$R_A\left(\frac{2}{1000}\right) = 140 - 100$$

$$\Longrightarrow \boxed{R_A = 20k\Omega}$$

Further for R_K, we have:

$$R_K\left(\frac{2}{1000}\right) = 1.5$$

$$\Longrightarrow \boxed{R_K = 750\Omega}$$

Now that the DC points are set, let us move on to small-signal. Below are the characteristics given for small-signal in the Datasheet.

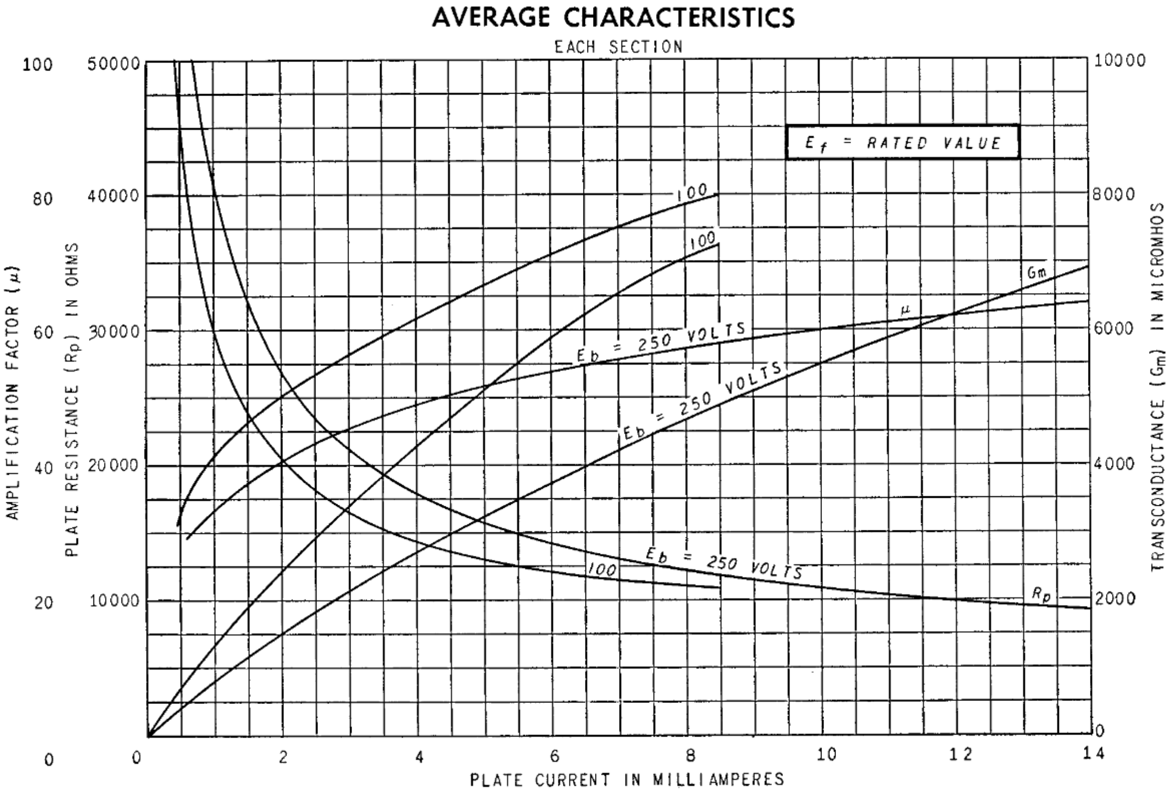

Figure 5: Small-Signal Characteristics

From the characteristic we can estimate our $g_m = 2.5 \cdot 10^{-3}\Omega^{-1}$ and $r_p = 20k\Omega$. The small signal gain A_v is given by:

