

Designing a Headphone Amplifier and Building a Prototype

ECE 222 - Final Project

Ashton Tokarski and Iliana Balaskas

May 11, 2026

Abstract

In this project, we work to design, simulate, build, and test a two stage headphone amplifier. In the comprehensive report below we will go through the background to our design, as well as the testing completed in HSPICE using our simulated circuit. Following a completion of the test decks, we then implemented our design onto hardware and tested it in a variety of steps and methods. Pictures and observations are explained below, and further attachments can be found on our Blackboard submission.

Our Design

The initial design of our amplifier follows that of our project proposal. The two-stage amplifier consisted of an OPA1656 op-amp connected to a BUF634A buffer in order to achieve both the desired voltage gain and output current drive. The op-amp stage was used to set the gain and input impedance of the circuit, while the buffer stage was implemented to lower the output impedance and drive the headphone load. The initial design was first tested in HSPICE using the provided test decks and was successfully verified by the TAs before moving on to hardware implementation.

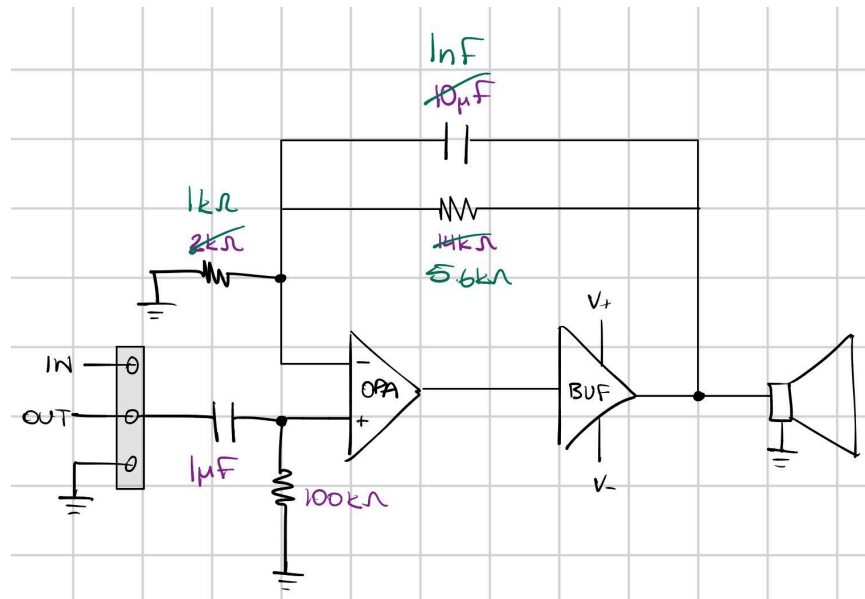


Figure 1: Initial design schematic

Following our initial design, we took our plans to the lab to implement our circuit with hardware. Below is a list of materials provided by the TAs:

- Perfboard
- 2x 10k Pot
- 2x 3.5mm connectors
- 2x 9V batteries
- 2x battery connectors

- 3x chip mounts
- OPA1656
- 2x BUF634A

In addition to these components, we also used:

- 2x 1k Ω resistor
- 2x 5.6k Ω resistor
- 2x 100k Ω resistor
- 2x 1nF capacitor
- 2x 1 μ F capacitor

As seen from the component list and Figure 1 above, our initial values for the resistors and capacitors were not available in the lab. As a result, values were changed and retested in HSPICE. Once we confirmed these components were successful in the simulation, we included them in our final circuit design. Note: The schematic below, Figure 3, is reflective of our final perfboard used for testing.

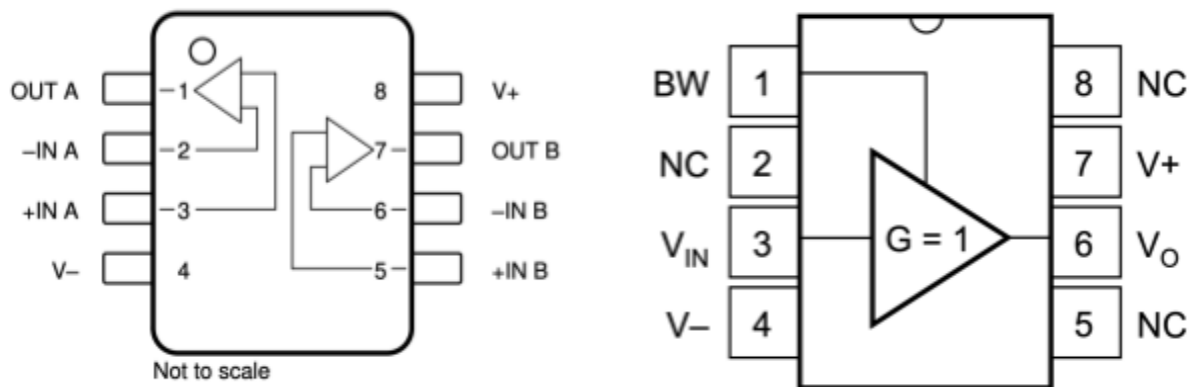


Figure 2: Pin configurations for the OPA1656 op-amp (left) and BUF634A buffer (right) used in the final amplifier design

