Designing an Audio Amplifier

Milos Cejkov cejkovm@yahoo.com

Reeve Groman bassriff33@msn.com

Kathleen Sindoni elisepierce@yahoo.com

1. Abstract

Amplifiers, which are devices that increase the gain of an audio signal, dominate modern audio technologies. In this project, we designed and built our own audio amplifier from scratch in order to demonstrate that such a key device can be constructed using basic electrical engineering principles.

After performing major circuit calculations by hand, we modeled our circuit in PSpice, which is computer software that analyzes electrical circuits. In particular, we studied the variance that using budget electrical components introduced into the circuit overall by comparing three different amplifiers that we constructed.

We found the variance between our three amplifiers to be minimal, confirming our method of building a low budget, low power audio amplifier.

2. Introduction

The term amplifier refers to any device that increases the amplitude of a signal, usually measured in voltage or current. This versatile device is used in a variety of different electronic applications. Especially in audio technology, a wide range of amplifiers can be produced based on product specifications (i.e. power, voltage, current).

Currently, there are many types of audio amplifiers available for consumers. Sound signal amplification is used for instruments, such as the guitar or the bass. They are also used commonly in home theater systems and with stereo speakers. The basic design behind all of these amplifiers is derived from the simplest concepts of circuit design.

For our project, we set out to design an audio amplifier. The inputs of our circuit were stereo signals from a portable music player. Although we used a low-power speaker, we needed to achieve approximately three times gain over the entire circuit. In addition, the amplifier had to be produced at a low cost with available materials. Before building the actual amplifier, we realized that we had to design, simulate, and test the circuit. Each step was necessary to understand the concepts involved in amplification.

3. Background

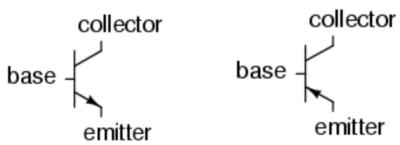
Before beginning the design process, it was necessary to understand several core concepts of electrical engineering. When designing electronics, three main specifications govern all circuit components; voltage [V; measured in volts (V)], current [I; measured in amps (A)], and resistance [R; measured in ohms (Ω)]. These three concepts are connected by Ohm's Law, where $1V = 1\ A * 1\ \Omega$.

For amplifier circuits, it is also important to consider both types of current in the design because both alternating and direct current run through the system. Alternating current (AC) acts like a sinusoidal curve, providing the signal for the amplifier. On the other hand, direct current (DC) runs through the circuit as a voltage source. Used together, AC source creates the signal at the horizontal axis, which is determined by the value of the DC source. Each is analyzed independently of the other, but without one type of current, it is meaningless to include the other.

3.1 Circuit Components

Some basic components in amplification are resistors, capacitors, and transistors. Resistors produce a voltage based on the amount of current passing through the circuit. Capacitors consist of two metal plates separated by a weak conducting material. At DC, these devices temporarily store the charge. However, at AC, the frequency is high enough to complete the circuit. At this point, the capacitors act like wires. The main advantage of these devices is the ability to block the direct current while allowing the AC signal to flow through

Transistors are the most important part of amplifier circuits. Capable of controlling an output signal in comparison to an input signal, a transistor can produce gain. In other words, the transistor is responsible for the amplification component of the audio amplifier. Although there are several types of transistors, simple bipolar junction transistors were acceptable. These devices consist of three terminals: the base, the collector, and the emitter. Simply put, they are terms used for labeling measurements, calculations, and schematic diagrams.



PNP BJT NPN BJT

Fig. 3.1 – Sample schematic representation of a bipolar junction transistor in two configurations

3.2 Classes of Amplifiers

Assembled in different configurations, resistors, capacitors, and transistors can create several classes of amplifiers that can be distinguished by performance characteristics. For our research, three economical designs were the most essential. Class A amps are very linear (meaning the integrity of the signal is maintained through the amplification process); however, this amplifier topology is known to be very inefficient. In addition, Class A amplifiers invert the signal (meaning the function is reflected over its axis).

Class B amps are much less linear, leading to higher distortion of the signal, but they are much more efficient. Since a Class B amp only amplifies half of a signal, two Class B amps are generally used in synchronization.

