**Title:** Class AB Audio Power Amplifier

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**General Objective:** Bipolar Junction Transistors (BJTs) and Metal Oxide Field Effect Transistors (MOSFET) can serve as the building block for an amplifier circuit. An amplifier could be defined by class which describes whether the circuit will operate within a linear or switching mode. By combining the Class A and Class B amplifier, the Class AB amplifier is designed to have a higher efficiency than Class A amplifiers by yielding the largest amount of output power, while having lower distortion than Class B amplifiers. The Class AB amplifier makes for a good template for an audio power amplifier. Using this information, an audio power amplifier should be designed to uphold the following constraints:

* An 8 Ω load resistance which will model a speaker.
* A DC open loop gain of at least 140.
* A DC closed loop gain between 9 and 10.

The circuit design project is derived from an IEEE paper proposed by Nuno Paulino and can be referred to by the appendix.

**Background Information:**

Generally speaking, a BJT will operate by varying current, while a MOSFET will vary voltage. Though both transistors may be used for audio electronics, a BJT transistor is more commonly used. For my design I decided to primarily rely on NPN BJTs.

1. **What are Bipolar Junction Transistors?**

BJTs are three terminal devices made up of N-type or P-type doped semi-conducting material. A BJT may be doped either by Silicon or Germanium. The terminals consist of the Collector (C), Base (B), and Emitter (E). As Sedra Smith states in *Microelectronic Circuits Seventh Edition*, a BJT can be classified based upon its charge carriers.PNP transistors are when more holes are present than electrons, while NPN transistors have more electrons than holes. The general physical structure of an NPN and PNP transistor can be described as follows:

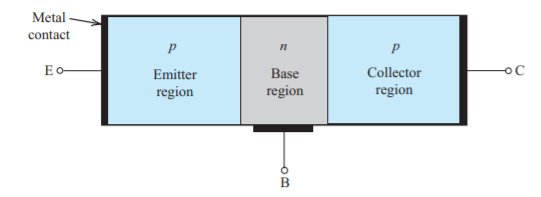
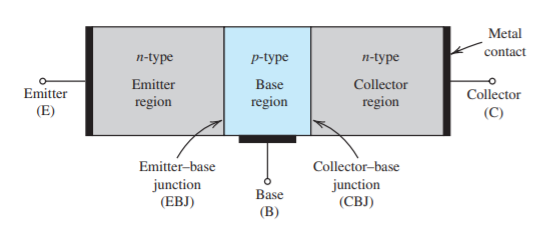


Figure a and 1b. NPN and PNP simplified structure

Based upon the structure, the BJT may be modelled as two diodes:

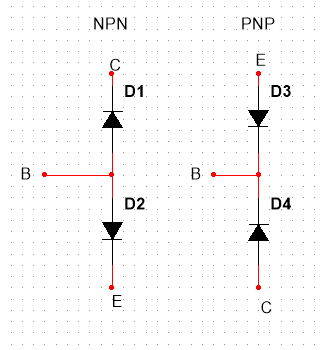


Figure . Equivalent NPN and PNP circuits

A BJT’s operation mode may be determined by the bias state of the PN-junctions and can be thought of as the bias of each diode:

|  |  |  |
| --- | --- | --- |
| **Mode** | **C-B Junction Bias** | **E-B Junction Bias** |
| **Cutoff** | Reverse | Reverse |
| **Active** | Reverse | Forward |
| **Saturation** | Forward | Forward |

When operating in Cutoff mode no current will flow through the transistor except for an extremely small reverse current. By initially operating in cutoff mode, the transistor could act like a switch by swinging between the transistor’s extreme “on” and “off” voltages with an initial “off” state. When operating in active mode, current flows in a direction depending on if it is forward active or reverse active, either way this allows for the amplification of current. Saturation mode is acts like an “on” switch since there is a high current flowing through the base of the transistor due to the free electrons flowing from emitter to base as well as from collector to base. Typically, active mode operation regions are preferred and will be utilized for this circuit.

1. **Common Amplifier Configurations**

There are three basic configurations which act as the foundation for BJT amplification:

* 1. **Common Collector**-This circuit acts as an emitter follower which will result in a voltage buffer due to the circuit’s impedance resulting in a current gain instead of a voltage gain. This is accomplished by wiring the base as an input, emitter as an output, and collector as a common to both. Adding a Zener diode to this circuit could create a voltage regulator.
  2. **Common Base**-This circuit may be used to create a current buffer or voltage amplifier by wiring the emitter as an input, the collector becomes the output, while base is grounded. This amplifier configuration is commonly used within microphones for their preamp stage due to the low input impedance. Additionally, VHF and UHF range frequency amplifiers also wiring this configuration to prevent feedback by isolating both the input and output.
  3. **Common Emitter**-This circuit typically acts as a voltage amplifier by wiring the base as an input and collector as output. The emitter tied both terminals to a group reference or power supply rail, thus acting as a common. This amplifier is often configured for radio frequency circuits and low-noise amplifiers.

1. **Amplifier Classification**
   1. **Class A-**Consists of a singled ended amplifier which is biased at approximately the center of the input signal’s swing. Typically, it can be constructed with one transistor operating in the linear region and uses a voltage divider to bias the base and individual resistors to bias the collector and emitter.
   2. **Class B-**Is known as the push-pull amplifier due to the amplifier conducting over half of the input signal swing. Class B’s consist of two active transistors in which one transistor conducts the first half of the signal while the second conducts the second half due to a phase difference of 180◦.
   3. **Class AB-**This amplifier is a modified Class B amplifier by biasing the active transistors so that they both conduct during an overlap of each input cycle. This creates a smoother crossover point transition and lowers distortion. Class AB’s typically will bias the output transistors with either diodes or a voltage multiplier typically consisting of another transistor.
2. **Differential Pair**-A differential pair could be used to source one or two inputs into an amplifier by using two transistors both biased with collector resistors and either an emitter resistor or current source. If both transistors’ resistors are equal then the circuit may be examined as a differential half circuit in which both transistors are symmetrical, so the amplifier consists of two common-emitter amplifiers and only one half of the amplifier is needed to be analyzed and then multiplied by a factor of two.
   1. **AC Analysis**-For AC analysis, a quick useful chart delivers the gain when compared to the input and outputs of T1 and T2 as follows, and can be cited within the appendix from David Williams, proving each of the formulas:

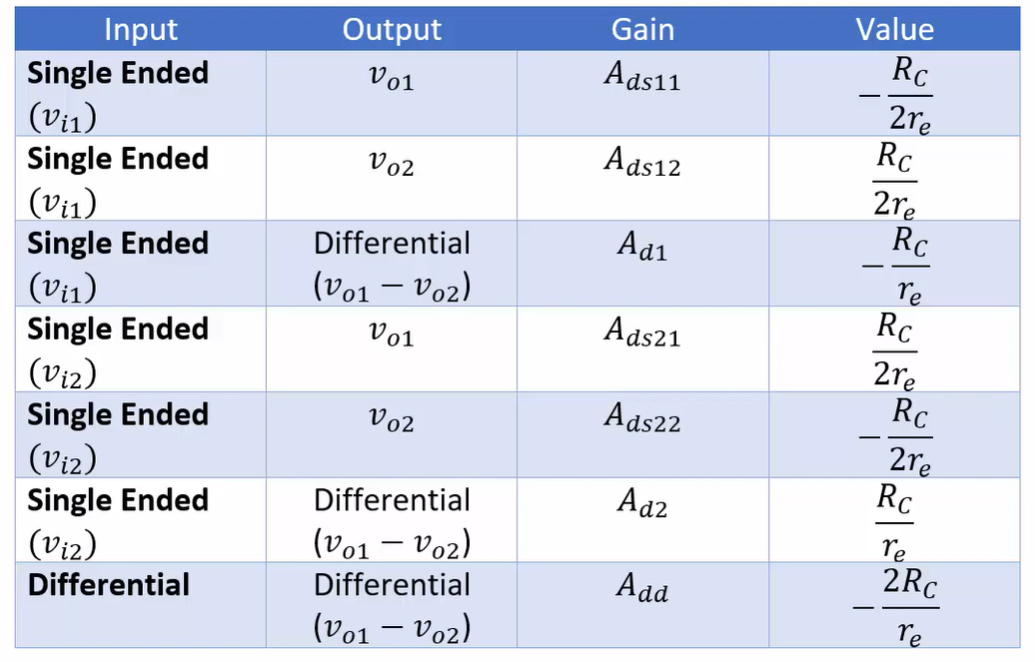


Figure . Gain Calculation Cheat Sheet for BJT Diff. Amplifiers

**Procedure**

The procedure of this project consists of two aspects: Analysis and Design. While one could create their own audio power class AB amplifier from scratch, a template which reflects similar to the internal circuit of the average operational amplifier, is proposed as a starting point. To better my understanding of both multistage transistor amplification and operational amplifiers, I decided this would be a good starting point, and I could always add any sort of modifications, after the initial analysis. Furthermore, my analysis derived from MATLAB code can be referred to within the appendix.

