Audio Amplifier

Final Report

ENEE 417- 0106
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I. **Introduction**

The purpose of this lab report is to outline the procedures and techniques used to build an amplifier circuit as well as the comparison of the measured and expected results.

The requirements laid out for this project were to build a stereo audio frequency preamplifier and power amplifier with a relatively high input impedance (>10Kohm); a low output impedance (<1ohm); a fixed closed loop gain of approximately 20; and a few Watts of output that can easily drive a pair of speakers.

The reason for building this amplifier was to gain experience and first hand knowledge of what trade-offs are made during the design process. For example, raising the input impedance may unfavorably affect some of the other circuit characteristics that are being considered. Building and testing this circuit was an exercise in optimizing as many characteristics as possible while staying within the constraints of the project. This project also provided a chance to work with the materials and chemicals used in some chip manufacturing. If simply obtaining a manner in which to amplify a signal were the true purpose of the experiment, then a much more efficient way of accomplishing this would have been through the use of a pre-manufactured op-amp.

II. **Simulated Circuit**

Several amplification circuit designs were considered, but most were very similar. They included a differential or preamp stage (1), a common emitter gain stage (2), and an emitter follower power (current) amplification stage (3) to drive the load. Figure 1 is the layout of the amplification circuit that was simulated in PSpice. This design uses BJTs in the differential amplification stage. One of the original designs used JFETs in order to help maximize Input Impedance. The JFET design simulated correctly, but wouldn’t work when actually built on the breadboard. This was possibly due to a mismatch between the JFETs that were simulated and the JFETs that were available in practice. The BJTs are somewhat less durable and resulted in decreased input impedance, but they were easier to work with while still meeting all requirements.
To obtain a useful differential amplifier stage, the characteristics of the BJTs needed to be as similar as possible. Matching BJTs were selected after testing several of them with the transistor tester. Figure 2 shows the LabView representation of the Ic/Vce characteristic curves of the BJT. Beta can be determined for a given operating point by finding the DC VCE, and then varying the small-signal base current. As the base current changes for a fixed VCE, the collector current moves from one curve to the next in figure 2. For example, at VCE = 2.5V, IB = 2.5 uA (yellow), a small signal change of 0.25uA in iB results in a change of iC of approximately 0.4 mA, for a beta ~ = 160.

This plot represents the current characteristic of the BJT transistor vs. base current and VCE. Using the transistor tester, similar plots were developed and multiple transistors could be tested at once. This resulted in matching two BJTs fairly closely, which gave a pair that could be used in the differential amplifier.

The PSpice simulations were done with the measured values of the resistors used in the actual circuit. In order to be consistent, the simulated rail voltages were set to the DC levels used in the final testing of the circuit. Figure 3 shows the DC voltages of the simulated circuit and Figure 4 shows the DC currents of the simulation. This amplifier circuit design utilizes two capacitors in order to reduce high frequency feedback that was experienced with the built circuit. This feedback possibly originated with the voltage sources used to power the circuit.
DC Voltages and Currents – Simulated

Figure 3: DC Voltages of PSpice Simulation

Figure 4: DC Currents of PSpice Simulation
Gain - Simulated

Figures 5 shows the simulated closed loop gain amplitude versus frequency log-log plot for the circuit. Figure 6 shows the simulated closed loop gain phase versus frequency linear-log plot. The gain remains at approximately 30dB throughout the test range of 10Hz through 100KHz.

![Simulated Closed Loop Gain Amplitude vs Frequency (log vs log)](image)

![Simulated Closed Loop Gain Phase vs Frequency (linear vs log)](image)
Input Impedance – Simulated

Figure 7 shows the input impedance amplitude versus frequency linear-log plot. Using the BJTs in the differential pair brought the input impedance down significantly as compared to the 100K input impedance simulated with the JFETS. Figure 8 shows the input impedance phase versus frequency linear-log plot.