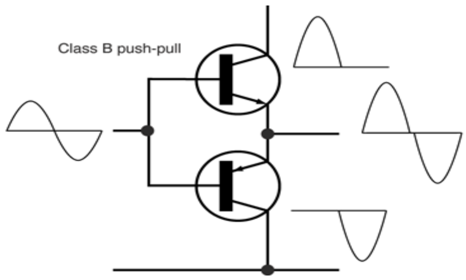


Fig. 3.2 – Two Class B amplifiers being used to amplify a complete signal

The compromise between these two topologies is the Class AB amplifier. The Class AB is more efficient than the Class A with lower distortion than the Class B. Often the different types of amplifiers are used in combination with other amplifiers into order to achieve the specifications of a particular design.

3.3 Negative Feedback

Another popular method of controlling amplifier distortion is negative feedback. A portion of the amplifier's output is transferred back to the input. Overall, this method controls the gain of the amplifier even when affected by outside factors (i.e. temperature). In addition, the recycled output signal reduces amplifier distortion.

In order to measure the success of an amplifier, designers use many tests for circuit variables. One manner of representing the performance data is through a Bode plot. A logarithmic frequency scale spans the x-axis (measured in Hertz). The y-axis measured gain in decibels, which is also a logarithmic measurement. Combined, the two axes present the output gain of an amplifier over a wide range of frequencies. After a certain point, the gain reaches a maximum level. At even higher frequencies, gain becomes inversely related to frequency as the performance drops off.

This continues until the point that the gain drops with an increase in frequency. This point is known as the 3dB point. For optimal performance, the 3dB point of an amplifier should fall beyond the amp's active range of frequencies.

4. Methodology

4.1 Design Requirements

From the very beginning of the design process, the design specifications were crucial to the choices for topologies and components. Our amplifier had to be able to amplify a signal from a portable music player (a 0.8V – 1.1V supply voltage load). In order to reach satisfactory amplitude, 1.7 times gain was necessary for each section of the input stage. Class A designs are capable of this gain, and their high inefficiency was not a major factor in the small scale of our experiment. However, these amplifiers invert the input signal. The DC voltage remains the same, but the AC signal reflects over its x-axis. As a result, two Class A amps were used to correctly orient the output signal and provide the necessary gain. Each Class A amplifier was a common emitter BJT. Together these two amplifiers constitute the input stage of the audio amplifier.

Considering a starting voltage of around $1V_{PP}$ (1 volt peak to peak) , two amplifiers with approximately 1.7 times gain brought the output gain up to around 3 times after the input stage. As the current flows into the output stage, the voltage becomes irrelevant. Instead, the designer needs to increase the power gain in order to drive the speakers at the output. Class AB amplifiers are capable of producing power gain (at the slight expense of the previous voltage gain). A Class AB amplifier consists of two PNP common emitters and two NPN common emitters in a loop.

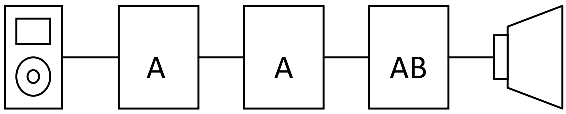


Fig. 4.3 – Block diagram of the circuit set-up.

Audio signals in the modern music industry are now broadcast almost exclusively in stereo sound. To account for the dual signal amplification, the entire circuit (Fig. 4) was repeated. The final output of the amplifier was fed through a low power audio speaker, completing the circuit. Actual values for circuit components are dependent on the DC based calculations for our 12V source.

4.2 Theoretical Design

Given the design parameters for the amplifier circuit, theoretical values were calculated using a system of DC biasing. Though several circuit calculations are involved, the goal of DC biasing is to balance the circuit components based on the supply voltage and current at each stage. Incorrect resistors would shift the amplifier away the active region of operation.