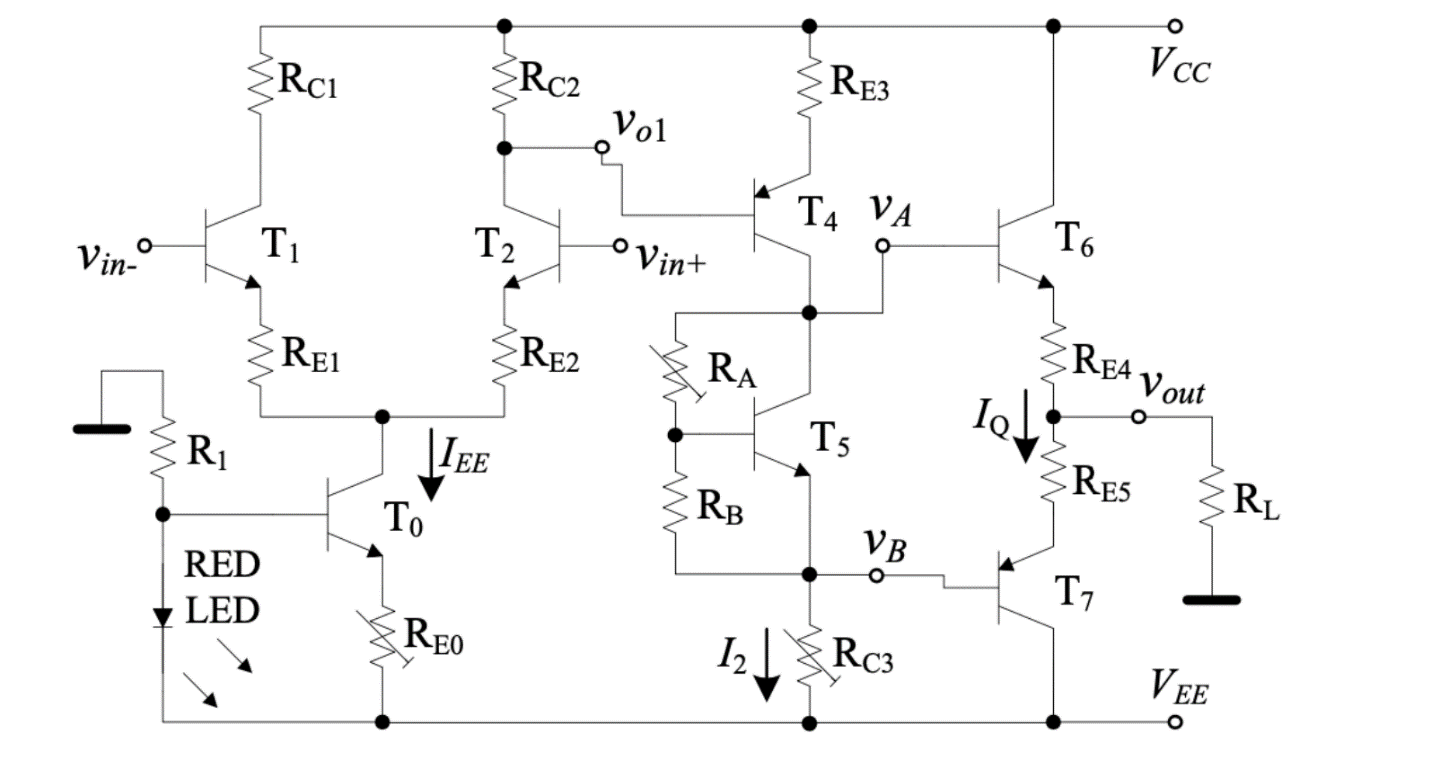
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Figure . Template Class AB circuit

Observing the template circuit, it is apparent that the transistors can be isolated as three stages: The first stage consisting of T1 and T2 create a single input-unbalanced output differential amplifier with one input where ’s positive is connected to the base of T2, while the negative is connected to T1. T0 acts as a current source for the input stage, in which the base voltage is set when a red LED is on. The following stage coming out of T2’s collector, is a T4, a PNP common emitter which will drive the class AB push-pull output. T6 and T7 are two emitter follows which has a current determined by the of T5, which is a voltage multiplier. Together this is what creates the class AB output stage. models the speaker as an load resistor and and are used for circuit protection by preventing the rate at which thermal run away may occur so the output transistors will not be destroyed.

Given this background information, a few unknown values may be simplified by assuming that can be assumed for all Silicon BJTs. and since the differential amplifier can be recognized as a half differential amplifier with only one input is used. , and , meaning that the minimum value for .

For my circuit design, I decided to stray from the template’s suggestions by using common transistors such as 2N2222’s for the NPNs and 2N3905 for the PNPs, simply because these are transistors I currently own, and while the project is simulation based, I would like to breadboard the circuit if I have time or within the future to better my understanding. I am choosing a basic red LED similar to the ones used in ECE 2333, which will turn on when the voltage is approximately at . Changing these components could stray from the guidelines distributed by the template project that , and , meaning that the minimum value for , however I will keep these constraints noted as a general foundation.

# **DC and AC Analysis**

A DC analysis to find the operating point of the input circuit can be found by shorting the AC voltage sources, opening the AC current sources, and opening all capacitors.

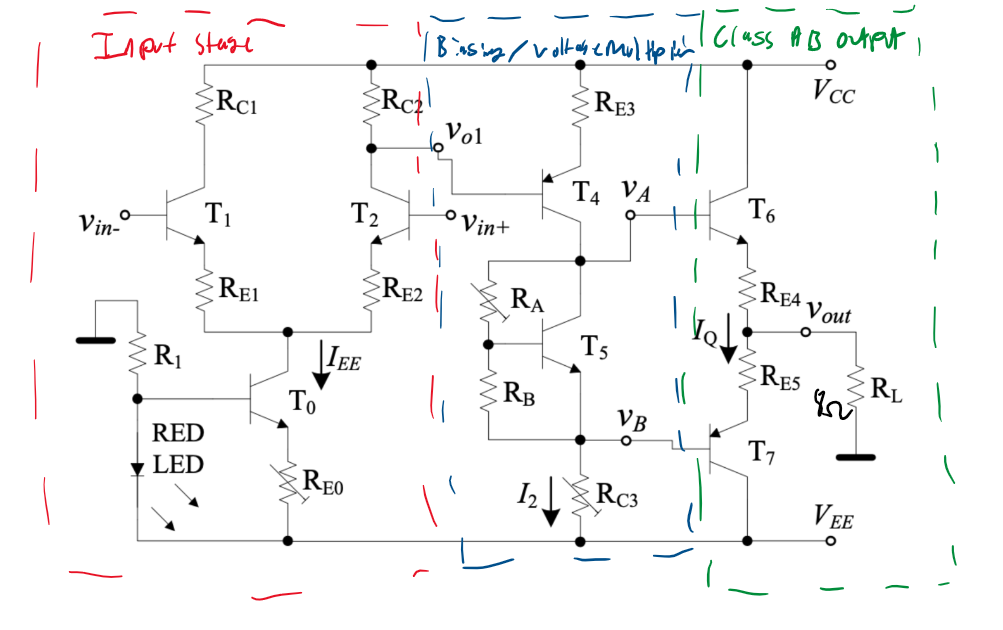


Figure . Template Class AB audio power amplifier for DC analysis, annotating each Stage

The initial step would be to determine what should equal. Since the load delivers across an resistor, the power supply can be calculated as .

Solving for ,

, .

Current across the load is then calculated as .

Additionally, this means a voltage peak is found from . From these constraints, the power supply should be larger than the voltage across the load, so I selected , yielding a and . is more than enough headroom for the circuit and a common power supply for audio electronics, especially for pedals and rack units.

### Current Source T0:

The DC analysis may begin with modelling T0 as a single BJT 2N2222 NPN transistor connected with coming into the collector, while out of the emitter a potentiometer goes to with the LED yielding in parallel connected to the base and a current limiting resistor . The current source can be viewed similar to a common base transistor:

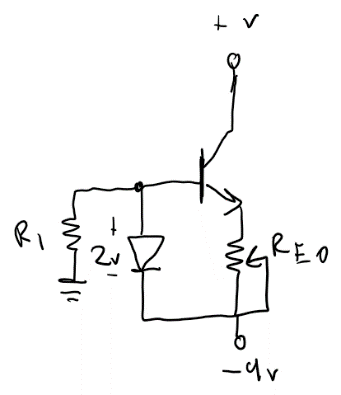


Figure . Simplified T0 for DC analysis

can be calculated as follows:

, where ,

therefore, a range for can be found as

Given there is not a common potentiometer of , which is the max value, I decided to select potentiometer which will start analysis at 50% of its value (). By Ohm’s law, which fits the constraint. Applying node analysis yields to determine the LED’s current and current limiting resistor,

.