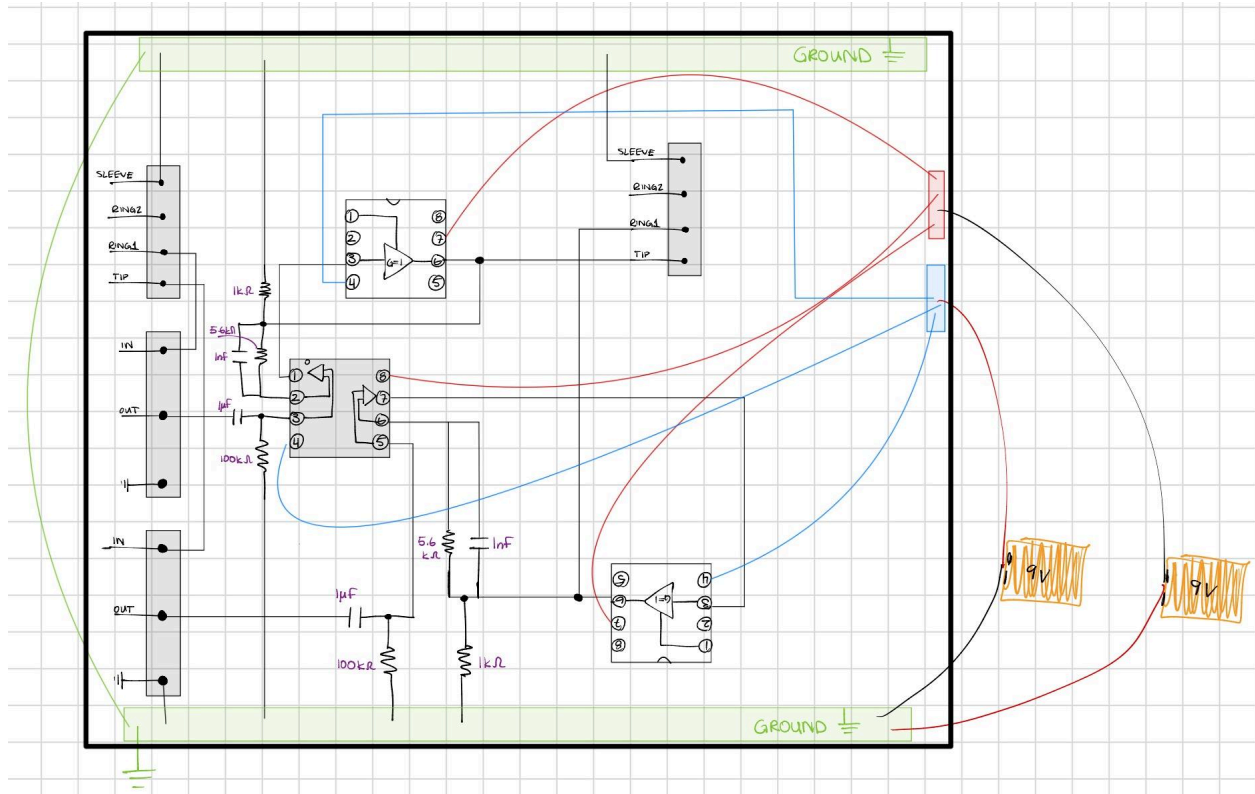


Figure 3: Final design schematic

HSPICE Results

To confirm the performance of the amplifier before practical implementation, several HSPICE test-deck simulations were used. The netlist file of the amplifier is shown below:

```
*** Description: Netlist for two stage headphone amplifier design ***
.SUBCKT DUT in out VDD VSS
** Stage 1 op amp **
XX1 in+ in- VDD VSS vo1 OPA1656
** Stage 2 buffer **
XX2 vi2 out VDD VSS BUF634A
** Feedback Loop **
Rf out in- 5.6k
Rg in- 0 1k
Rin in+ 0 100k
** High Pass Filter **
C1 in in+ 1u
** Additional pole **
C2 out in- .001u
** Allow for Convergence **
E12 vi2 0 VCVS vo1 0 1
.ENDS
```

Figure 4: Dut Netlist File

An extra voltage-controlled voltage source component is added to allow the simulations to converge properly.

Small Signal Gain BW

The first simulation tests the amplifier's bandwidth and midband gain. Having adequate bandwidth is important to accurately amplify the signal within the audible range.

```
**** ece 222 course project ****

***** ac analysis tnom= 27.000 temp= 27.000 *****
gain_mid= 5.9937      at= 251.1886
          from= 1.0000      to= 10.0000x
gain_db= 15.5539      at= 251.1886
          from= 1.0000      to= 10.0000x
bw_f1= 1.5959
bw_f2= 32.5885k
bw_3db= 32.5869k
```

Figure 5: Bandwidth Test Deck Output

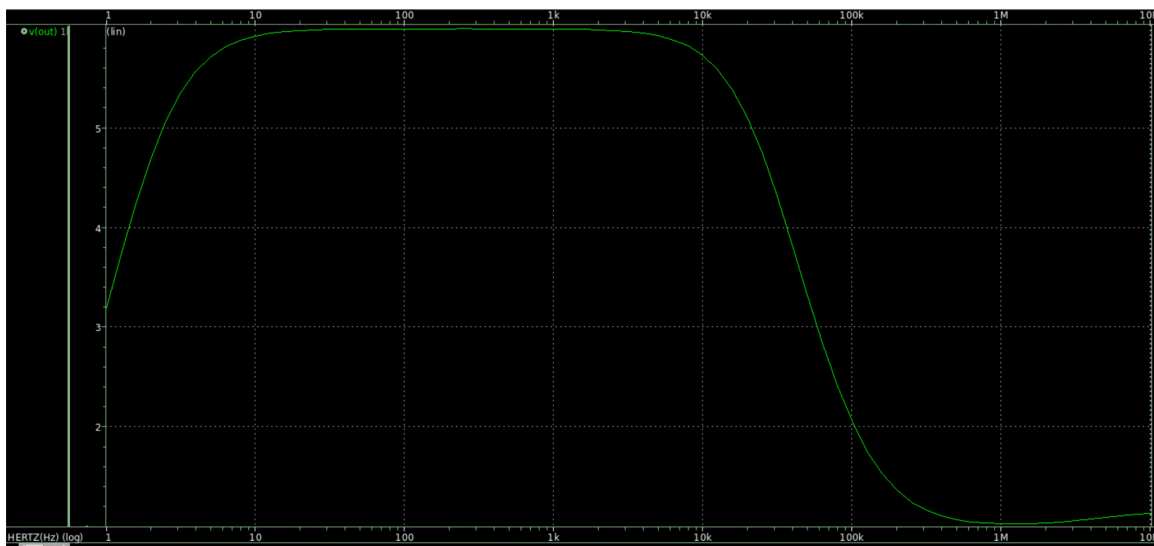


Figure 6: Bode Plot of Amplifier Output

Zin

The next simulation tests the amplifier's input impedance. Having high input impedance is important to avoid loading the signal source and to maintain an accurate input signal.

```
***** ac analysis tnom= 27.000 temp= 27.000 *****
zin_1k= 100.0003k
zin_5k= 100.0001k|
zin_10k= 99.9995k
zin_15k= 99.9995k
zin_20k= 99.9989k
```