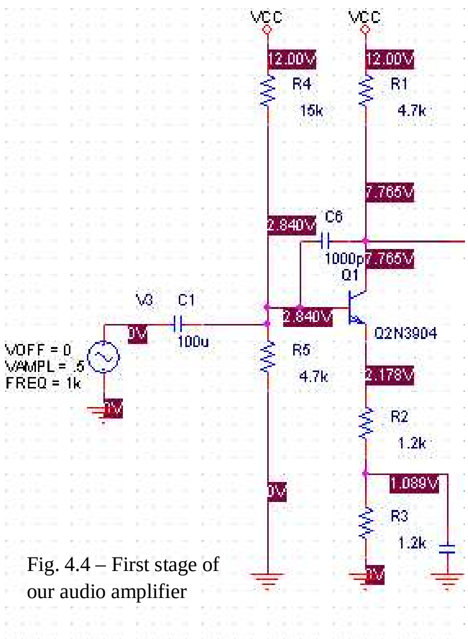


Fig. 4.4 – First stage of our audio amplifier

4.1.1 The First Stage

Once we developed the general design, we created a schematic of our actual circuit. The base of the first common emitter BJT receives the AC signal input. At this point, two resistors provide the DC voltage. The output of the first amplifier, at the collector, is connected through a negative feedback loop. Two resistors and a capacitor at the emitter ground the circuit.

From the layout of the schematic the resistor values can be chosen to match the specifications of voltage and current. At the first stage, the required voltage going into the base was 3V. The parallel resistor values at this point have to be in a 3:1 ratio going from the DC source to ground, giving us the 15k and 5k values at R_{B11} (refers to the first resistor at the base of the first transistor)and R_{B12} (refers to the second resistor at the base of the first transistor

Within the transistor, the calculations became more difficult. Ideally, there should be a drop of .7V between the 3V input at the base and the emitter. Since the emitter goes to ground, the voltage drop between the emitter and ground becomes 2.3V. The complicated setup of the emitter leads to a new equation for determining the resistance.

$$A = \frac{\beta R_L'}{R_\pi + \beta R_{E1}}$$

Where:

A = gain

$\beta \approx 400$

R_L' = the sum of the resistors in parallel with R_{C1}

$$R_\pi = \beta \frac{V_t}{I_C}$$

The current (I_C) in this equation is dependent on the circuit and V_t is provided by the manufacturer. Solving this equation for a gain of about 1.7 will produce the resistor value for the first resistor on the emitter. From there, the other resistors can be determined using the V=IR equation. The entire process of determining resistor values is what constitutes DC biasing.

All of the capacitors in the first stage are equal to 100µF (microfarads), except for the capacitor involved with the negative feedback, which is 1000pF. These values were chosen because they are large enough to be completely ignored at DC and they quickly become ‘shorts’ at AC.

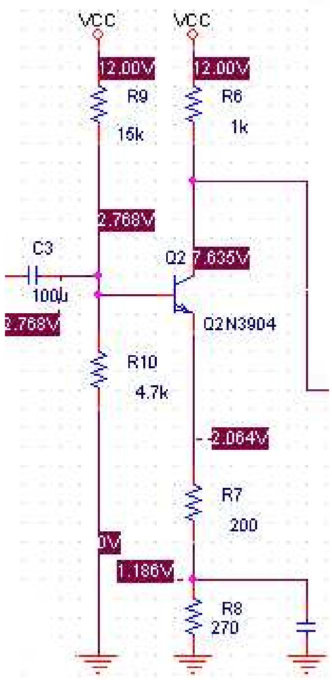


Fig. 4.5 – Second stage of our audio amplifier

4.1.2 The Second Stage

The second stage of our amplifier was very similar to the first stage of the circuit. Since they were both Class A amplifiers in a common emitter configuration, this schematic looks very similar to the first half of the input stage. The largest difference in the design is the lack of a negative feedback loop.

For this section of the circuit, the ideal voltage entering the base of the transistor was 3V. The current increases from 1μamp in the first Class A amplifier to 5μA in the second. Even though this will result in different resistor values, the equations involved in the calculations are the same in both instances.