The current limiting resistor may be less than or equal to resistor to flow approximately through the LED due to Ohm’s law and may be adjusted further into the analysis. Based on this, I selected . Since the base is grounded by , and the next transistor can be applied to the output of the collector.

Confirming this with Multisim’s simulation yields some tolerance since I assumed values such as , as well as the fact that while Multisim allows the current of the LED(ON) to be set to , the voltage cannot be set to However, generally the simulation matches the analytical values and based on the potentiometers, any biasing can be adjusted later within the analysis/experimentation.

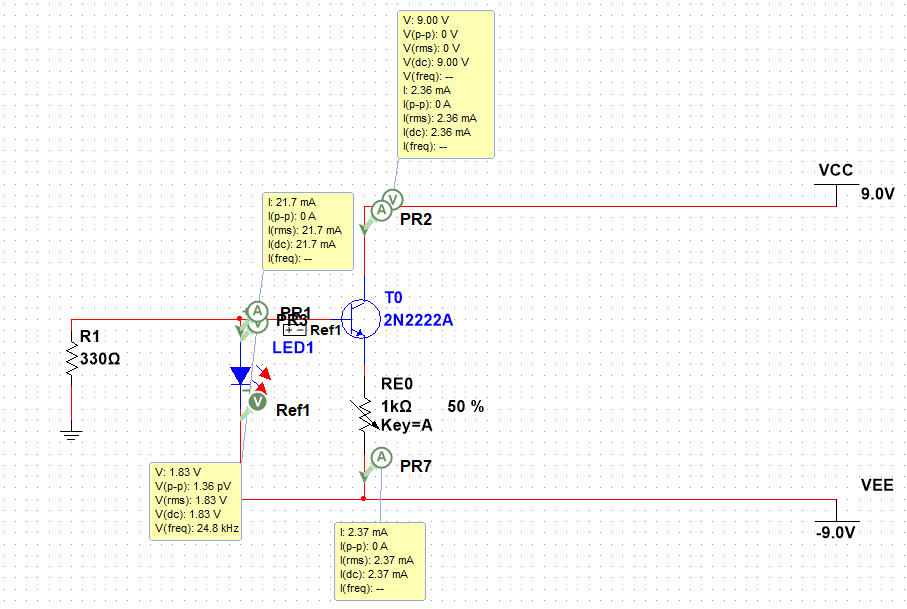


Figure . T0 Multisim DC analysis simulation

The AC analysis for this part of the circuit is included within the T1 and T2 analysis since T0 is simply a constant current source that determines the emitter current and impacts the value of and .

### Single Input Differential Amplifier T1 and T2

Transistors T1 and T2 only have one AC signal with the positive terminal running through T2’s base, while the negative is connected to T1, and the output signal will come out of T2’s collector as . This can be treated as a differential half-circuit, meaning only one half of the amplifier needs to be analyzed due to the biasing resistor’s symmetry. Therefore, T2 gets analyzed.

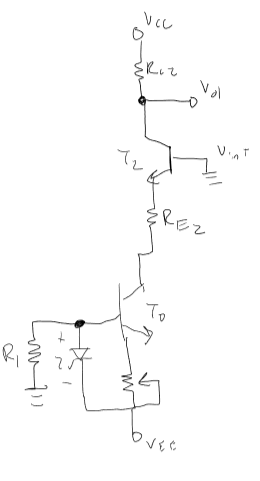


Figure . Differential Half-Circuit connected to T0 current source

Since this circuit splits, the current becomes , which is also the current for , , and . The collector resistors can actually be determined by applying the hybrid-π model and performing a small signal analysis:

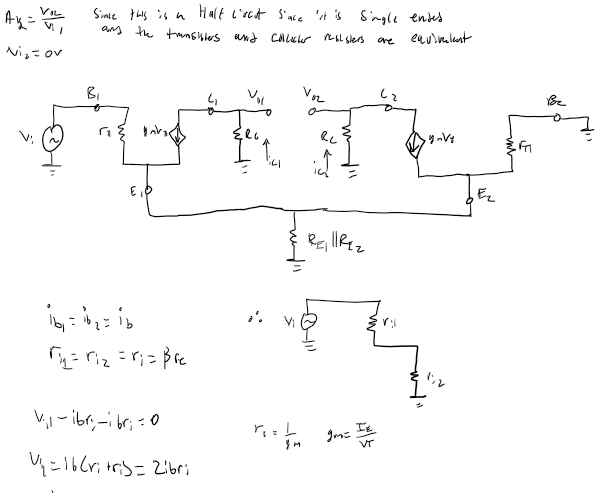


Figure . Hybrid Pi Model of Differential Input T1 and T2, start of proof

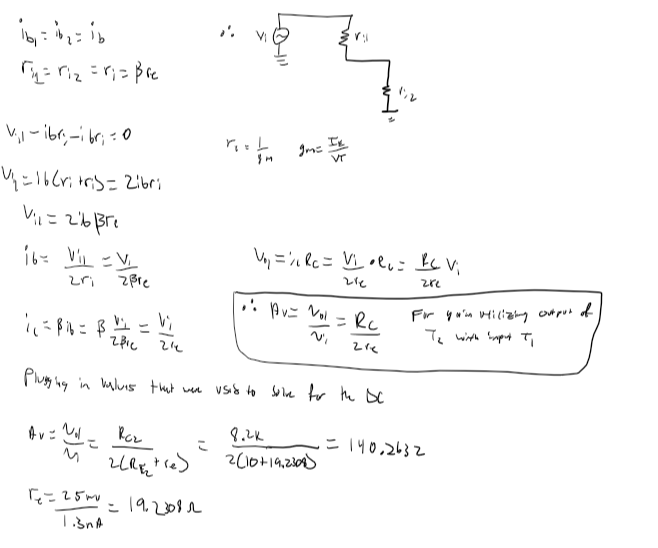


Figure . Proof continued

Since we are ignoring because it is a half-circuit where , can be determined as and the gain can be approximated when , as,

, where and .

Assuming then,

Ω and .

Keeping in mind that there needs to be a DC gain of at least , RC can be solved for by rearranging the equation and knowing that the minimum value for , the gain equation may be rearranged to solve for . Therefore, . Since the circuit needs a gain of at least 140, the gain equation may be rearranged to find a collector that suits 140.

If

Ω

Though this is a negative gain, it is simply because of the phasing and will be inverted within the next stages. Concluding and . Finally, the voltage can be regarded as , which is found by which will act as the base voltage of T4.

Combining the differential input with the current source in Multisim yields,

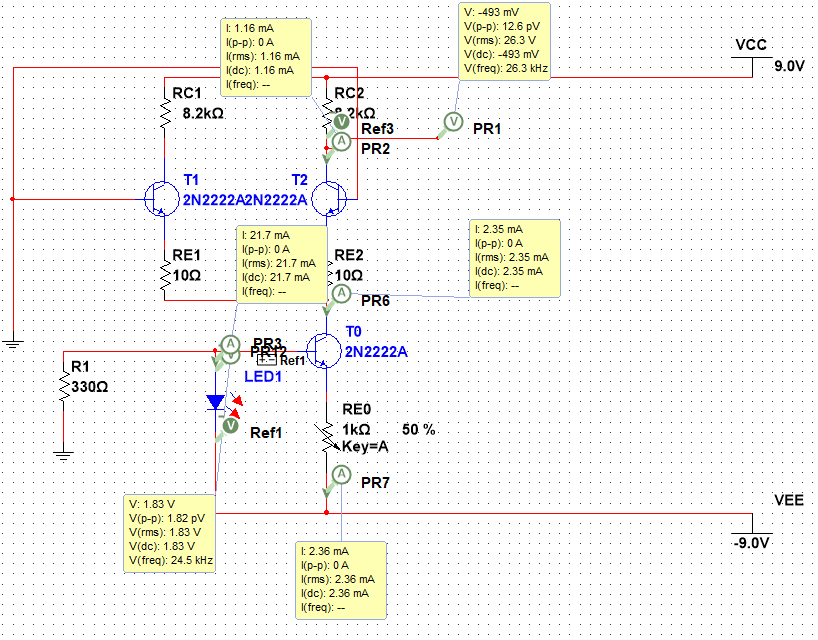


Figure . T0, T1, T2 Multisim DC analysis simulation

Notice that due the analytical assumptions the output voltage is off, but this is where and comes into play as variable resistors. yields a range when turned down to minimum value of - contrasting a maximum value of when turned up all the way. This also makes sense because referring to the MATLAB analysis in the appendix and changing the value when IEE is solved for by manipulating RE0 to its minimum and maximum values delivers a negative voltage to a positive voltage of . This adjustment of these potentiometers will become crucial when combining with the rest of the circuit.