Figure 7: Input Impedance Test Deck

Zout

The next simulation tests the amplifier's output impedance. It is important to have low output impedance because a fraction of the power from the amplifier will be dissipated due to the amplifier's output impedance. The fraction of the total power dissipated by the amplifier is equal to the ratio between the output impedance and the total impedance of the amplifier and headphones. If the impedance of the headphones is much greater than the impedance of the amplifier, this number becomes close to zero. As well, due to the capacitive and inductive effects of the headphones, the impedance will be different at different frequencies. This causes the power through the headphones to change depending on the frequency of the signal, which affects the frequency response and sound quality.

```
***** ac analysis tnom= 27.000 temp= 27.000 *****
zout_1k= 419.4153u
zout_5k= 2.0998m
zout_10k= 6.3000m|
zout_15k= 6.3000m
zout_20k= 8.4003m
```

Figure 8: Output Impedance Test Deck

Transient Power

The next simulation tests the amplifier's transient power. Testing the amplifier's transient power verifies the amplifier will be able to drive headphones of various impedances.

```

***** transient analysis tnom= 27.000 temp= 27.000 *****
vout_peak= 2.7697 at= 1.2546m
          from= 1.0000m to= 2.0000m
vout_pp= 5.5414 from= 1.0000m to= 2.0000m
pout_rms= 119.9504m
idd_avg= -33.0115m from= 1.0000m to= 2.0000m
iss_avg= 33.0447m from= 1.0000m to= 2.0000m
idd_peak= -92.3048m at= 1.2546m
          from= 1.0000m to= 2.0000m
iss_peak= 92.3709m at= 1.7549m
          from= 1.0000m to= 2.0000m

```

Figure 9: Transient Power Test Deck

Transient THD

The next simulation tests the amplifier's total harmonic distortion. The amplifier's THD is an important metric for measuring how accurately it recreates the input signal. Unfortunately the practical amplifier did not achieve the simulated THD, leading to noise in the audio, and we were unable to troubleshoot this issue.

```

thd_db=-128.9878 up to the harmonic: 40
snr_db= 4.4016

***** job concluded

```

Figure 10: Total Harmonic Distortion Test Deck

Transient FPBW

The next simulation tests the amplifier's full power bandwidth. This simulation provides important metrics for evaluating the amplifier's performance across different frequencies. Having a large FPBW, the range at which the amplifier can deliver its maximum rated power, ensures the headphones can make a variety of sounds at high volume.

```

***** transient analysis tnom= 25.000 temp= 25.000 *****
*** parameter freq = 1.0000k ***

vmax= 4.7953 at= 250.0000u
      from= 0. to= 1.0000m
vmin= -4.8046 at= 750.0000u
      from= 0. to= 1.0000m
vdc= -4.6692m
slope= 30.1592k
slewrates= 30.1592k

```

Figure 11: Transient Full Power Bandwidth Test Deck

Hardware Implementation

Note: Input waveform images are not included, as all followed the expected flat-line response and therefore were omitted to avoid redundancy.

To create our two stage amplifier on our perfboard, a number of steps were taken to reach the final design. We began by focusing on the first channel, first stage. The first stage was initially tested on a breadboard to verify our circuit before soldering onto the perfboard. A load resistor of 34Ω (two 68Ω resistors in parallel), were used at this point in the hardware design.

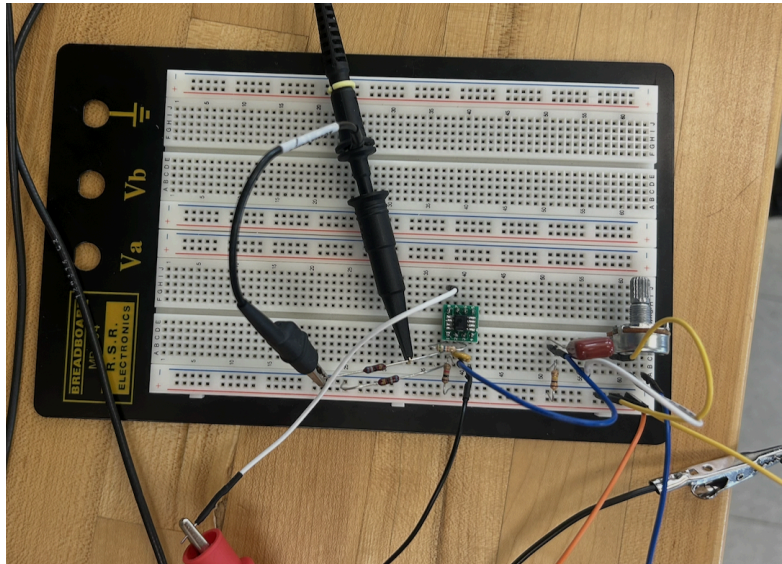


Figure 12: Breadboard setup for first stage

Our first stage was then tested using the oscilloscope. At this point, we had not yet attached our batteries to the circuit, and instead used a power supply to generate $\pm 9V$. To verify the performance of our circuit, using a power generator, we sweep across the target frequency range (18Hz to 25kHz) and screenshot the waveform at these various frequencies to ensure the circuit meets the specifications.