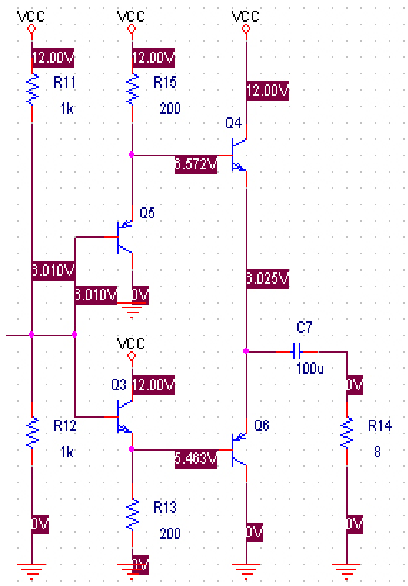


Fig. 4.6 – Third stage of our audio amplifier

4.1.3 The Output Stage

The original design for our amplifier called for two Class A common emitters followed by a Class AB output stage. Since the output stage of our amplifier consisted of an entirely different amplifier, the schematic diagram of the final stage bears only a faint resemblance to the input stage design.

The resistors connected to the input bases of the output stages are arranged in a parallel circuit as seen in the first and second stages of the amplifier, but the rest of the Class AB follows another design entirely. Instead of a single transistor, it consists of four transistors connected in a loop. In the diagram above, the top-left and bottom-right transistors are NPN transistors. The other two are PNP transistors. All the resistor values in this circuit can be found by manipulation of the equation V=IR. At this stage of the amplifier, the current was 20μA. Using the V=IR equation and the ideal voltage drops, we found the resistor values at the DC bias points.

After the entire circuit was biased, we discovered that certain resistors required for our circuit were either not manufactured values or not available to us. We were forced to make some changes to the circuit, replacing the unavailable resistors with others that were close to our calculated values.

Theoretical Resistor Values	Actual Resistor Values
5k	4.7k
180	200
1.1	1.2k
280	270

Fig. 4.7 – Difference between calculated resistors and similar available resistors

The adjusted circuit design needed to be biased again in order to account for the changes in resistor values. From the second bias, we obtained our ideal bias points for the circuit involving our actual components.

4.3 Computer Simulation

The computer simulation plays an important role in the process of building an audio amplifier. It gives more accurate results than the theoretical design and it also allows circuit designers to picture the changes of the signal through the amplifier as it passes through different stages. By performing the computer simulation, we could see if the amplifier we designed was working properly. If it does not produce expected results, changes can be made before physical components have been used.

After designing the amplifier in OrCad Capture, a schematic creation software, we were able to perform the simulations and see if our amplifier was capable of operating near theoretical values. In order to perform simulations, we decided to use the program PSpice.

The time-domain simulation in Figure 4.9 shows how the signal changes over time. In the first stage of our amplifier, which is class A, the signal is inverted. The signal was reoriented in the second stage. The last stage, which is a class AB amplifier, maintains the integrity of the signal.

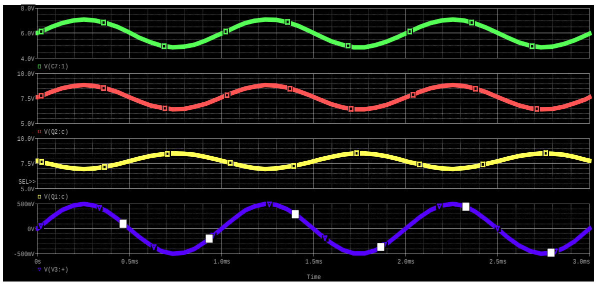


Fig. 4.9 – Time-Domain Simulation (each graph is scaled differently)
First stage Second stage Output/third stage Input signal

The dB test graph (Figure 4.10) emphasizes the changes in gain between the stages. In the first stage, the output signal displayed significant gain. But the output of the second stage presents an even higher gain as the signal is amplified again. The output of this amplifier has slightly lower gain than the output of the second stage. The Class AB amplifier used sacrifices minimal voltage gain for significant power gain. Represented by the gain drop off, the 3dB point (195.019kHz) falls after our ideal range of operation. The human ear can here between 20Hz and 20kHz and our range of operation from 30Hz to the 30kHz is acceptable.