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

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

$$\implies \boxed{A_v = 25}$$

Using the obtained A_v, we need to choose an R_G. Like discussed earlier, we need to find the 3-dB frequency of the dominant pole caused by the interaction of the miller capacitance between grid and anode with R_G. From the datasheet $C_{GA} = 1.5pF$

$$\frac{1}{2\pi R_G C_{GA} A_v} \geq 20kHz \implies \boxed{R_G \leq 212k\Omega}$$

Last but not least, we need to make sure our output never exceeds V_A. This will cause harsh clipping and/or unexpected behaviour. Since the below calculated peak is lesser than 140V, we are good to go.

$$\boxed{100 + 1 \cdot 25 = 125V < 140V}$$

2.2.4 Final Schematic

Let us allow for some more fine tweaking by adding potentiometers and fixed resistors in series to let us tweak within a given range of values. Thus we would have the below schematic:

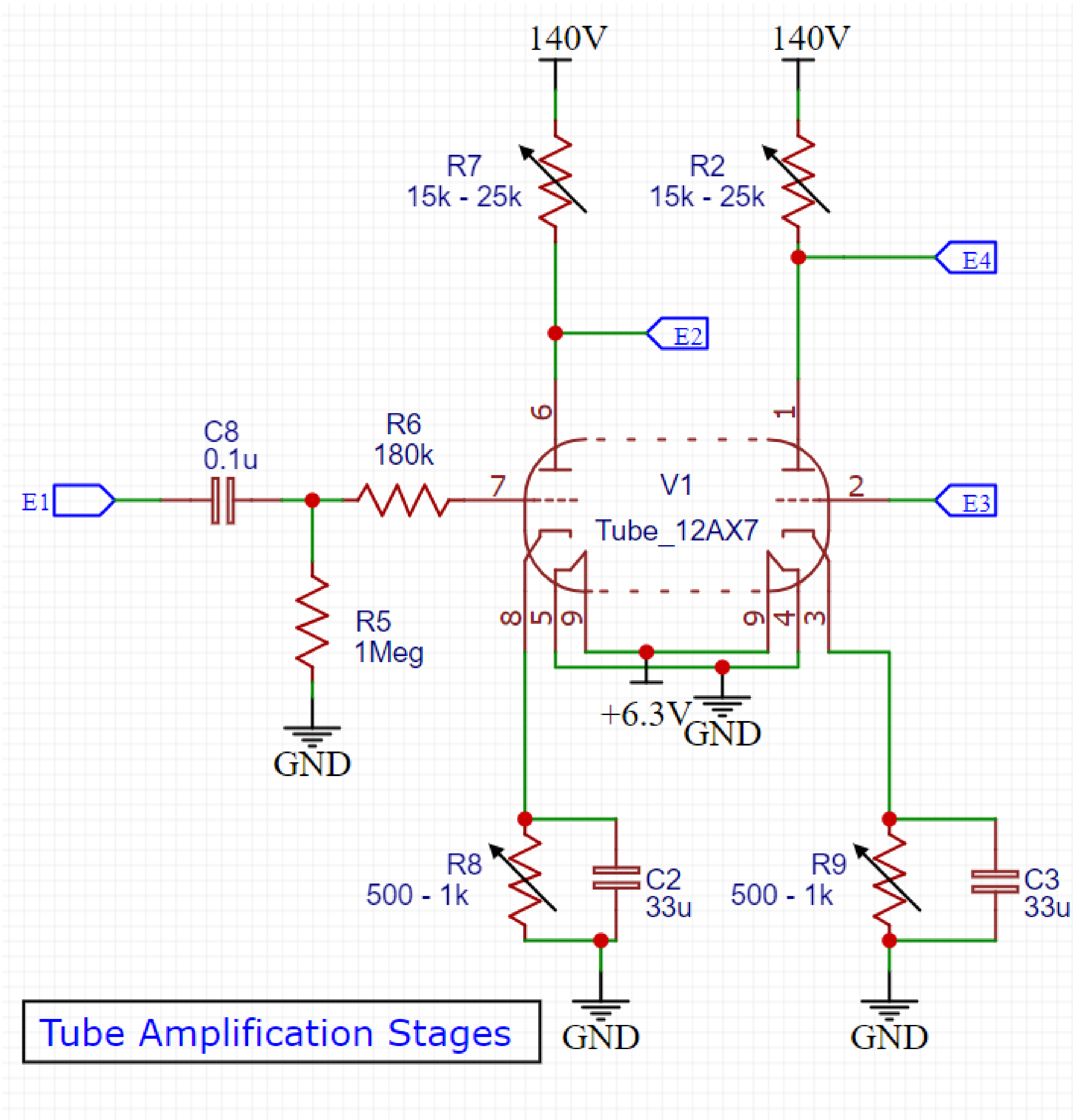

Figure 6: Schematic - Tube Stage

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 using LTSpice:

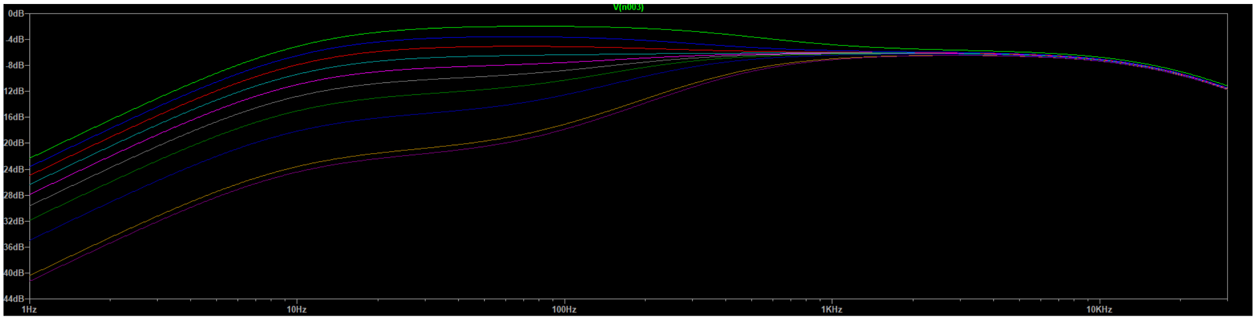

Figure 7: Tone Control Response

Although this was achieved with hit-and-miss and LTSpice simulation, this isn't to say there is not motivation behind this. Note that we can't use a simple bandpass owing to the fact that the signal coming out of the amplifier's first stage has a passive highpass for AC coupling. But we can try to cascade this with two paths resembling a low pass and a high pass respectively but with a potentiometer to control the response and a resistance in series with C6 to avoid having a purely capacitive path (otherwise AC coupling won't happen). We include the transfer function below for completeness.