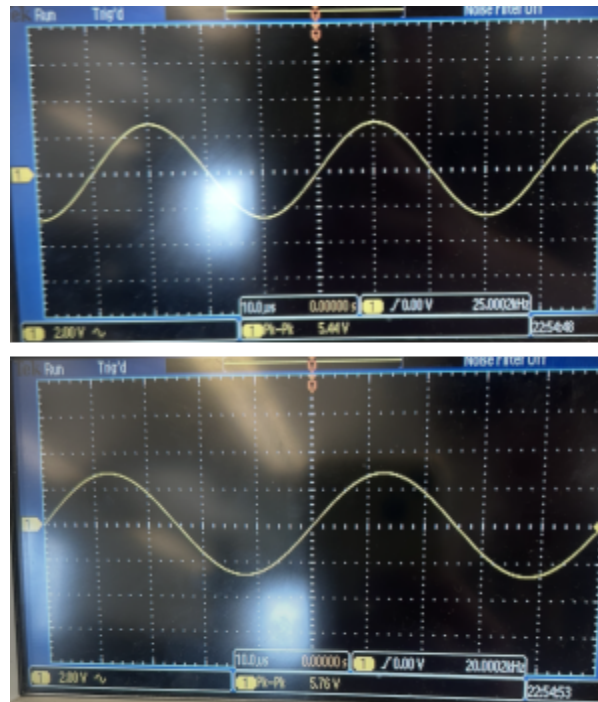


Figure 13: Output waveforms for 20kHz and 25kHz

Note: Images were taken through the whole frequency range but omitted for the breadboard part as we reverify on the perfboard.

Now that we confirmed a successful first stage on the breadboard, we moved on to soldering the first stage onto the perfboard. Jumpers were replaced with solder, and now the potentiometer and input jack were also soldered into the circuit. The same load as on the breadboard was once again used at this step (soldered and removed later). Once all connections on the perfboard were soldered, the circuit was once again checked using an oscilloscope. At this point, evaluate our circuits performance in AC small-signal and large-signal transients using sinusoidal and square-wave input signals.

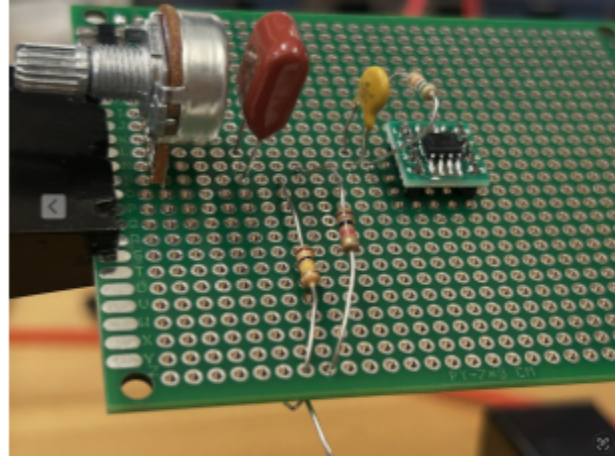
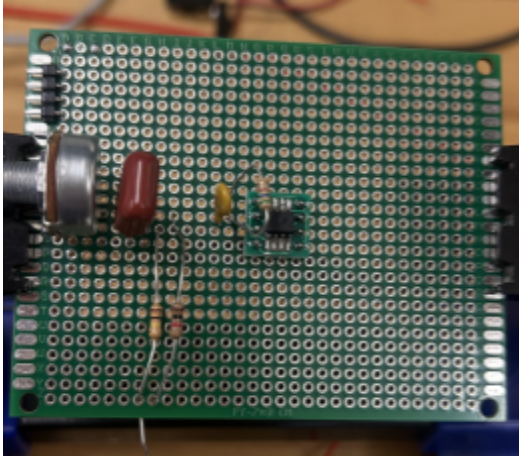


Figure 14: First stage implemented on perfboard

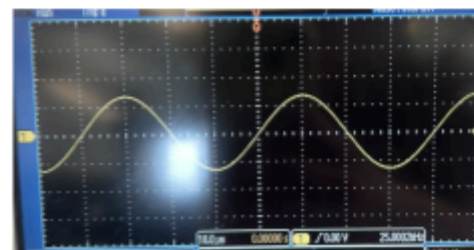
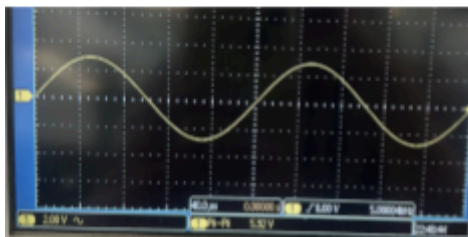
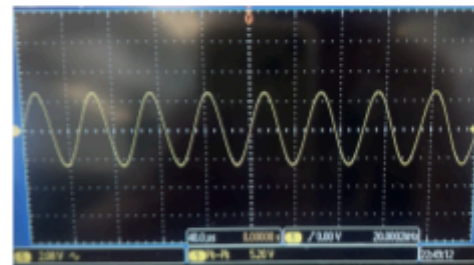
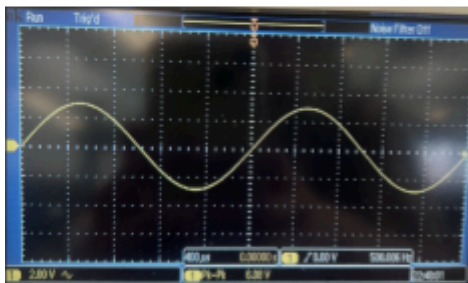
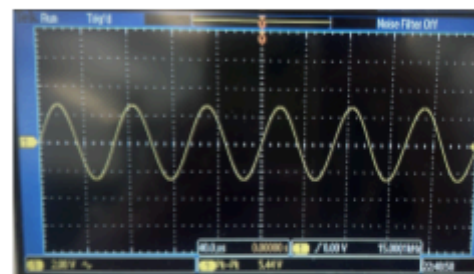
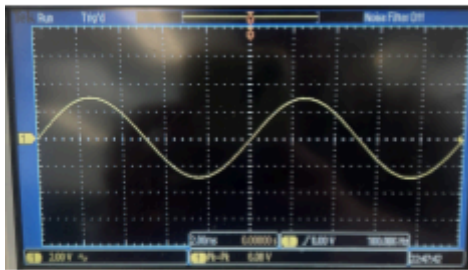
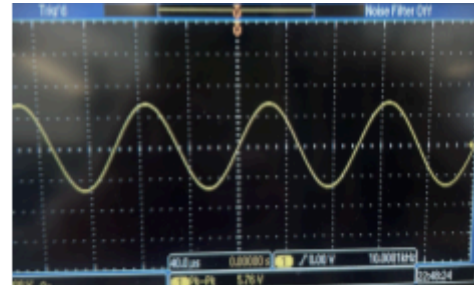
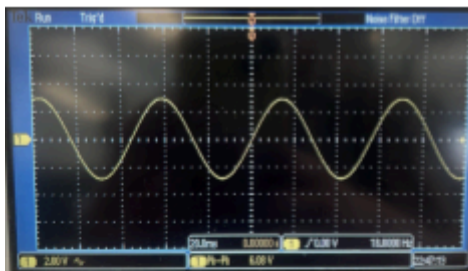


