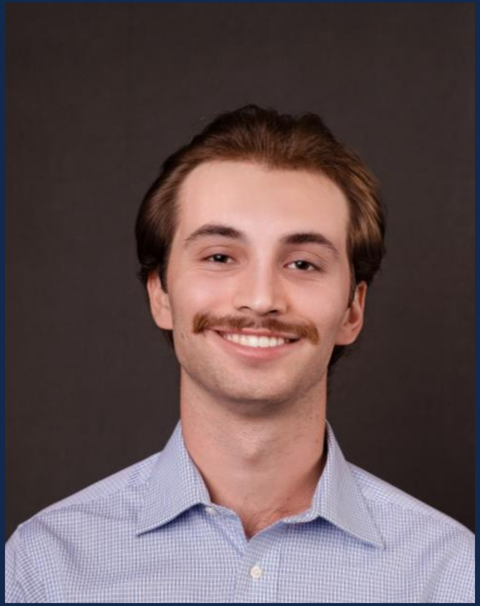
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

LabEscape Ultrasonic Directional Speaker

Electrical & Computer Engineering

04/30/2026

Team #34



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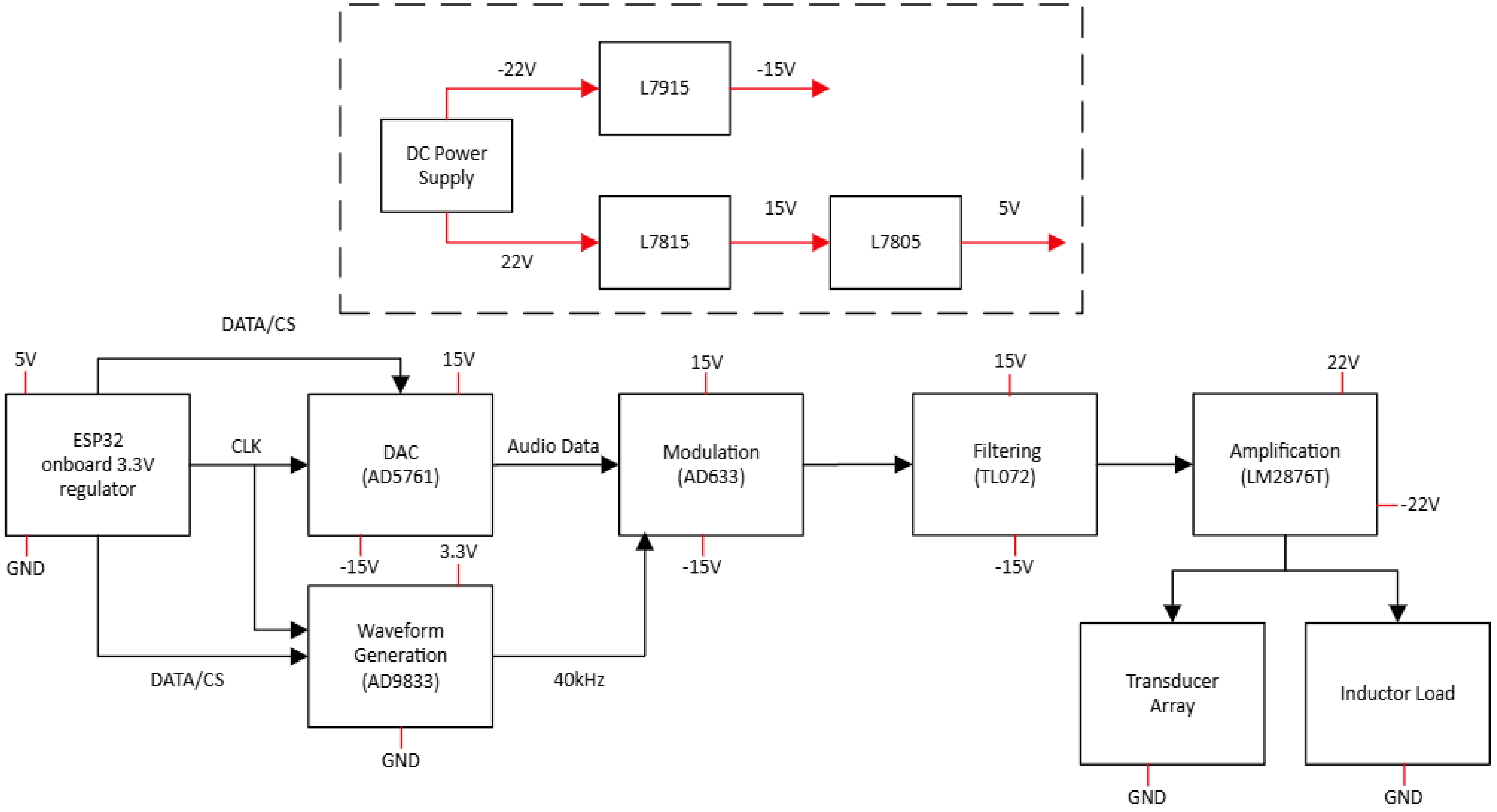
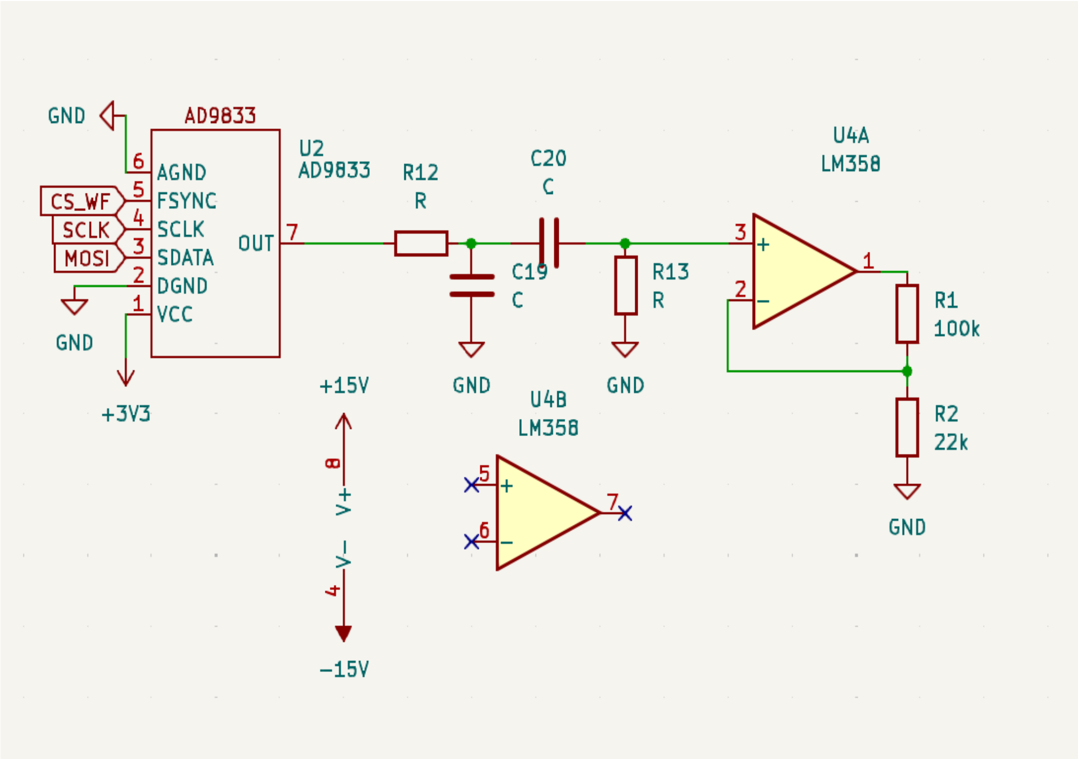
Objective and Overall Design



Design Changes

- Switch from AD5660 DAC to AD5761 (unipolar vs bipolar output).
- 3.3V inputs to DAC and AD9833 for digital interfacing.
- 5V input to ESP32, since we are using a devboard with onboard regulator.
- Added parallel inductive load for power factor correction.