Figure 7: Simulated Input Impedance Amplitude vs Frequency (linear vs log)

Figure 8: Simulated Input Impedance Phase vs Frequency (linear vs log)
Output Impedance - Simulated

Figure 9 shows the output impedance amplitude versus frequency linear-log plot for the simulated circuit. This impedance remains under 1 ohm for most of the test period. Figure 10 shows the output impedance phase versus frequency linear-log plot of the simulated circuit.
The use of the differential amplifier at the input of the audio amplifier enables the application of feedback to correct any non-linearities in the output, and maintain the output waveform at exactly the correct multiple of the input. Otherwise, letting the output float, there would be no way to ensure that the output was actually at the appropriate level.

These simulations show that the input impedance remains high, around 75K, throughout the 20 – 20KHz range of interest (Figure 7), while the output impedance remains very low, at under one ohm over the same region (Figure 9).

The relatively flat phase behavior of both the input and output impedance over the range of interest helps to keep the amplifier stable while using feedback. A large phase difference could result in positive feedback at certain frequencies, and a useless circuit. The low output impedance will be particularly important for this application, due to the very low (8 Ohm) impedance of the speakers that will be driven by the amplifier. This low output impedance will enable the amplifier to deliver the current required to actually drive the speaker. Since audio speakers have such low fundamental impedance, the low output impedance of an audio amplifier is perhaps the single most important and unique aspect of audio amplifier operation.

Finally, the amplifier provides approximately 30dB of gain throughout the desired frequency range.

**III. Fabrication**

Simulating the circuit was only the first portion of the overall process. The design process can be broken down into the following steps:

1. Circuit Design – OrCAD, PSpice
2. Breadboard test of the design
3. Layout (Eagle, then Paint)
4. Mask Printout
5. Mask Transferring
6. Chemical Etching
7. Via Drilling
8. Mask Removal for solder
9. Soldering
10. Testing

**Board production:**
We first constructed the circuit on the breadboard in order to evaluate it before soldering the components in. This way, we were able to work some kinks out of the design, such as fine-tuning the values of the biasing resistors, and making sure that all of the transistors were properly installed. This allowed us to find that our circuit was performing as expected, except for some high frequency feedback noise. We then chose to build the circuit on the PCB, in hopes that the feedback could be eliminated by the use of the less noisy PCB, so that we could avoid a more complicated solution.

Using the simulated circuit above (Figure 1), the EAGLE software was used to produce the layout found in Figure 11.

![Figure 11: EAGLE Layout](image-url)
We were able to produce the board fairly easily, as we were able to learn from the experience of two other groups in our section. Specifically, heating the pattern for longer than recommended by the mask manufacturer enabled us to transfer the whole mask to the board and to obtain a working board (with all traces intact) on the first try. The chemical etch process took longer than we anticipated, perhaps because we removed less of the copper in cleaning than the other groups. We drilled the vias before removing the mask, which may have made the removal of the mask substance more difficult than it needed to be. However, the drilling and soldering went smoothly, and there were no real problems until test. We did not immediately trim the excess leads from the components, but in an effort to minimize noise we did later cut them back to just past the solder joints.

**Testing & Troubleshooting:**
The feedback noise problem had not gone away, and was combined with additional problems in transistor matching. These problems caused some of the transistors to leave forward active during portions of the signal. As the noise saturated the circuit during the higher voltage portions of the signal, DC output became unstable and large. During the test process, we suffered the loss of a few transistors. This gave us the opportunity to find more closely matched input transistors.

On closer inspection of the simulation results, we realized that there was a frequency range at around 100 kHz at which the gain was greater than unity and the phase changed rapidly. We concluded that at these frequencies, small noise signals were fed back positively to the amplifier.

In an attempt to reduce the feedback of the high frequency noise, we first tried adding a shunt capacitor to the feedback connection to pass the very high frequency feedback to ground. This appeared to work initially, but didn’t solve the problem permanently. Then we tried trimming the leads that were still extended to their full length on the backside of the PCB, in order to reduce any coupling that could be occurring between them. Finally, we added Miller capacitors to the second stage (common source voltage gain stage). This added pole reduced our gain slightly, but eliminated the high frequency feedback problems.