Figure 15: Sinusoidal waveforms for first stage

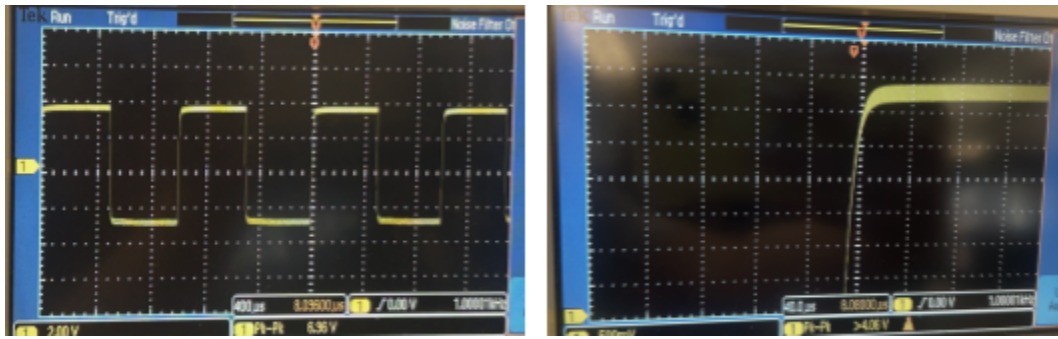


Figure 16: Square waves for first stage

The square-wave response demonstrates stable transient behavior with minimal overshoot. The fast rise to settling behavior indicates that the amplifier maintains stability while preserving the high-frequency response. This confirms an acceptable large-signal transient performance for audio applications.

Now that we have successfully implemented the first stage, we can now move on to the second stage. The first BUF634A buffer was soldered on and attached following its data sheet. As with the first stage, once all connections on the perfboard were soldered, the circuit was once again checked using an oscilloscope.