### The Voltage Multiplier (T4, T5)

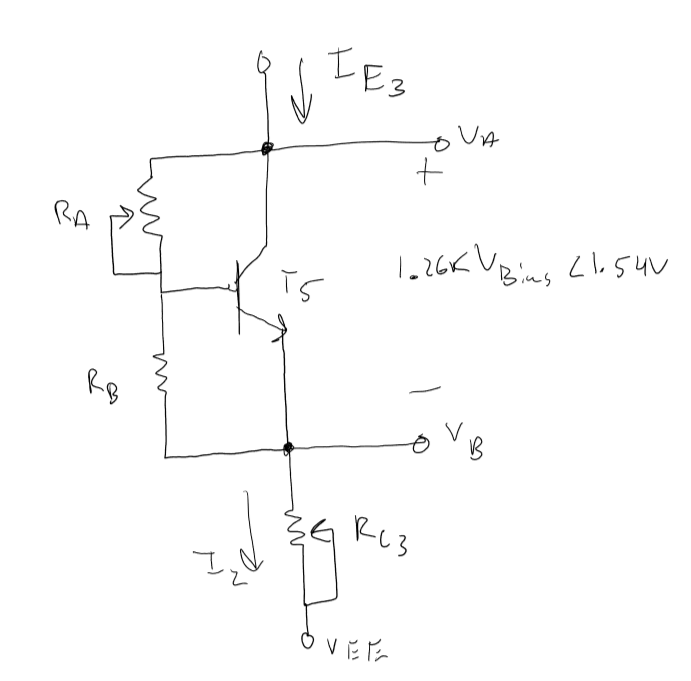


Figure . Simplified T5 Voltage Multiplier

and can be viewed as two parallel resistors going into the base of T5, therefore the voltage at the base will be the equal to the voltage across . Notice that is really the sum of the voltages across the biasing resistors. Therefore,

From the guidelines,

The biasing resistors are really here for flexibility to prevent thermal runaway by calculating a desired for the class AB output. Knowing this it is safe to assume that and should be set as the same values with being a potentiometer for flexibility. The resistors may be solved for as a set of ranges based on Ohm’s Law I decided to make both resistors as but given is a variable resistor, I initially set the value to be much lower to abide by constraint, as well as knowing the relationship of the resistors is based upon a voltage divider, that is to say,

)

Initially setting and , the combination yields a resistance factor of 11, and increasing will decrease the factor but increase the voltage, which can be useful for tweaking voltage and current values later. From this calculating the current to confirm the resistors lie within the range,

Based on the current, solving for again yields,

Which fits within the range. Furthermore, a collector current range should be calculated as well using KCL,

T4 which is actually a typo in the template and offsets the rest of the transistors numbering but will be renamed in my final circuit, controls the current and voltage going into the voltage multiplier by biasing T5 as a PNP common emitter circuit. Exiting T5’s emitter is another potentiometer which acts as a biasing control initially for T4, and will control the current through second stage’s branch which should not exceed . For simplicity and control, this was selected the same as as a potentiometer which can be adjusted for proper biasing later. The template states that should have a minimum of , however this circuit will need a larger resistor to control the overall output voltage that will be delivered to the load, by manipulating the current flowing into the voltage multiplier and controlling the voltage delivered by the differential input stage. By setting at the halfway point , the input voltage to T4’s base will be taken as , therefore . Given that the PNP is connected upside down, the emitter is connected to , so when calculating the current, Ohm’s Law can be utilized as follows. The constraint here is that

Solving for ,

Selecting the common resistor value, recalculating which is approximately the value of current that will flow into the voltage multiplier and through . The voltage delivered to the collector of T5 can now be calculated as a temporary since T5 is an NPN transistor.

Therefore,

To further calculate the proper biasing ratios of the resistors, the class AB output should be analyzed and worked backwards from.

### The Class AB Output T6 and T7

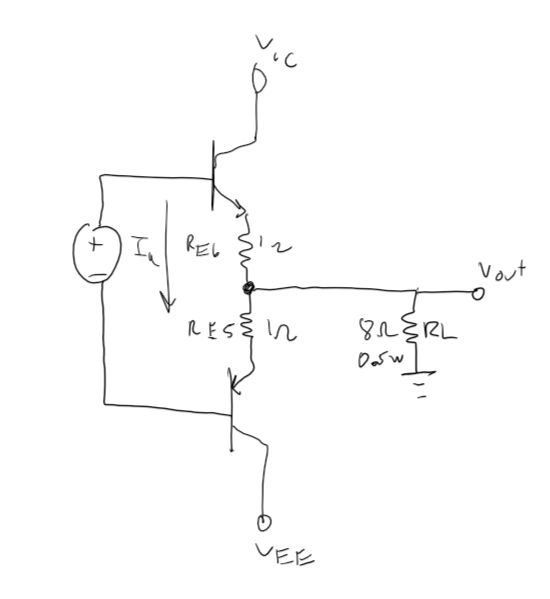


Figure . Class AB output stage

to account for thermal runaway. Since , there are no more components to solve for, however the current still needs to be determined and to be less than 10mA. The current going to the load was calculated earlier as , with a voltage of , this will help determine the resistance values of and . The current flowing into cannot be the same as which is the current flowing through . KCL proves that , which yields an extremely small current that will ultimately be less than , once the proper biasing values are established. For now, is so small, it can be ignored. The current flowing through is also that flows into the load, so the voltage of . From this the differential voltage generated at the output of the voltage multiplier can be calculated as,

Knowing this, the biasing resistors and will need to yield a differential voltage of which means will have to be lowered to manipulate the ratio of the resistors. By utilizing the range of the collector current , the total resistance ranges used to calculate can be solved for,

Therefore,

Meaning if remains , should be between these ranges to yield a differential voltage . Setting and recalculating and using the ranges for yields a range with a min of to a max of which the minimum voltage that will fit in, and by re-biasing the to reduce the current slightly, , and everything checks out. Finally putting all of this together and running a Multisim simulation and concluding the DC analysis,

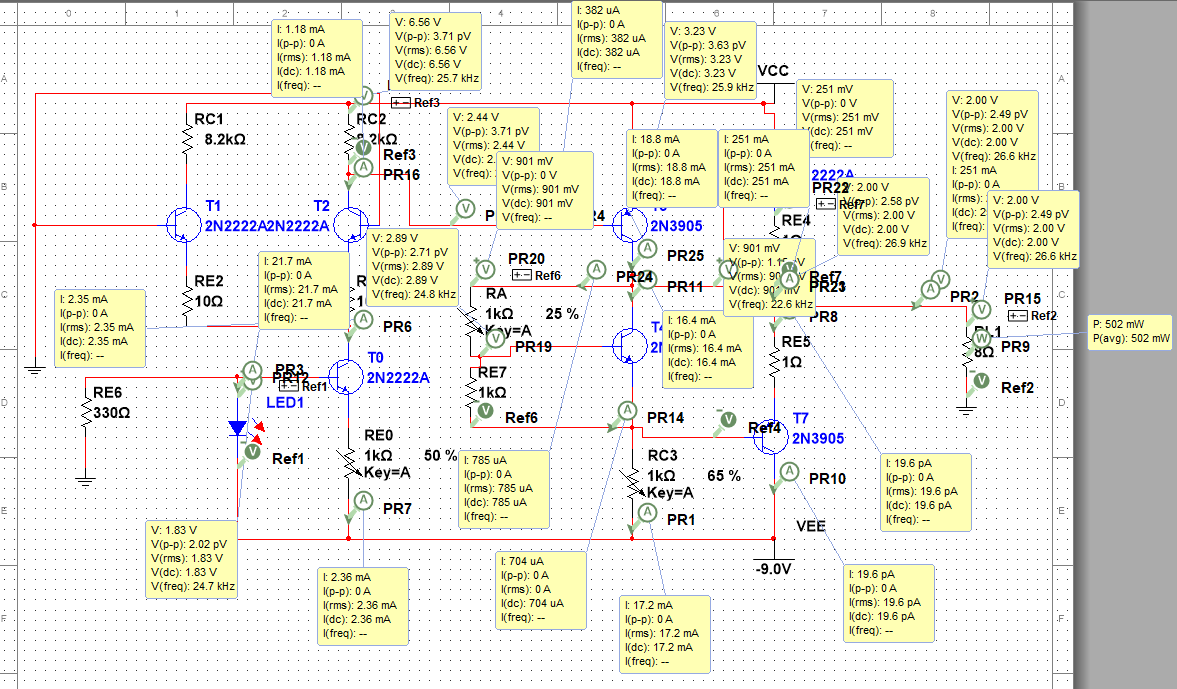


Figure . Multisim Simulation of DC analysis delivering .5W to RL

Additionally, the voltage at the emitter of T6 and collector of T7 can simply be calculated for AC analysis as follows. Given that there are no biasing resistors for T6’s collector and T7’s emitter, and since the , then . For T7, , and , therefore, , which is confirmed by simulation,