AD9833 Programmable Waveform Generator

Through software, the AD9833 reads two 16-bit inputs to set a frequency defined by the following equation:

$OpCode = (f_{analog} * 2^{28}) / (f_{MCLK})$.

High Pass Filter DC Offset Removal

- The initial output from the AD9833 has a DC offset.
- High pass filter removes DC offset and centers sine wave about 0V.

TL072 Amplification

- Initial output of about 300mV amplitude.
- Gain of 8.5 to get about 2.5V amplitude.

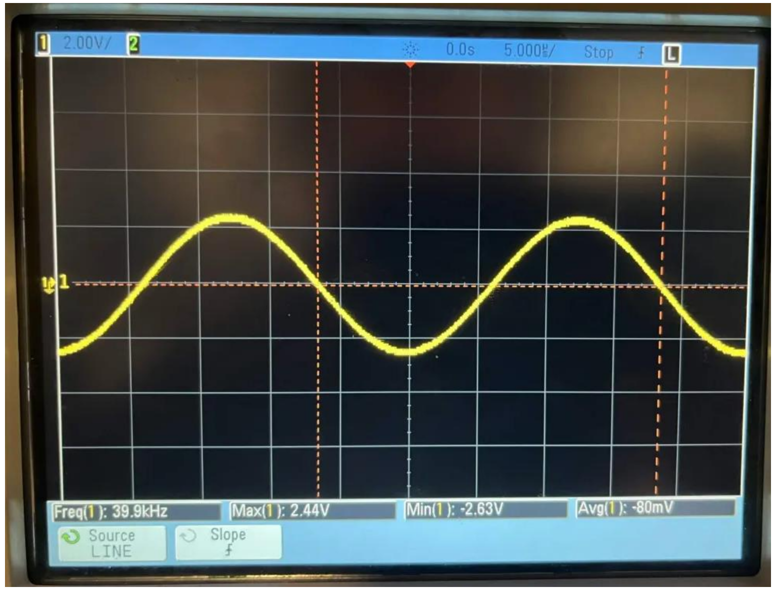
Subsystem Requirements & Verification

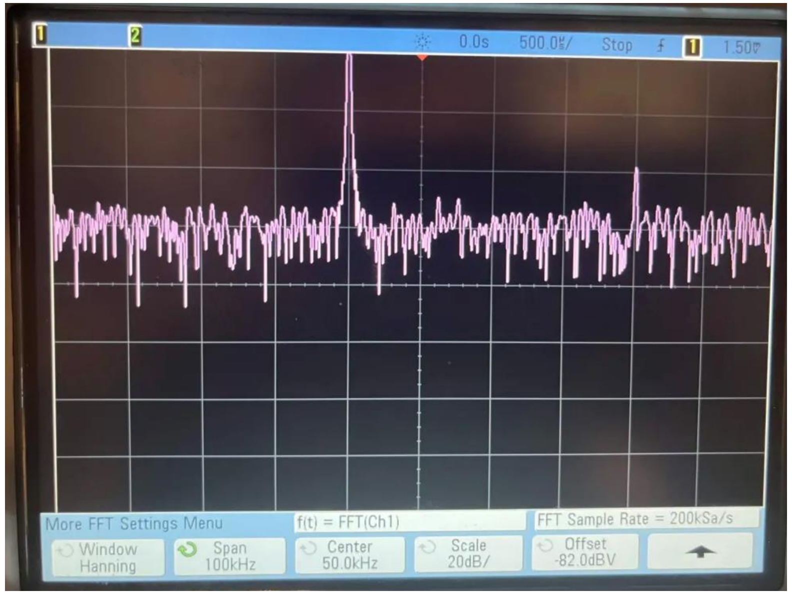
Requirements

1) Wave has high resolution without noticeable gaps or quantization.
2) The created waveform will not have large amounts of harmonics in the signal.