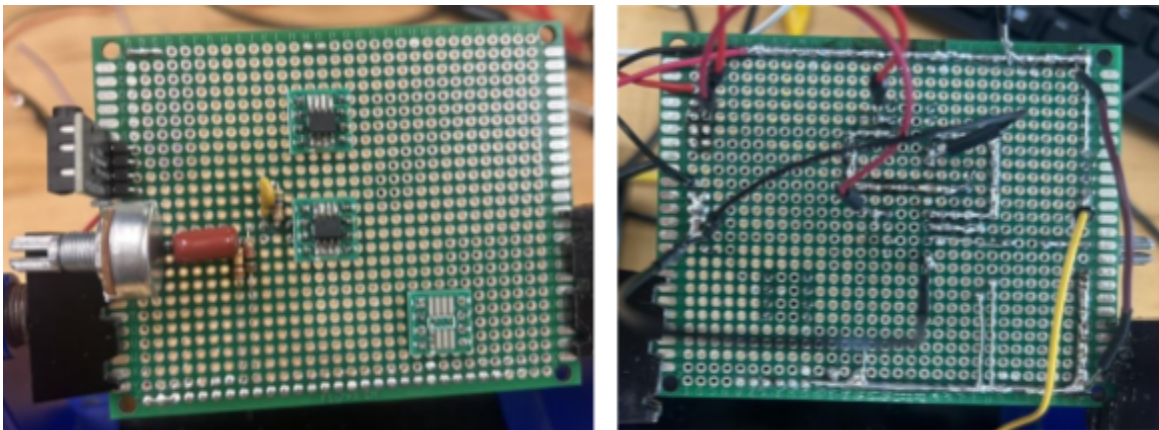


Figure 17: Perfboard for second stage implementation

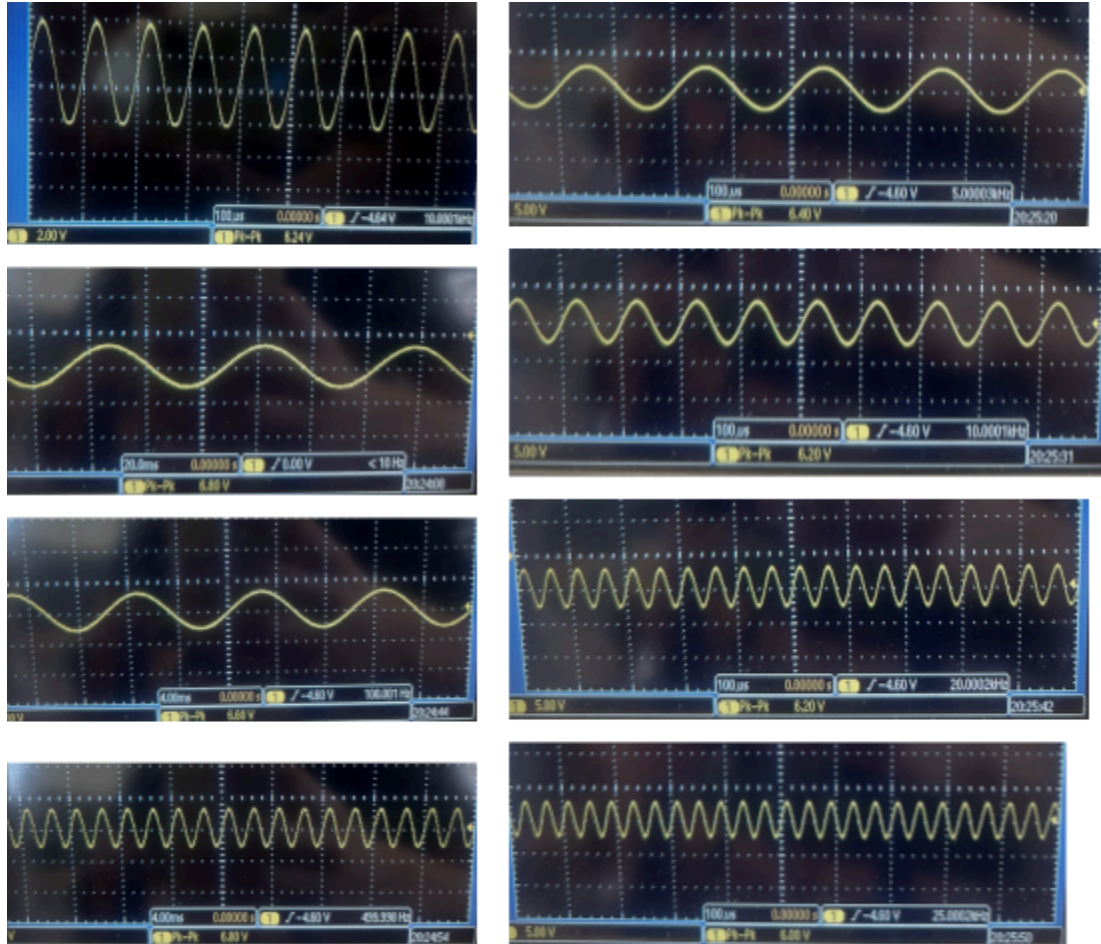


Figure 18: Output waveforms for second stage

With successful implementation of the second stage, we could now move on to the second channel. The steps taken above to solder and execute the first channel were repeated in an almost identical fashion for the second channel. Note: The second channel is implemented through the other set of ports on the op amp (ports 5-7). It is key to match your design for your second channel to your first for a correct output to be made. Once the second channel was soldered, both channels were tested using the oscilloscope a final time.

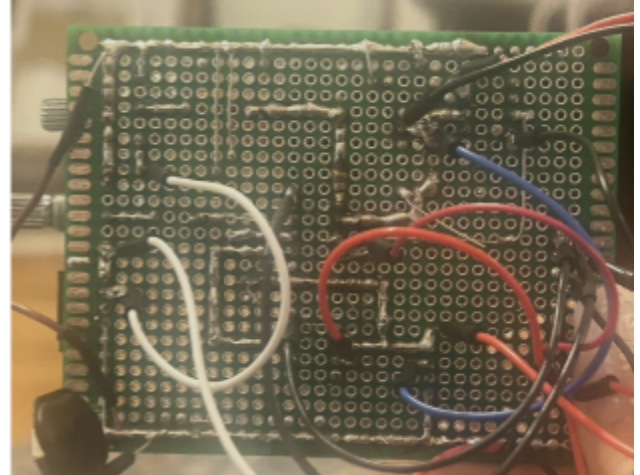
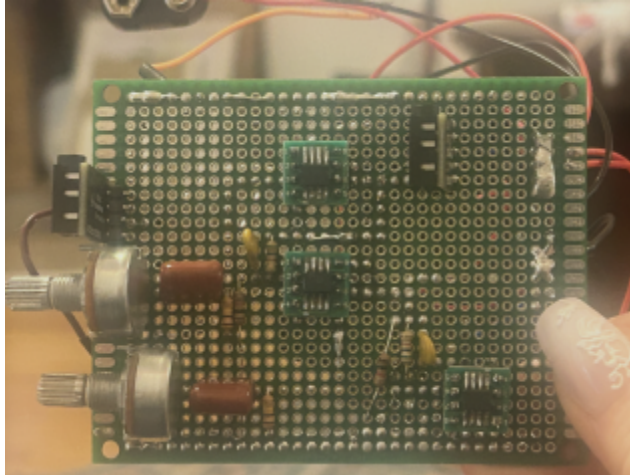


Figure 19: Final hardware design on perfboard (2 channels)