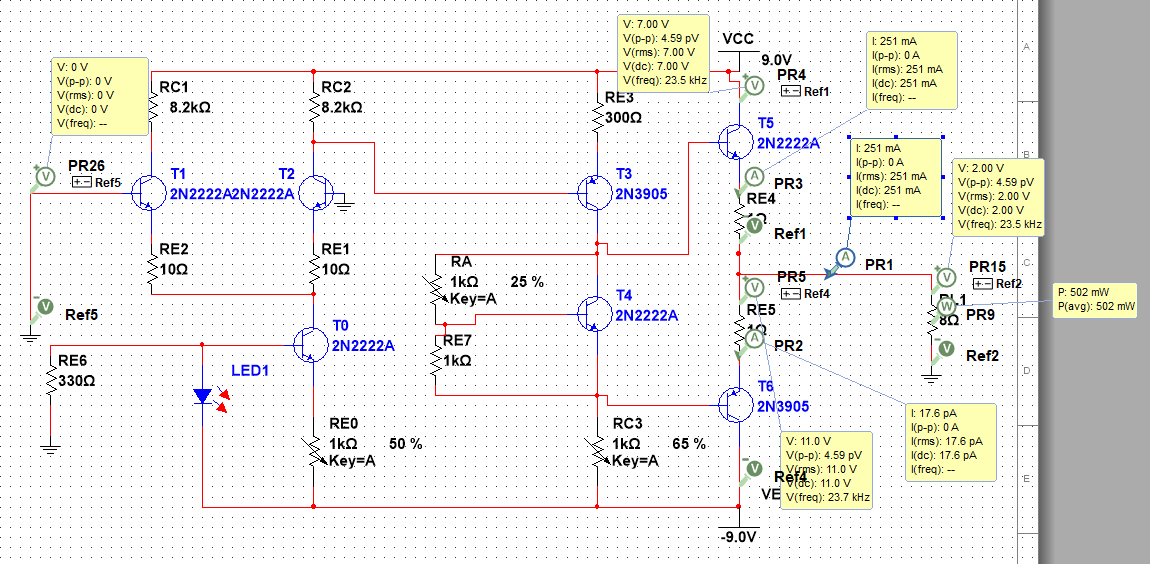


Figure . Class AB voltage simulation

In terms of the rest of the AC analysis, only a small signal model is needed for T4, since T5 only manipulates the voltage bias of T6 and T7 which deliver current to the load as an output. Therefore, any gain generated from T5, T6, or T7 is so small it can be neglected. From this, the PNP common emitter T4 stage can use a hybrid T model for AC analysis to calculate gain:

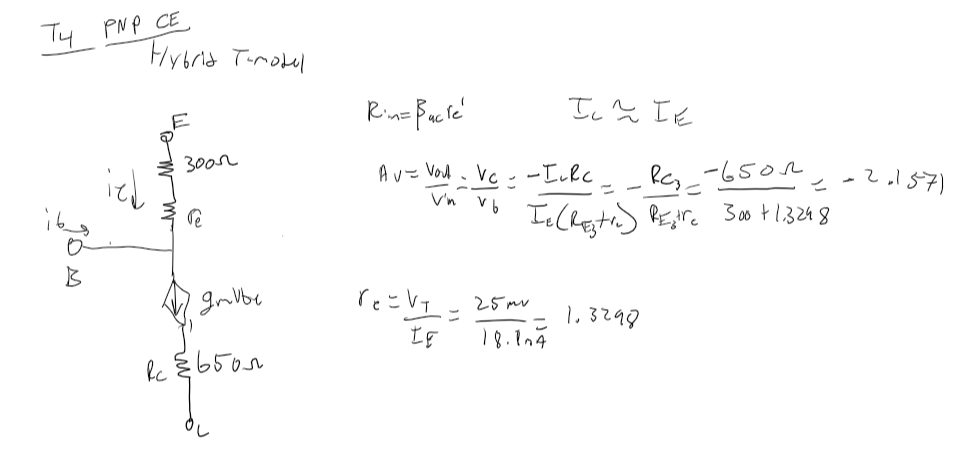


Figure . Hybrid T model for T4

Multiplying both stages of the circuit I exceed a gain of since,

Though this gain is negative, the class AB output inverts the signal between 180 and 360, therefore a negative gain simply means the signal is out of phase from the source and will further be inverted by the class AB output.

**Simulation Results:**

Adding in a small signal of at yields an output voltage of with a tolerance of , therefore finding the closed loop gain can be approximated from the simulation as , however increasing the resistance of the potentiometers, specifically and will increase the overall voltage and power of the circuit, yielding a larger gain. With both potentiometers increased to their max values, the gain becomes but no longer delivers due to the increase of voltage. This can be compared within the next two diagrams,

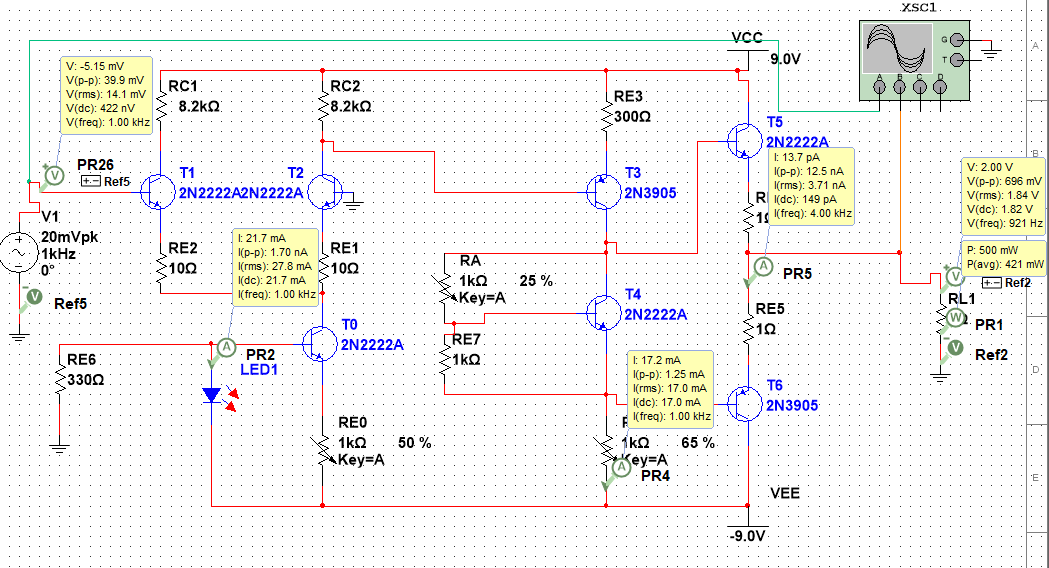


Figure . Simulation with analytical values

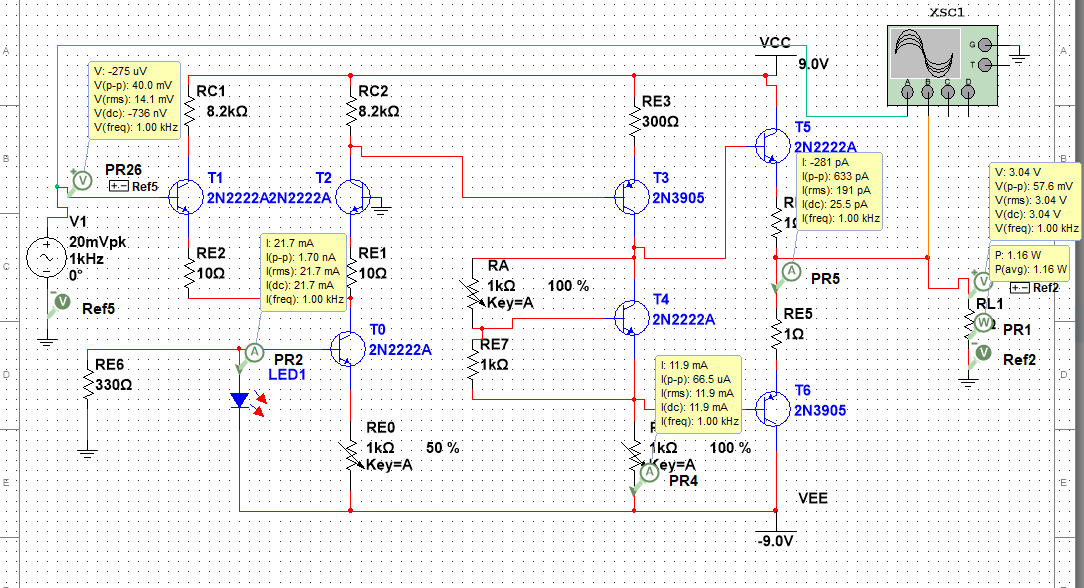


Figure . Increasing RA and RC3 to max resistance

Upon running a transient response, shows the outputted voltage across the load in purple, yielding , with its power in blue delivering , compared to the input in grey of . The transient response is what should be expected especially because I achieved a negative gain analytically, meaning the signal is inverted, which is now shown since the output’s minimum values are approximately where the input’s maximum peaks are and vice versa. This means the class AB output is properly working since class AB amplifiers invert the signal between to. Something worth mentioning is that in order to deliver the signal is being compressed which is why the positive peak of the output is now slightly distorted.