Verification

1) Use built in measurement tools:
    - Frequency would be within 100Hz, which is greater than original goal of 50Hz.
    - Amplitude of 2.5V.
2) Use built-in FFT tool:
    - Large peak at 40kHz, smaller peak at 80kHz.
    - Harmonic does not dominate the signal





AD5761 16-Bit Serial Load DAC

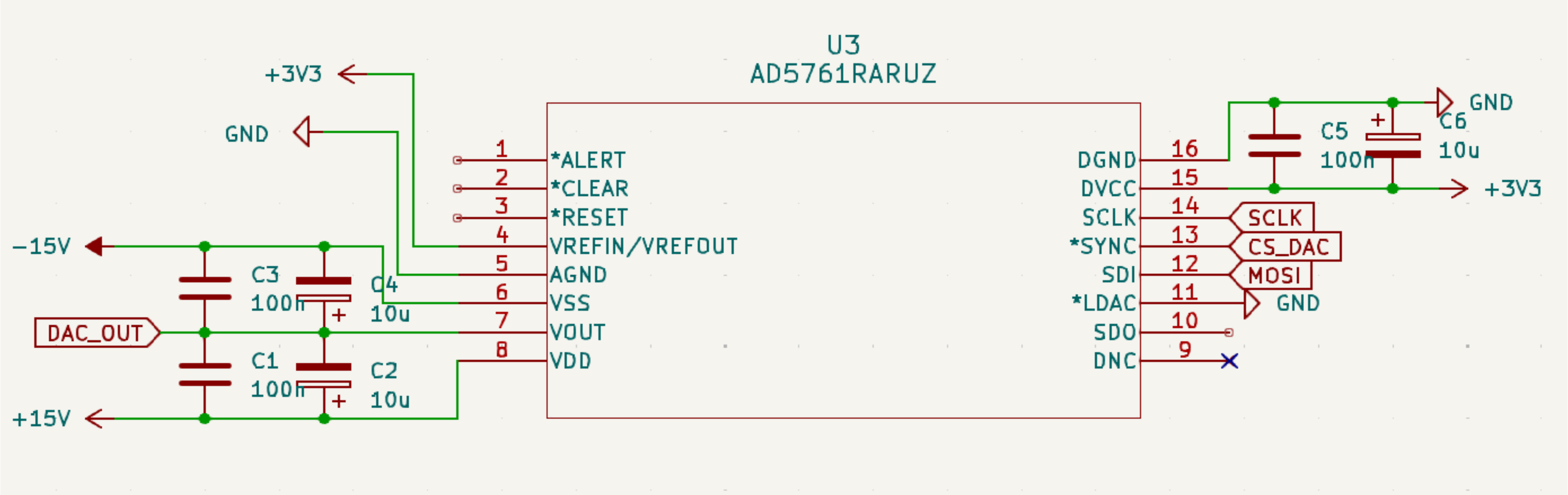
Through software, the DAC loads 24 bits of data at a time. The data is read from flash memory instead of RAM. Inside the code are two audio arrays, one of which encodes a sinewave, and the other encodes speech.

RC Smoothing Filter

- DAC outputs discrete voltages.
- Low Pass RC filter smooths the transitions between them

TL072 Audio Amplification

- Amplify signal to get better modulation depth in modulation subcircuit.