The elimination of the feedback noise, combined with the replacement of the differential pair, solved the noise and DC output problems, resulting in a fully functional Audio amplifier circuit with a gain of approximately 28 dB.

**IV. Results**

Once the circuit was constructed, testing began to compare the actual results to the simulated results. First, the DC voltages were measured (Figure 12) and the DC currents were calculated (Figure 13).

A DC voltage of -17mV was measured at the output. It was important to keep this value minimal because a large DC voltage would result in damage to the speaker. The simulated DC voltages and currents were very comparable to the actual results. All
transistors are biased to operate in the forward-active portion of their characteristic curves.

DC Voltages and Currents – Observed

Figure 12: Observed DC Voltages of Fabricated Circuit
Gain - Observed

In order to obtain closed loop amplitude versus frequency plots, the output voltage was measured for several different frequencies and compare to the input voltage. The resulting log-log plot is shown in Figure 14. This measured gain was approximately 28 or 29dB which is only slightly less than the 30dB simulated gain amplitude. As in the simulation, the gain amplitude is relatively flat over the region of interest.
Figure 14: Observed Closed Loop Gain Amplitude vs Frequency (log vs log)

Gain amplitude and phase plots were made using LabView as well, but the accuracy of these plots could not be determined. The suspicion of the accuracy of these plots came about because they did not match the measured amplitude gain at lower frequencies that was presented in Figure 14. These Labview plots of Amplitude versus Frequency (Figure 15) and Phase vs Frequency (Figure 16) are provided below.
Figure 15: LabView Closed Loop Gain Amplitude vs Frequency

Figure 16: LabView Closed Loop Gain Phase vs Frequency
Input Impedance – Observed

The input impedance was measured by using a source resistance at the input as shown in the following layout:

To determine Rin, the following equation was solved:

\[ Rin = R_s \times \left( \frac{V_{\text{nominal}}}{V_{\text{total}}} - V_{\text{nominal}} \right) \]

Where:  
\[
\begin{align*}
Rin &= 95 \text{ Kohm} \\
V_{\text{total}} &= 590\text{mV} \\
V_{\text{nominal}} &= 280\text{mV}
\end{align*}
\]

The resulting input impedance at 1kHz was 86Kohms. This is 13% larger than the simulated value of 75 Kohms.

We planned on taking LabView frequency sweeps for the input impedance, but we were not confident in the plots that LabView was generating. Because of this, we took only these manual measurements instead.
**Output Impedance – Observed**

A source resistance was used to calculate the output impedance as well. In order to obtain the plot of Figure 17, the following equation was solved for several frequencies:

\[ R_{out} = R_s \times \left(\frac{(V_{oc} - V_o)}{V_o}\right) \]

where \( R_s = 2.2 \, \text{ohm} \)
- \( V_{oc} = \text{open circuit voltage} \)
- \( V_o = \text{output voltage} \)

![Figure 17: Observed Output Impedance vs Frequency (linear vs log)](image)

This plot shows that the output impedance is less than 1 ohm throughout the test range. This low output impedance will allow the amplifier to provide enough current to drive the 8 ohm speakers.
Finished Circuit

Figure 18 is the final completed circuit. The large metal plates on the power transistors are used to dissipate rails are connected to +15V, -15V, and GROUND (from top to bottom). The green wire connected to the capacitor on the left is the signal input and the green wire located on the right side of the circuit is the output.

Figure 18: Completed Audio Amplifier Circuit
V. Discussion

Observations

Our circuit was implemented with BJTs as the input stage, which should serve to reduce the input impedance. While we were not able to obtain an input impedance above 100 kOhms, we were able to get an input impedance of 85 – 95 kOhms. Our circuit was relatively simple in design, but seemed to perform fairly well once we resolved the feedback noise issue. We were able to obtain a fairly consistent gain of about 28 dB over the audio frequency range.