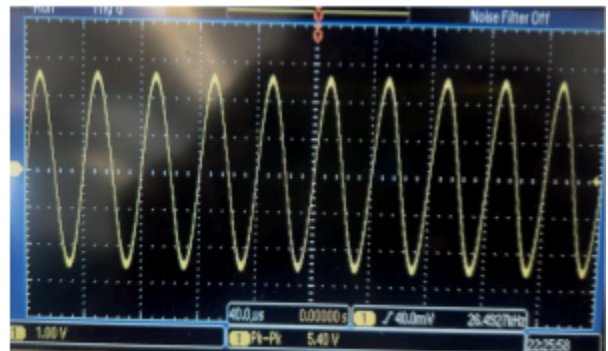
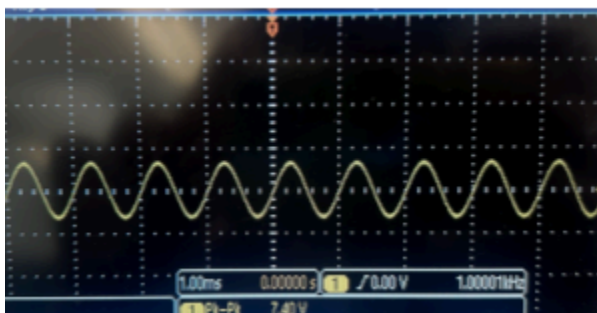
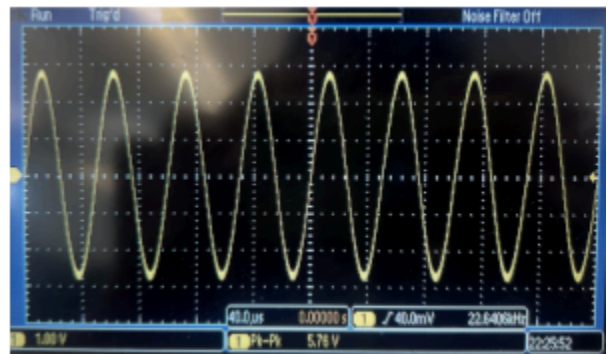
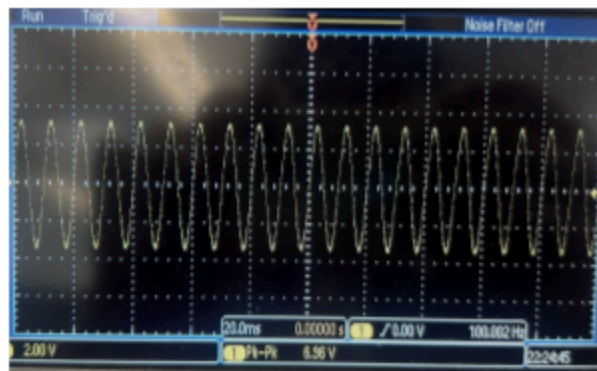
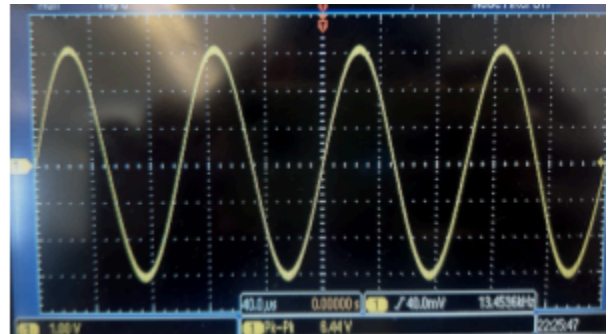
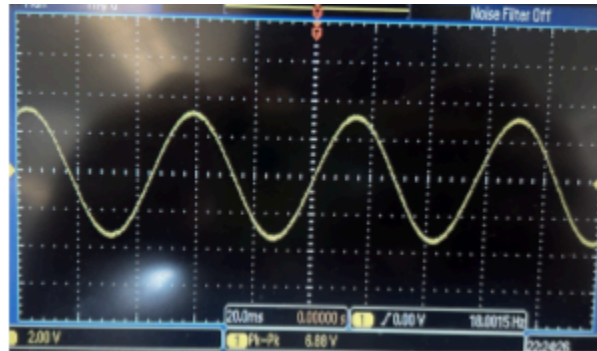


Figure 20: Output waveforms for final design

Audio Testing

With completed hardware, whose inputs and outputs were verified at numerous stages using the oscilloscope, we can now move on to testing the amplifier with the TAs. We are asked to evaluate the acoustic performance using a music data file as input and record the output to a new music data file. The performance is then evaluated by listening to the music data file using a music player software.

Being the first group to complete our hardware, the testing software was not fully set up at the time of our completion. Below are images from the software exhibiting successful outputs from both of our channels. Additionally, the output was listened to using a pair of aux headphones. This output was listened to by both partners, the TA, and numerous other students. The acoustic performance of our amplifier was strong and the implementation of our hardware was thereby verified.