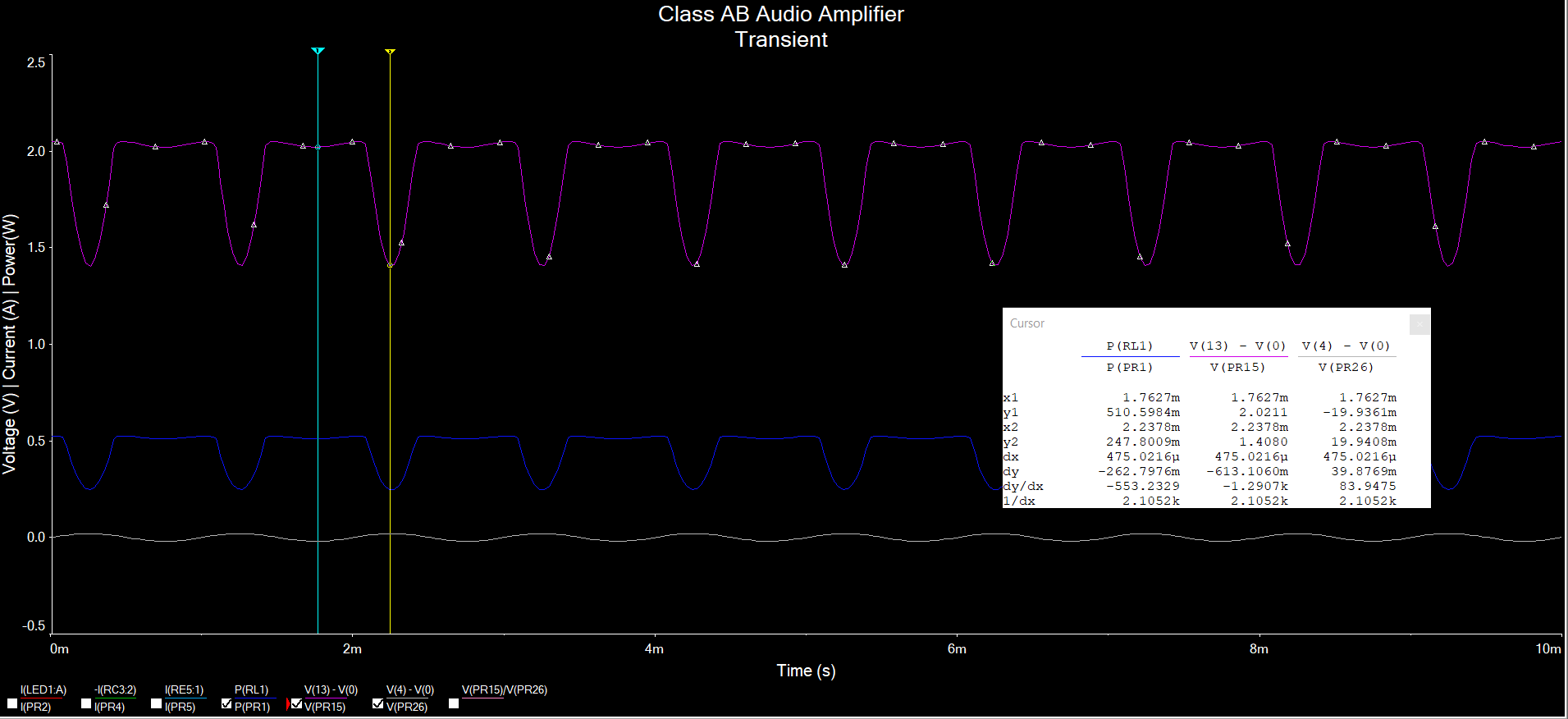


Figure . Transient Response

Getting rid of the distortion can be done in a number of ways. If the input voltage is increased, then the output signal will clip more and act more like a fuzz circuit rather than a clean amplifier, decreasing the signal further to a signal such as , gets rid of the noise, however the input signal is so small now that while it is a sinewave, it is practically a DC signal.

For measuring the frequency response of the circuit, I ran an AC sweep when feeding in a signal at ,

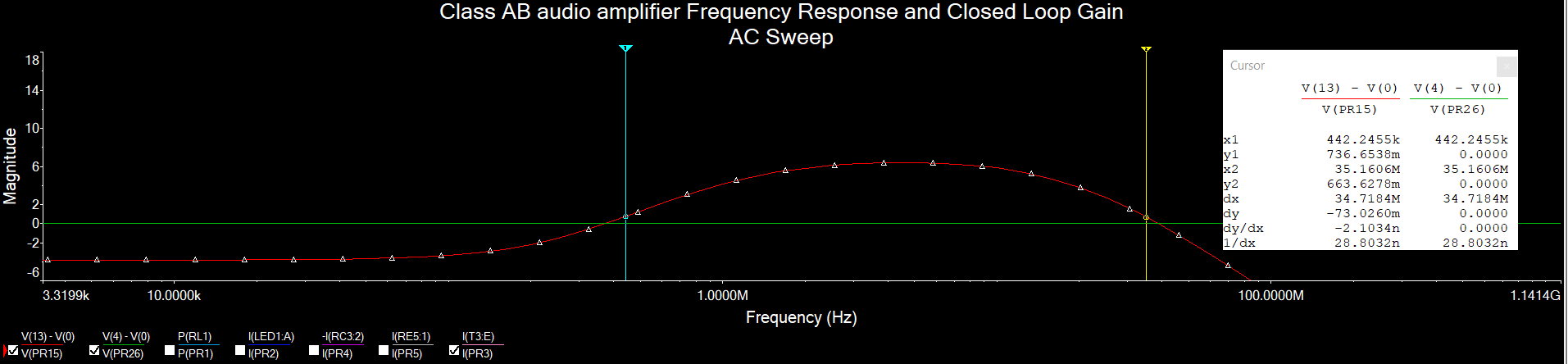


Figure . Frequency Response using dB vertical scale

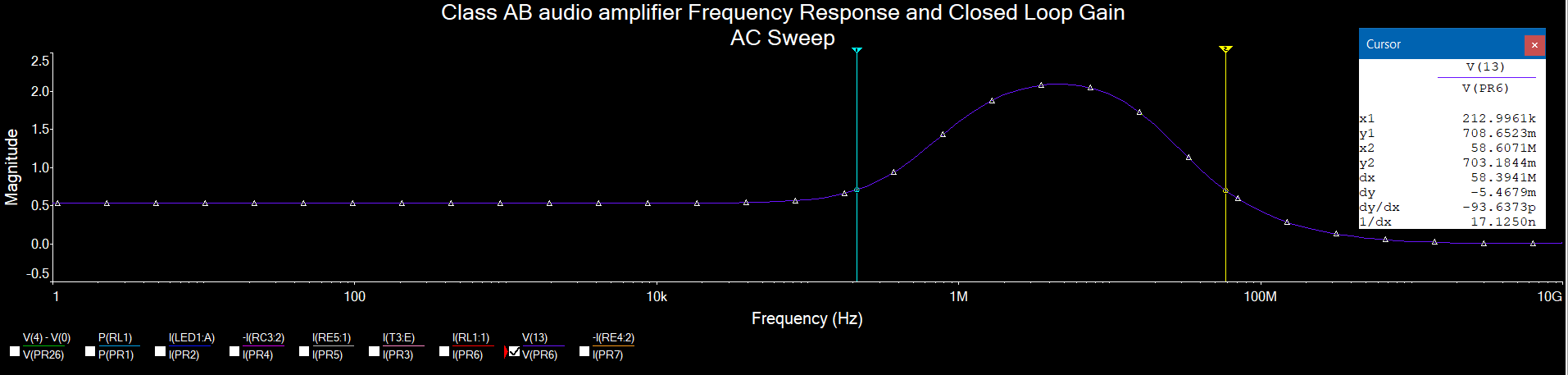


Figure . Frequency Response with linear scale

By measuring when the curve reaches a value of , the cutoff frequencies of the amplifier are found at approximately to . The human range of hearing is approximately to so the amplifier’s bandwidth is not ideal for audio. The AC sweep also yielded a closed loop gain of approximately or , which could be because of the compression of the signal to obtain a value of to the load.