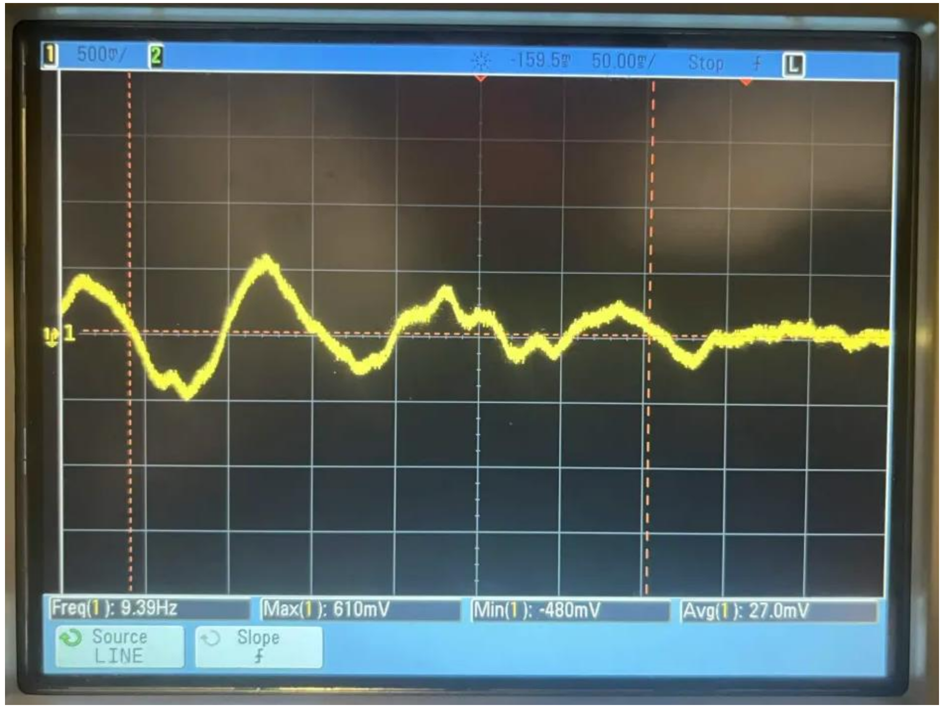
Subsystem Requirements and Verifications

Requirements

1) The output audio wave can be comprehended.
2) Output waves do not have any artifacts from conversion.
3) The conversion between any two points will be within 0.01V of the desired voltage.

Verification

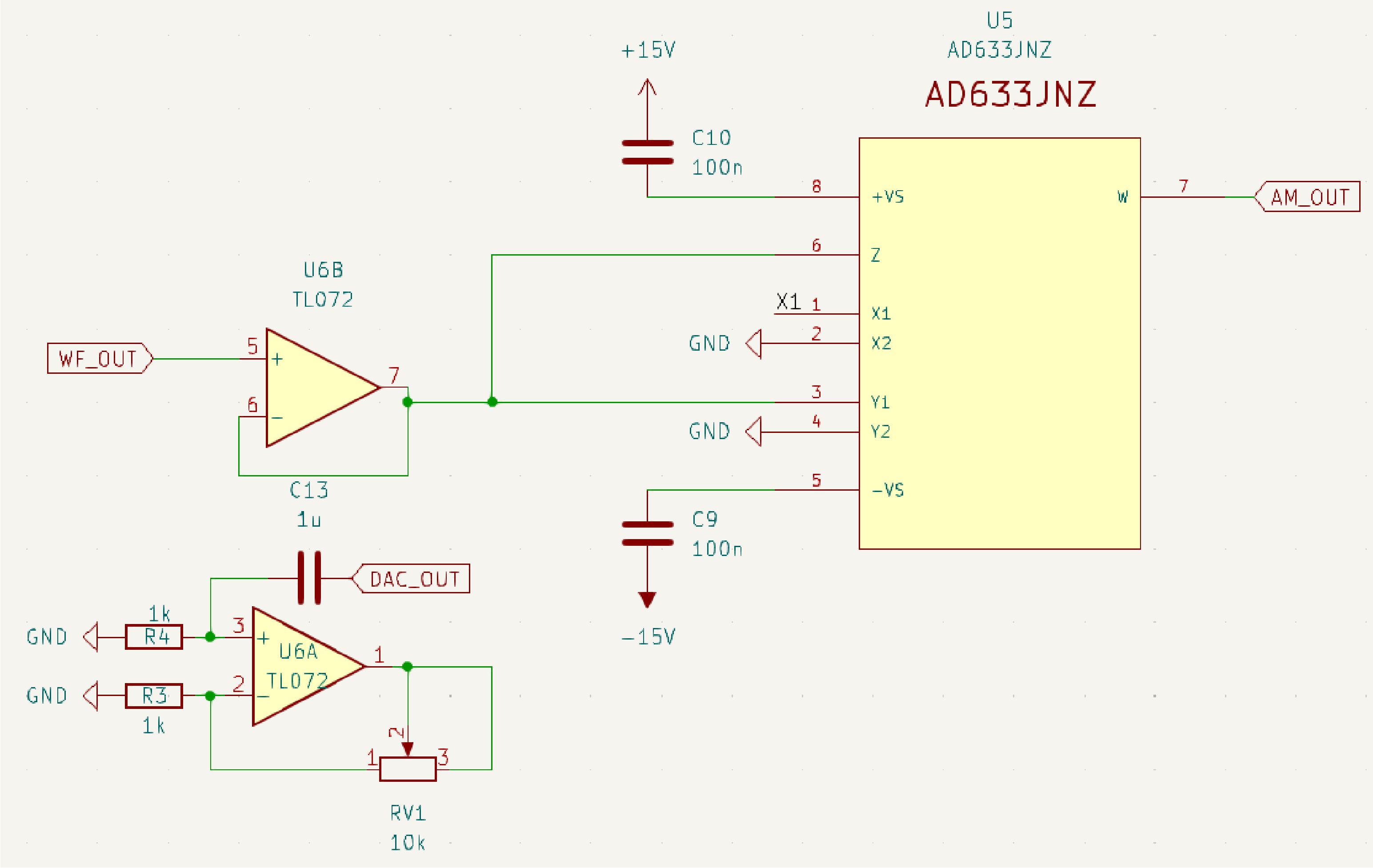
1) Test using directional speaker output.
   - We pulled the audio from the stored audio array.
   - Output was legibly the original audio.
2) Oscilloscope probing after RC smoothing filter.
   - RC filter easily and smoothly moves voltages to form smooth audio wave.
3) Arduino script runs sweep of voltage
   - Outputs from –10V to 10V at increments of 1V confirmed accuracy up to 0.1V.