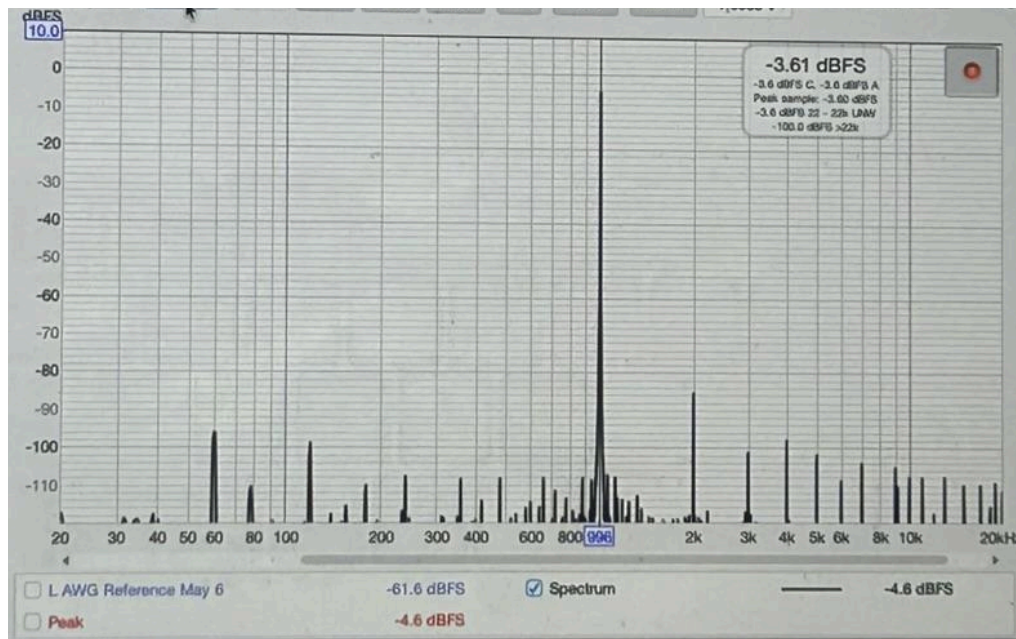


Figure 21: Audio output for first channel

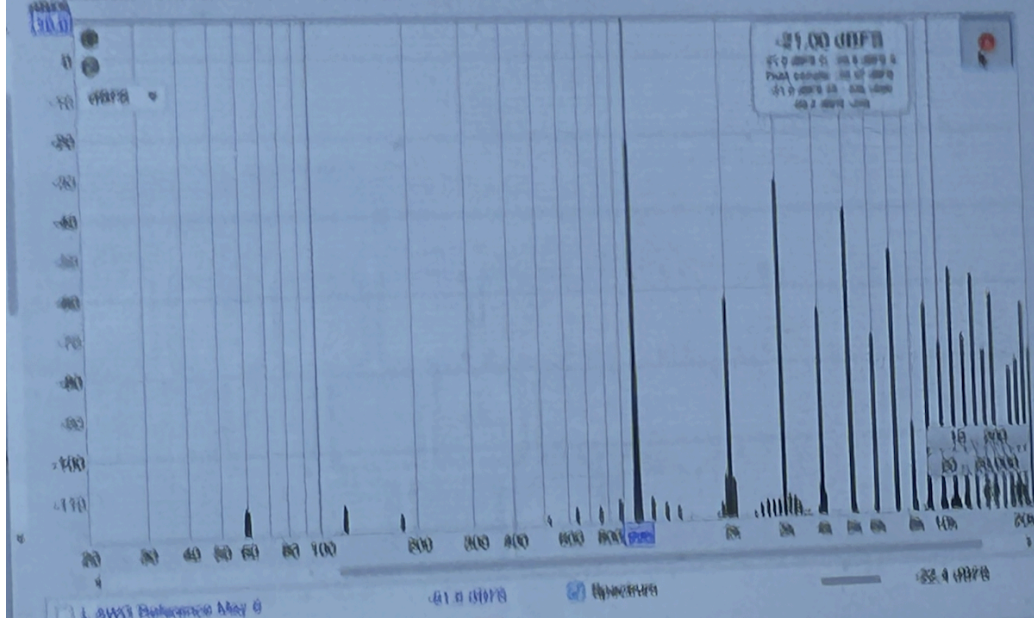


Figure 22: Audio output for second channel

Discussion

From below, we find a successful implementation of our design. No modifications to improve performance were needed. Quite the contrary, our implementation was better than expected, yielding a higher gain than expected. We find that with the audio output, along with the oscilloscope images at each stage, that all specifications are met. We can further verify the specifications now that we have finalized all of our component values and compare it to the proposal we initially submitted.

The closed-loop voltage gain for the non-inverting amplifier stage is determined by the implemented resistor values,

$$A_v = 1 + \frac{R_f}{R_g} = 1 + \frac{5.6k\Omega}{1k\Omega} = 6.6V/V$$

Using the nominal input amplitude of 0.3V, the output voltage becomes,

$$V_{out} = A_v V_{in} = 6.6(0.3) = 1.98V$$

Further, the resulting output power across the 32Ω load is,

$$P_{out,RMS} = \frac{V_{out}^2}{R_L} = \frac{1.98^2}{32\Omega} = 122.5mW$$

This exceeds the required specification of 100mW. The peak output current can be recalculated given,

$$I_{out,peak} = \frac{\sqrt{2}V_{out}}{R_L} = \frac{\sqrt{2}(1.98)}{32} = 87.5mA$$

This remains within the current drive capability of the BUF634A buffer from the specifications online. The input impedance is dominated by the 100kΩ resistor connected to the non-inverting input,

therefore $R_{in} \approx 100k\Omega$, which meets the specification of $R_{in} \geq 10k\Omega$ and matches our expectations from the proposal.

The final amplifier met the goals and specifications established at the beginning of the project. Throughout the design and assembly process, changes were made to the amplifier to overcome challenges that were faced, such as adding a capacitor to the feedback loop to stabilize the high-frequency gain, which was not initially anticipated. Throughout the design process, the amplifier was tested at various stages using the Gavvett oscilloscope and signal generators to ensure adequate amplification of signals at various frequencies.

The practical board faces an issue with a much higher THD than predicted by the simulations. This is likely due to parasitic effects from the physical implementation. A small amount of troubleshooting, and the board would be practical as a headphone amplifier.

Conclusion

In this project, we successfully designed, simulated, built, and tested a two-stage headphone amplifier using the OPA1656 and BUF634A. Beginning from our initial HSPICE simulations and project proposal, we implemented the circuit through both breadboard and perfboard testing before reaching a final two-channel hardware design. Throughout the implementation process, oscilloscope measurements were taken at numerous stages to verify the performance of the circuit across the desired frequency range and under both sinusoidal and square-wave inputs.

From both the measured outputs and calculated specifications, we find that the amplifier successfully satisfies the required project constraints. The amplifier achieved the desired gain, output power, bandwidth, and input impedance while maintaining stable output waveforms across the tested frequencies. Additionally, audio testing verified successful operation for both channels, producing clear and amplified sound through headphones.

Overall, this project demonstrated the complete process of circuit design, simulation, hardware implementation, and testing. The successful construction and operation of the final amplifier verified both the practicality of the design and the accuracy of the simulations used throughout the project.

Sources

[1] Texas Instruments, OPA1656 SoundPlus High-Performance, Bipolar-Input Audio Operational Amplifier Datasheet, Website, <https://www.ti.com/lit/ds/symlink/opa1656.pdf>

[2] Texas Instruments, BUF634A High-Speed, High-Current Buffer Datasheet, Website, <https://www.ti.com/lit/ds/symlink/buf634a.pdf>

[3] Professor Hui Wu, ECE 222 Project References and Test Decks, Course Materials and Provided References, University of Rochester.