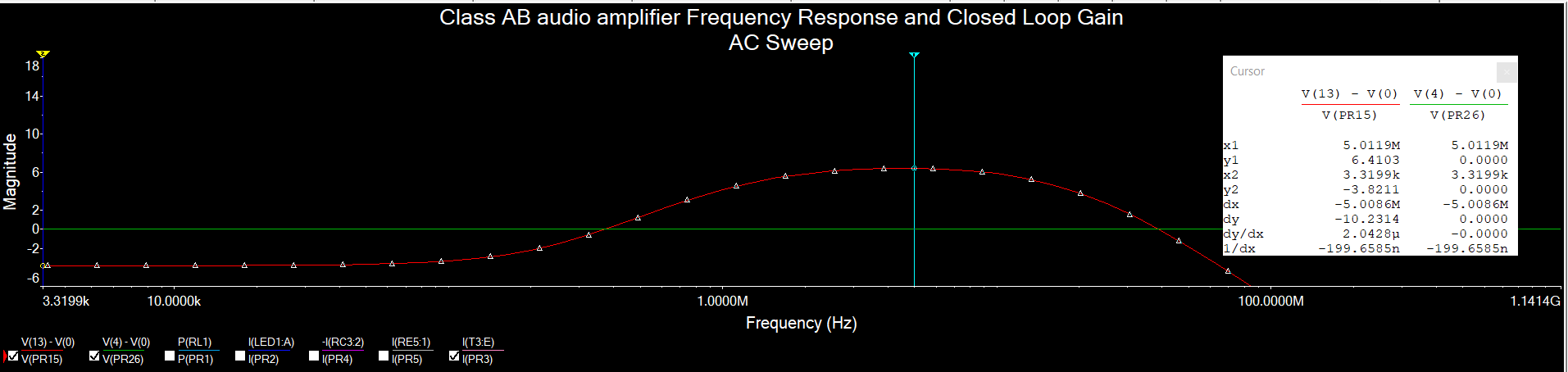


Figure . Measuring Closed loop Gain dB scale

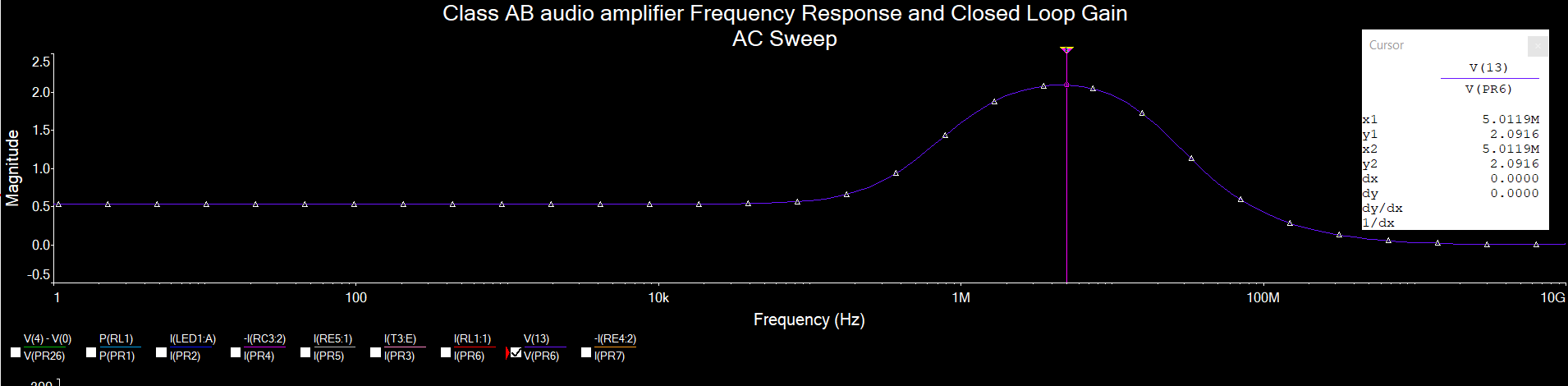


Figure . Closed Loop Gain linear scale

One way to fix the issue of clipping and to offset the filter is by implementing an emitter bypass capacitor in parallel with . By adding a cap, the circuit now breaks the frequency response at a cutoff frequency . Also keep in mind however, there are no coupling capacitors to isolate the stages within this circuit, the only other capacitance comes from the internal capacitance of the BJTs, therefore the cutoff frequency is far from perfect due to bleed from the different stages. The circuit still delivers the same amount of power due to voltage and current across the load.

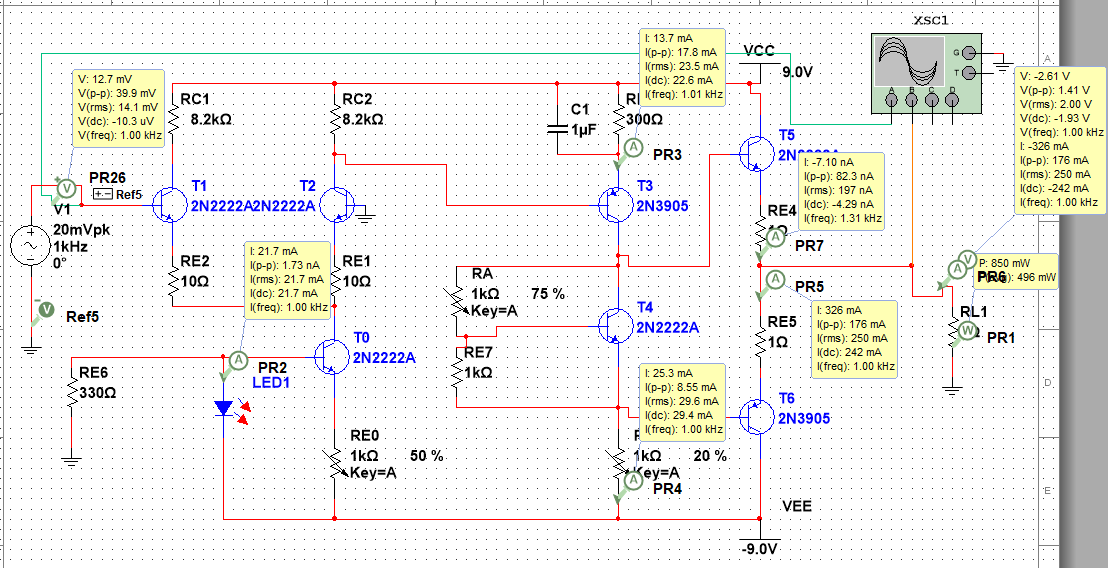


Figure . Adding Emitter Bypass Cap

There is no specified bandwidth necessarily for this amplifier, so I am not too worried about the bandwidth other than obtaining a bandwidth that will amplify audio that humans can hear.

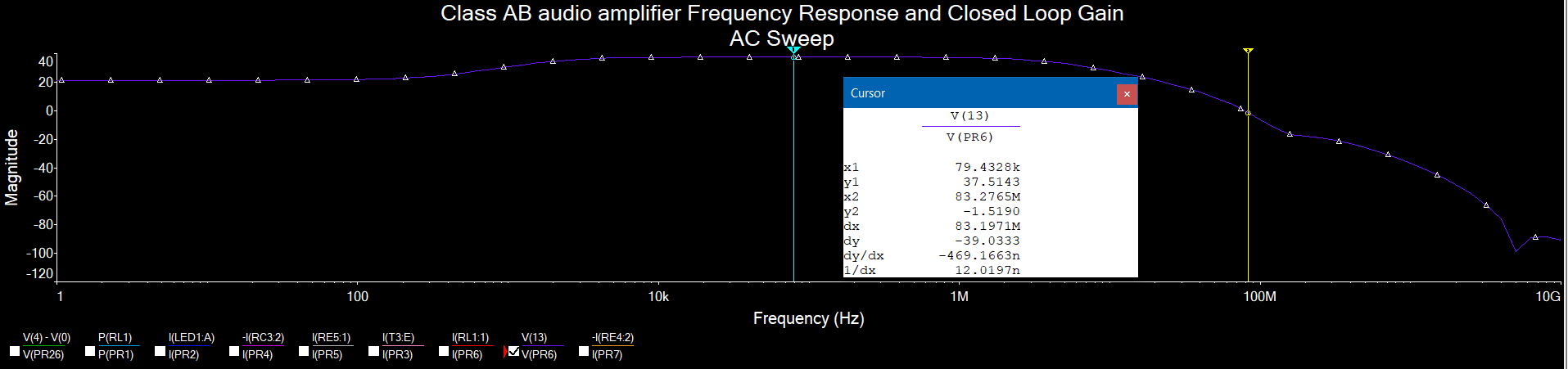


Figure . Frequency response shifted due to capacitor in dB

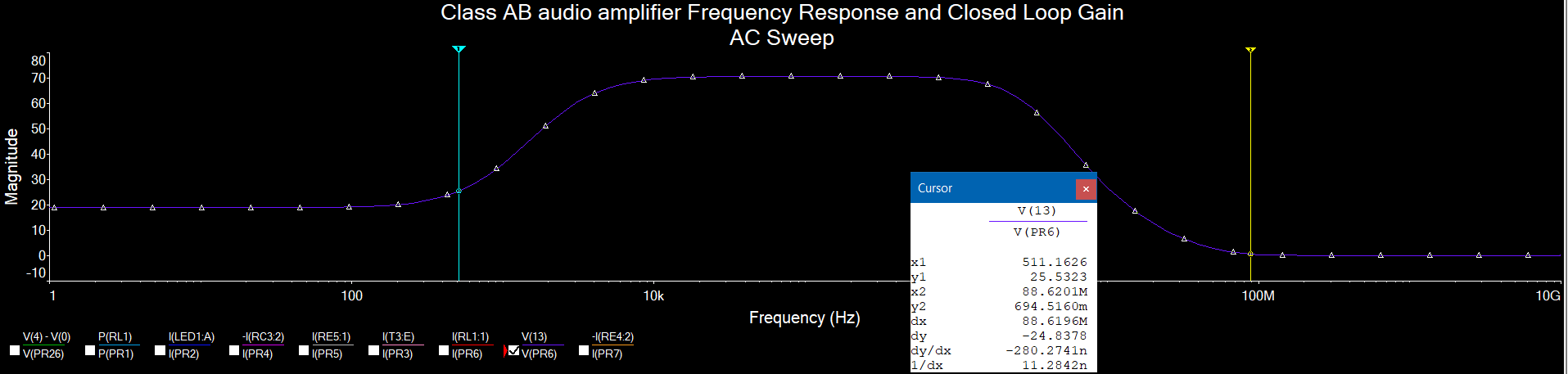


Figure . Frequency Response with linear curve

This now delivers a bandwidth of approximately from to . Since this acts a high pass filter, this also smooths out the transient response. The capacitor also bumps the AC closed loop gain up to or , Here I used an oscilloscope for this reading rather than Multisim’s transient response since it is easier to scale the input and output by for a clearer reading,