Carrier Signal:
- From the Waveform Generator
- 40 kHz Sine Wave

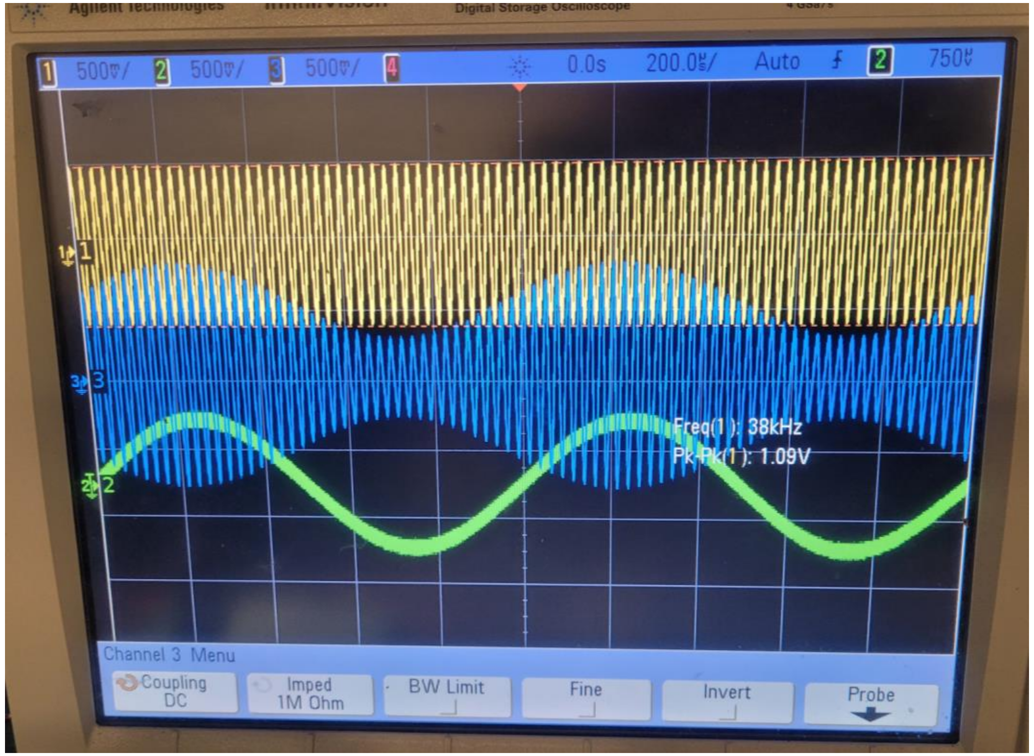
Modulating Signal (Becomes Audible):
- From the DAC
- High Pass Filter Applied to Remove DC Offset
- Non-inverting Amplifier for Gain