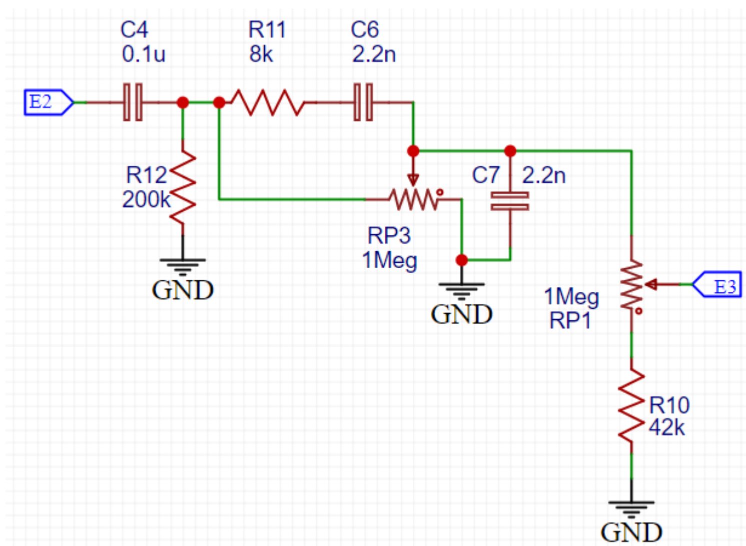

Figure 8: Schematic - Tone Control

$$\textbf{Work} = \frac{\textbf{In}}{\textbf{Progress}}$$

Note here that the signal was amplified to almost 25 times in the first tube stage. Hence we need to attenuate it at the end. Thus there is a 1 Meg pot in series with a $42k\Omega$ resistor to do the attenuation but also give some control on how much the second stage is driven.

2.4 Output Stage

By the time we reach here we have amplified our signal by another factor of 25 or so, which is possibly not what a digital practice amplifier or any home speaker is designed to take. This is the distinction between building a pre-amplifier for an upcoming power amplification stage and building a guitar pedal. The output stage includes a powered path and a passive path.

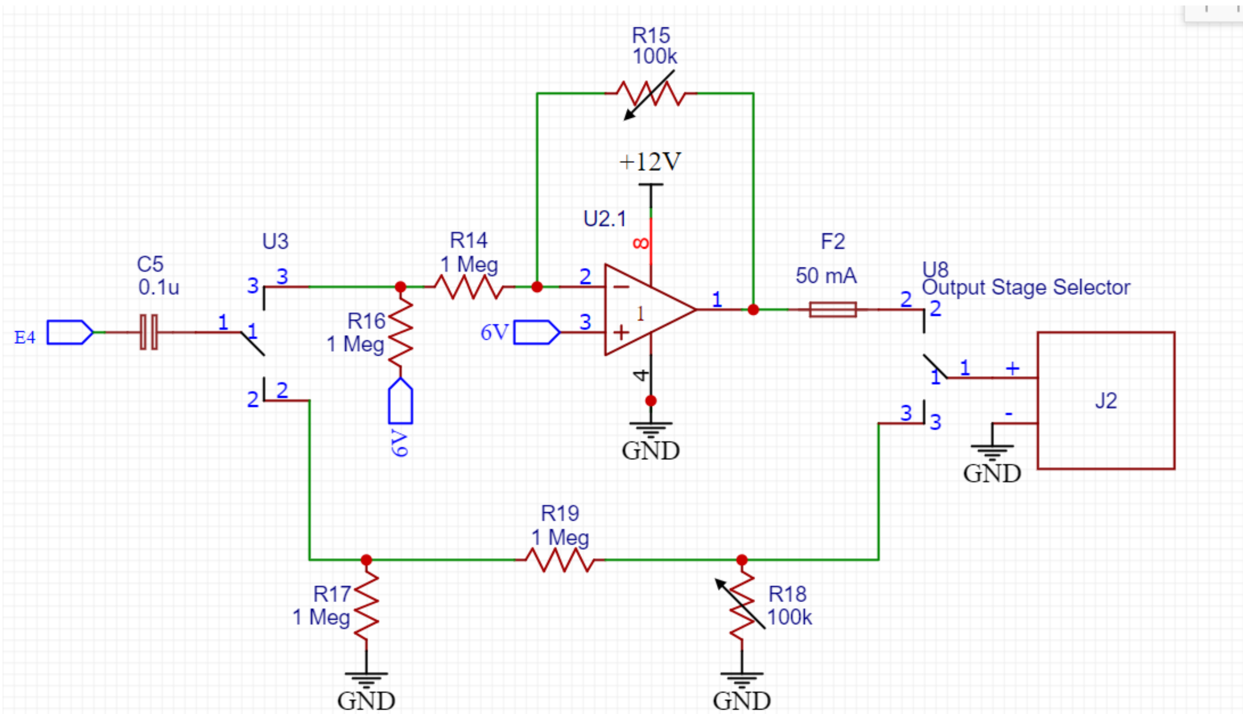

Figure 7: Schematic - Output Stage

We use the powered path **1.** When we are still prototyping and need to protect the amplifier with a fuse until the circuit is tried and tested or **2.** When our practice amplifier is not a "Hi-Z" amplifier in which case the current through the Amplifier will affect our 2nd Tube stage. When the powered path isn't necessary we switch to the passive path so as to cut down on the noise introduced by the powered amplification and fuse.