We found no real difficulties in the fabrication process; the difficulties we encountered were in design, test and troubleshooting, and measurement. First, in the design stage, the Eagle layout program proved to be a little sensitive and perhaps overcomplicated for the relatively simple project. While we performed most of the initial work in Eagle, the final layout was completed and fine-tuned in Microsoft Paint. Perhaps more time at the front end to learn the layout system, or the use of a different system would have been helpful. In the actual production of the board, the only difficulty was in getting a suitable mask from the printer; the temperatures required and the restriction that an ‘old’ laser printer be used caused a few headaches among various groups in our lab section. The test and troubleshooting process took most of our time, but there were no difficulties that could be attributed to the design and fabrication process used.

Finally, during measurement, there was an unusual behavior that we noticed in the LabView frequency-based data collection—specifically, that the A/D interface seemed to have a characteristic that totally overwhelmed the characteristic of our circuit. In order to investigate this behavior further, we took additional measurements with a -6 dB resistive input divider constructed of 2x 100 kOhm resistors. The input impedance for this circuit should have significantly greater input impedance than our amplifier input impedance, even at high frequency.

![Figure 19: Gain vs frequency for amplifier alone](image)
Figure 20: Gain vs. frequency with -6dB (100k / 200k) resistive divider

Note that with the resistive divider in place (a divider with significantly greater input impedance than the amplifier), rather than a 6 dB drop across the spectrum, there is a 6dB drop at the top end, and a 3.5 dB drop at the bottom. This seems to indicate that there is some difficulty in the computer interface supplying current at low frequencies, or some other issues interfering with the low frequency response, especially since the results differ so drastically from those taken by hand, which show no decrease in gain below 10 kHz.

Figure 21: Gain vs. frequency for the amplifier, measured manually

On further observation, we found a similar characteristic to Figure 20 for a simple voltage divider between the computer interface output and input. Finally, there is no
reason to expect that the input impedance would be low at low frequencies; indeed, the DC blocking capacitor at the input stage should serve to increase the low frequency input impedance, resulting in higher gain at low frequency. These observations seem to indicate that perhaps an op-amp buffer is in order at the output of the computer data interface, in order to measure the gain without interference from the circuit characteristics of the LabView electrical interface.

We had initially planned to measure the input impedance of the circuit using the LabView program, but since we could not verify the correctness the gain measurements, we abandoned that plan and were left with only the single 1 kHz input impedance measurement.

Future Circuit Improvements

For future improvement, we would use JFET input stages to increase the input impedance. We would also implement tone control at the input to the amplifier, using active low and high frequency band-pass filters. Additionally, we would add a simple potentiometer-based resistive divider for volume control, as our gain was somewhat too large for the supply voltage at the signal level supplied by the CD player. We cut the input using an off-board (bread-boarded) resistive divider, which should ideally be moved onto the board for cleanliness.

Suggestions for Future Laboratories

The material covered was interesting and useful. Specifically, the coverage of noise and ground-loop concerns was interesting, useful, and not sufficiently covered in other undergraduate courses. While it was nice to be able to work on a circuit with which we were already somewhat familiar, the use of a different circuit than the audio amplifier (if possible) may help provide a broader background to senior level undergraduates.

As with most things, hands-on experience proved to be the best way to fully understand concepts learned in the classroom. The project was not overly complicated, so each aspect could be studied in depth without having to “rush through” portions of the design process in order to meet a deadline. This also allowed time to work through the testing process carefully when things went wrong. Groups that were fortunate enough not to run into any problems had the option to move on to creating a tone control circuit. Our group came up with a good design for the tone control circuit, simulated it in Pspice, and created the layout with EAGLE. Unfortunately, we ran out of time before we were able to take the tone control circuit any further. All in all, the lab was interesting, useful, and enjoyable.