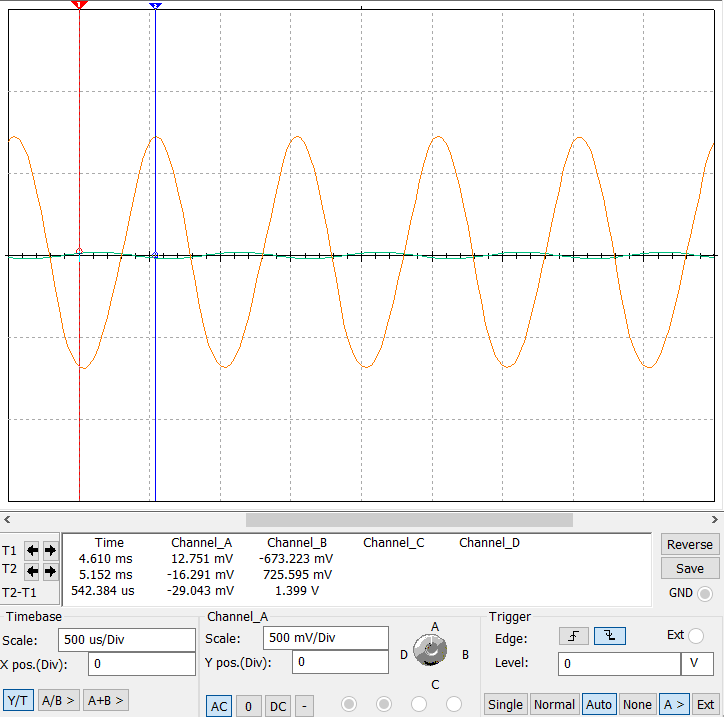


Figure . Transient Response with Oscilloscope, after adding Emitter Bypass Cap

Furthermore, an input capacitor could go into T1’s base and potentially act as a high pass filter to lower the lower cutoff frequency further since it does not actually reach to calculate the lower cutoff frequency.

**Conclusion:**

This amplifier project was something I was incredibly interested in since audio electronics is the primary reason I decided to study Electrical Engineering. Unfortunately, I was unable to complete aspects of the class AB amplifier due to time management between school, work, as well as into some design issues I was unable to figure out. Some issues I encountered upon designing the class AB was an issue of achieving to the load while maintaining a clean signal. Since the load compresses the signal down to , every time I attempted to check my gain calculation with an oscilloscope, my positive peak was compressed down to to maintain the power delivered, an while I could adjust the bias to achieve a large open gain, I would disregard the delivered, since increasing voltage would increase current and therefore increase power. A potential solution to cleaning up the compressed signal is to filter out the distortion, this can be done by adding a capacitor in parallel to , and grounded to. Due to time management, while I was able to perform calculations for DC analysis and some of the small signal analysis, I was unable to analytically calculate the amplifier’s frequency response. Specifically because the gain issue prevented myself from being completely sure of what my components values should correctly be and contributed to mathematically finding some of the small signal parameters, as well as while I was able to find parameters such as , , and from Multisim’s edit transistor parameters which come from their respective datasheets, I was unable to calculate or find values for , since I could not find a values for or since while could have been approximated as and for silicon is I could not determine , to calculate . The appendix shows my attempt at calculating what I could for frequency. I think if this class was in person and I had more time to ask for feedback, I could solve the issues within the circuit, but unfortunately, I am in a situation of simply handing something in for credit at this point. I will say moving forward, this project allowed me to research more besides reading our textbook, I also referred a lot to Paul Horowitz’s *The Art of Electronics 3rd edition*, which became extremely helpful when understanding the differential amplifier circuit and how to calculate its gain, as well as learning about efficiency of class AB amplifiers and prevention against thermal runaway. I will actually be partaking in an in person internship this summer at a music shop that focuses on modding/troubleshooting/repairing vintage audio electronics ranging from amplifiers to analog tape machines, so overall this class served as a fantastic introduction for this internship, and while I was unable to fully complete this project, I hope the material of this class combined with what I will learn this summer will give myself a clearer understanding of analog audio electronics, and could help me finish some of my personal projects.

**Appendix:**

D. Williams, “Gain of BJT Differential Amplifiers”. (2017). Retrieved 4 May 2021, from https://www.youtube.com/watch?v=IsTC6pobL08&ab\_channel=DavidWilliams

N. Paulino, J. P. Oliveira and R. Santos-Tavares, "The design of an audio power amplifier as a class project for undergraduate students," 2013 IEEE International Symposium on Circuits and Systems (ISCAS), Beijing, China, 2013, pp. 2565-2568. https://ieeexplore.ieee.org/abstract/document/6572402/

## MATLAB Analysis

# Power

clear all

clc

Vcc=9;

Vee=-Vcc;

Vp=Vcc/2

Vbe=0.7;

Veb=0.7;

VT=25e-3;

%Load Resistor

PL=0.5;

RL=8;

IL=sqrt(PL/RL)

VL=sqrt(PL\*RL)

PL=IL\*VL

% T0 (Current Source)

VLED=2;

ILED=20e-3;

PLED=VLED\*ILED %anything over

RE0min=(VLED-Vbe)/1e-3

RE0max=(VLED-Vbe)/10e-3

RE0=(RE0max+RE0min)/2

IEE=(VLED-Vbe)/500

R1=(Vcc-VLED)/ILED

R1=330

ILED=(Vcc-VLED)/R1

Icc=IEE

%small signal analysis

Rin=VT\*Vee/500

% T1 & T2 (Differential Amplifier)

IE2=Icc/2

IE1=IE2;

IC1=IE2;

IC2=IC1

Re=VT/IE2

gm=1/Re

RE2=10

RE1=RE2;

Ad=10

RC2=(Ad\*2\*(RE2+Re))

RC2=8.2e3

RC1=RC2; %Used to be 11k

VC2=IC2\*RC2

Ad=(RC2/(2\*(RE2+Re)))

V01=Vcc-(IC2\*RC2)

% T4 Biasing Transistor

Vb=2.5

VE=Vbe+Vb

RE3=(Vcc-VE)/20e-3

RE3=300

IE3=(Vcc-VE)/RE3

VC=IE3\*RE3

I2=IE3;

VCE=VC-VE

%Hybrid T model Gain

Rc=650;

re=VT/5.8e-3

Av=-Rc/(1000+re)

Avtotal=Ad\*Av

Av\_dB=20\*log(abs(Avtotal))

%freq response

gm=1/re

rpi=VT/-1e-3

cpi=(173.3e-12)\*(gm)\*(8.063e-12)

fh=1/2\*pi\*cpi\*rpi

ft=gm/2\*pi\*cpi

%Emitter bypass cap calc

C1=1e-6

Freq=1/(2\*pi\*300\*C1)

%T5 Voltage Multiplier

VC=VE

VBiasMin=1.8\*Vbe

VBiasMax=2.2\*Vbe

RA=500; %potentiometer

RB=1e3;

IRmax=VBiasMax/RB

IRmin=VBiasMin/RB

IR=1.4/RB

VBBmin=IRmin\*(RA+RB)

VBBmax=IRmax\*(RA+RB)

ICMax=I2-IRmax

ICMin=I2-IRmin

RARBMax=VBBmax/ICMax

RARBMin=VBBmin/ICMin

RA=250

VCB=VBBmax-VC

VCB=VBBmin-VC

VB=IRmax\*(RA+RB)

VB=IRmin\*(RA+RB)

%Class AB Output Amplifier

%For NPN

VE6=2

VC6=Vcc

VCE=VC6-VE6

%For PNP

VE7=2

VC7=Vee

VCE=VE7-VC7