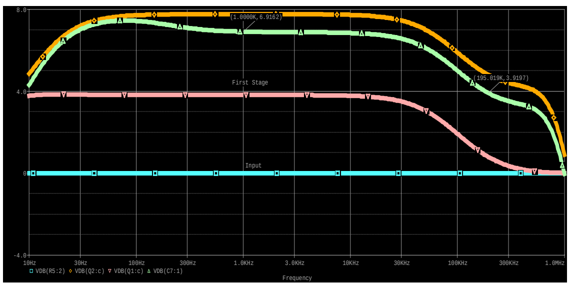


Fig. 4.10 – dB test
First stage Second stage Output/third stage Input stage

4.4 Lab Work

Using available resistors, BJTs, capacitors, and wire, we constructed our amplifier circuits on breadboards, which are devices often used for prototyping circuits. In this lab setting, we tested the voltages and calculated the actual values for the gain and the 3dB point. We powered our amplifier with a 12V DC power supply and supplied an AC input signal with a function generator. We used a digital multimeter to measure the voltage at the base, collector, and emitters of each of the Class A amps, and the base and emitters of the Class AB amp. We used an oscilloscope to read the gain at output of each amplifier. Using these values, we measured the 3dB point of the amplifier. Several problems arose while we were building and testing the circuits. There were several occasions in which the components were not correctly oriented in the circuit. The current flowing through them in the wrong direction overloaded the misplaced devices. Burned components needed to be replaced.

4.5 Final assembly

With a working physical model of our amplifier design, we had circuit boards produced to fit our models. Circuit boards are desired because they mount the circuit components neatly and permanently. To do this, our design was entered into a circuit board layout program. From there, our board went through an extensive manufacturing process.

Upon receiving the board, we soldered the components onto the printed circuit board. After completing the amplifier, we connected a speaker to the output using an 1/8" cable. We sent an audio signal through the input using a portable music player device. The sound signal from the audio player was indeed amplified through the output. We tested for this by inputting a source directly to a non-amplified speaker and then running the signal through the amplifier

5. Results

In the lab, we used a digital multi-meter to find the following voltages at the bases, collectors, and emitters of each transistor contributing to the final gain in each of the three team members' amplifiers. In Figure 5.1, the variables $\mathbf{V_{B1}}$, $\mathbf{V_{E1}}$, $\mathbf{V_{C1}}$ stand for the voltage at base one, emitter one, collector one and so on. In the final column of Figure 5.1, we calculated the average of our three values for each voltage.

Voltages	**Reeve**	**Kate**	**Miloš**	**Average**
$\mathbf{V_{B1}}$	2.83V	2.85V	2.83V	**2.84V**
$\mathbf{V_{E1}}$	2.15V	2.17V	2.15V	**2.16V**
$\mathbf{V_{C1}}$	7.79V	7.75V	7.8V	**7.78V**
$\mathbf{V_{B2}}$	2.75V	2.76V	2.75V	**2.75V**
$\mathbf{V_{E2}}$	2.03V	2.04V	2.04V	**2.04V**
$\mathbf{V_{C2}}$	7.69V	7.68V	7.70V	**7.70V**
$\mathbf{V_{B3}}$	5.97V	5.96V	5.57V	**5.97V**
$\mathbf{V_{E3}}$	6.57V	6.58V	6.57V	**6.57V**
$\mathbf{V_{E4}}$	5.32V	5.33V	5.33V	**5.33V**
$\mathbf{V_{E5}}$	5.94V	5.95V	5.95V	**5.95V**

Fig. 5.1 – Actual voltages at different stages

Figure 5.2 displays a comparison of the theoretical values, the computer simulated values, and the actual lab tested values. Note that the theoretical values are based on the actual resistor values used in the physical model, not the original resistor values designed for our amplifier.

Voltages	Theoretical	Simulated	Actual	ΔV
V_{B1}	2.86V	2.84V	2.84V	0.02V
V_{E1}	2.16V	2.18V	2.16V	0V
V_{C1}	7.3V	7.77V	7.78V	0.48V
V_{B2}	2.86V	2.77V	2.75V	0.11V
V_{E2}	2.16V	2.07V	2.04V	0.12V
V_{C2}	7V	7.64V	7.69V	0.69V
V_{B3}	6V	6.01V	5.83V	0.17V
V_{E3}	6.7V	6.57V	6.57V	0.13V
V_{E4}	5.3V	5.46V	5.33V	0.03V
V_{E5}	6V	6.03V	5.95V	0.05V

Fig. 5.2 – Comparison of theoretical, simulated and actual values at different stages of the amplifier

Figure 5.3 displays the gain at each stage of the amp. The first stage is the first class A amp, the second stage is the second class A amp, and the third stage is the class AB amp. We multiplied the final gain of each amp by 0.708 to calculate the gain drop off point in order to find the 3dB point. Using the function generator, we increased frequency of the signal of the input until the oscilloscope read the gain drop off point we had calculated. This frequency is the 3dB point, which is where the signal is no longer amplified.