2.5 Power Regulation

12V, 6V, 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. Below are the methods used to get these power lines.

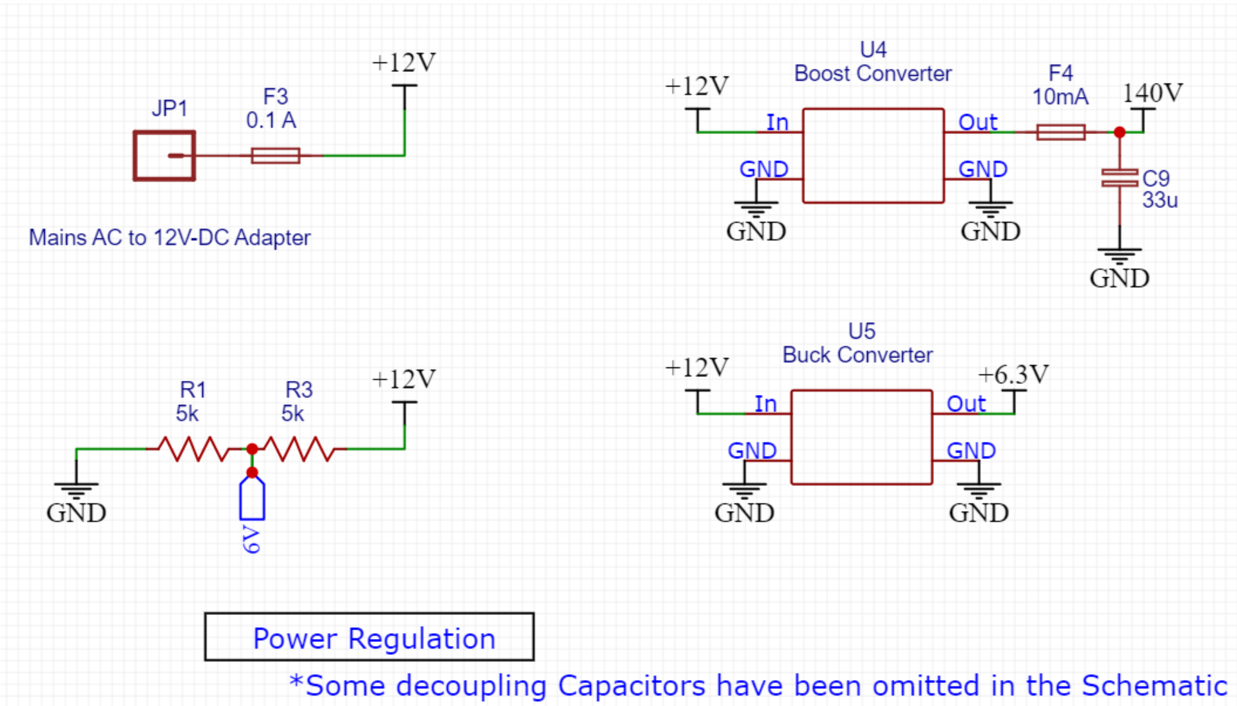

Figure 8: Schematic - Power Management

Choosing the fuse is a balance between safety and allowing the pedal draw more when required. The current drawn from the 140V line is about $4mA$ in total. If we consider above $10mA$ to be dangerous, we may choose a $10mA$ fuse on this line. For the total amount of current in everything combined, we can limit it to not more than $0.1A$ just as a rough estimate.

3 Methodology & Practical Implementation

4 Results