	Reeve	Kate	Miloš	Average
1^{st}(A) Stage	1.56	1.562	1.562	**1.561**
2^{nd}(A) Stage	2.44	2.406	2.063	**2.303**
3^{rd}(AB) Stage	2.16	2.188	2.063	**2.137**
x 0.708	1.56	1.549	1.46	**1.523**
3dB Point	140.4 kHz	157.6 kHz	188.3kHz	**162.1kHz**

Fig. 5.3 – Gain at different stages in the amplifier

Figure 5.4 displays the comparison of the theoretical, simulated, and actual gain values of each stage of the amplifier.

Stage	Theoretical	Simulated	Actual	ΔGain
1^{st} Stage	1.7	1.55	1.56	.14
2^{nd} Stage	1.7	1.65	1.56	.14
Final Output	3	2.21	2.14	.86

Fig. 5.4 – Comparison of theoretical, simulated, and actual gain in each stage

After conducting our lab tests, we returned to the computer simulation and altered the feedback capacitor value at the first stage. We noted that the higher the value of the feedback capacitor the lower the 3dB point, and the lower the value of the feedback capacitor, the higher the 3dB point. Because of this, it can be inferred that the feedback capacitor value and the 3dB point are inversely related.

6. Conclusion

Upon finishing our circuit according to the initial specifications, our design was successful in amplifying an audio signal. The measured gain of 2.14 was close to our expected gain of 3. But no electronic device is perfect. Components and wires are mass produced, leading to differences between “identical” circuits. Although we constructed three circuits from the same design, each amplifier presented slightly different values. This is because the rapid production rate of these devices creates flaws in the individual components and variability in their actual values.

In our research, we observed that changing the value of the capacitor in the negative feedback loop alters the 3dB inversely. Changing the value of resistors in the circuit can also alter the gain. In our endeavors, we had trouble finding the exact resistors values we wanted. We had to substitute these with resistors that were close to our ideal values. Overall, they had an impact on the gain, but it was not enough to prevent the amplifier from operating. Though we may have gotten results closer to our theoretical values had we used the exact resistor values, the gain produced was acceptable for our experiment and proved that we can amplify sound.

7. Acknowledgments

First of all, we would like to thank Ilya Chigirev for teaching us about audio amplifiers, helping us in our design and also taking time off his schedule in order to help us put this project together. We would also like to thank our RTA Daniel Hogan for helping us in our project and guiding us with our research paper and presentation. However, this amazing summer program would have been impossible had it not been for the efforts of the NJ Governor’s School of Engineering and Technolgoy, (Donald M. Brown, Director, and Blase Ur, Program Coordinator), the Rutgers University School of Engineering (Dr. Yogesh Jaluria, Outgoing Interim Dean, and Dr. Thomas Farris, Dean), the NJ Governor's School Board of Overseers, Kristin Frank, and the counselors of Governor’s School. We would also like to thank our sponsors (Rutgers University, the Rutgers University School of Engineering, the Motorola Foundation, Morgan Stanley, PSEG, Silver Line Building Products, and the families of 2001-2008 program alumni) for providing the funds in order to make this unique summer program special and enjoyable for the most talented students in the State of New Jersey and the engineers of the future. Once again, we would like to thank everyone who made the 2009 Governor’s School of Engineering and Technology a truly memorable experience.

8. References

[1] Singmin, Davis, Patronis, Watkinson, Self, Brice, Duncan, Hood, Sinclair. *Audio Engineering – Know It All***.** 2009, MA

[2] Douglas Self. *Audio Power Amplifier Design Handbook Third Edition*. 2002, MA.

[3] John Linsley Hood. *Audio Electronics*. 1999, MA.