AD633 (Analog Multiplier) [1]:
W = ((X1 − X2)(Y1 − Y2) / 10V) + Z.
X1 = Audio
Y1 = Z = Carrier
X2 = Y2 = 0
Output: W = (1 + (Audio / 10V)) × Carrier

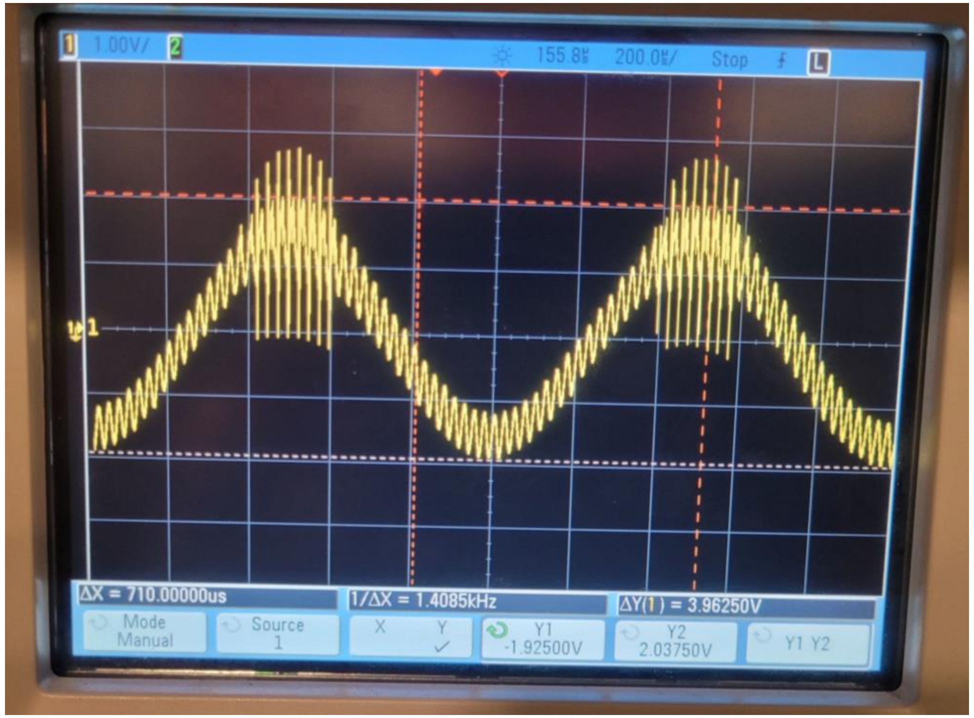


Subsystem #3: Amplitude Modulation

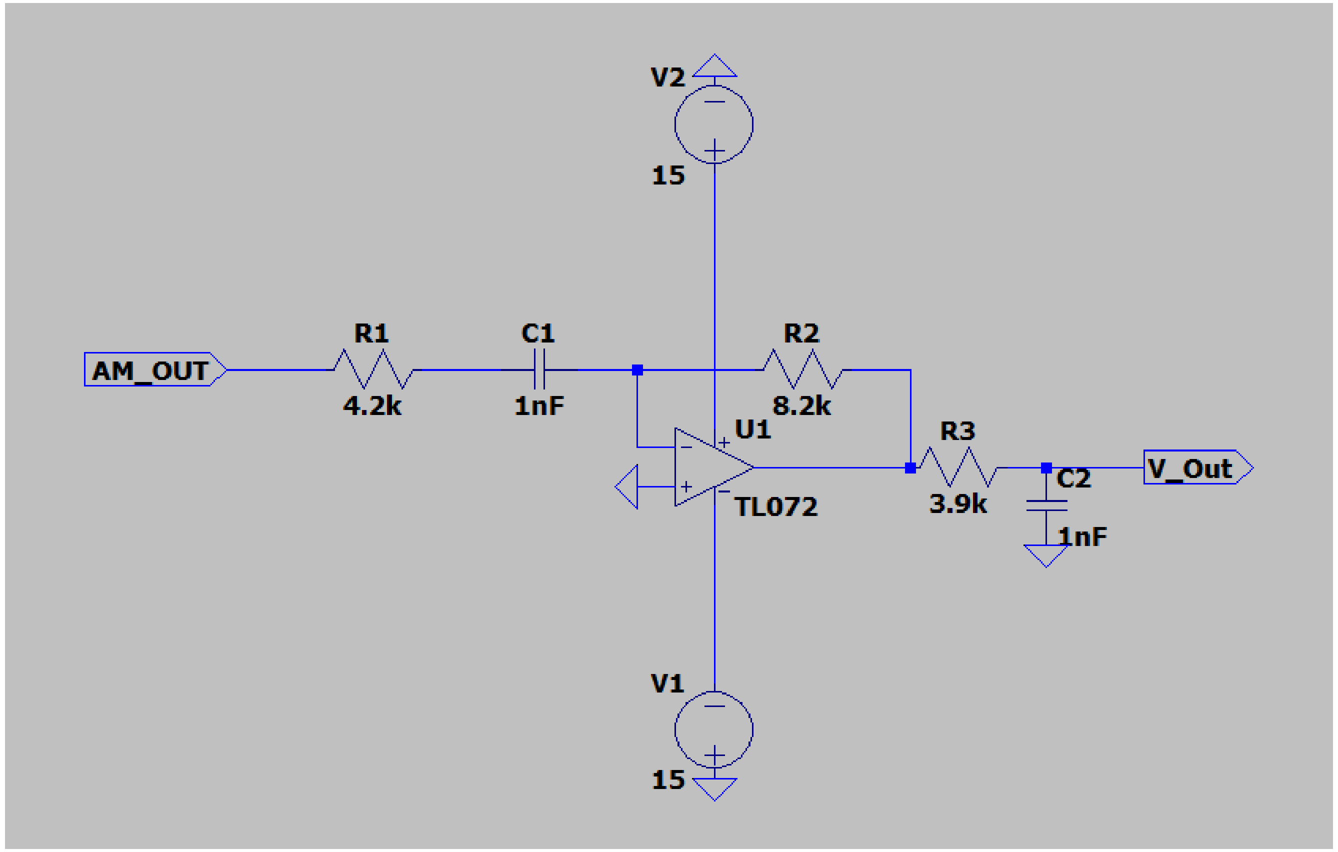
Verifications



Maintains 40 kHz Carrier Frequency



Modulating Signal DC offset is only (2.0375 - 1.925) / 2 = 0.05625 = 56.25 mV



$$Gain = -(\frac{R2}{R1})$$

$$Cutoff = \frac{1}{2\pi RC}$$

Bandpass Filter

- Active Bandpass Filter using an amplifier
- Filter out harmonics and prevent large voltage drop
- TL072: good voltage range and low distortion

Bandwidth and Gain

- High pass has a cutoff of 37894 Hz
- Low pass has a cutoff of 40809 Hz
- Final bandwidth of 37.89 to 40.81 kHz
- Magnitude of the gain is 1.95

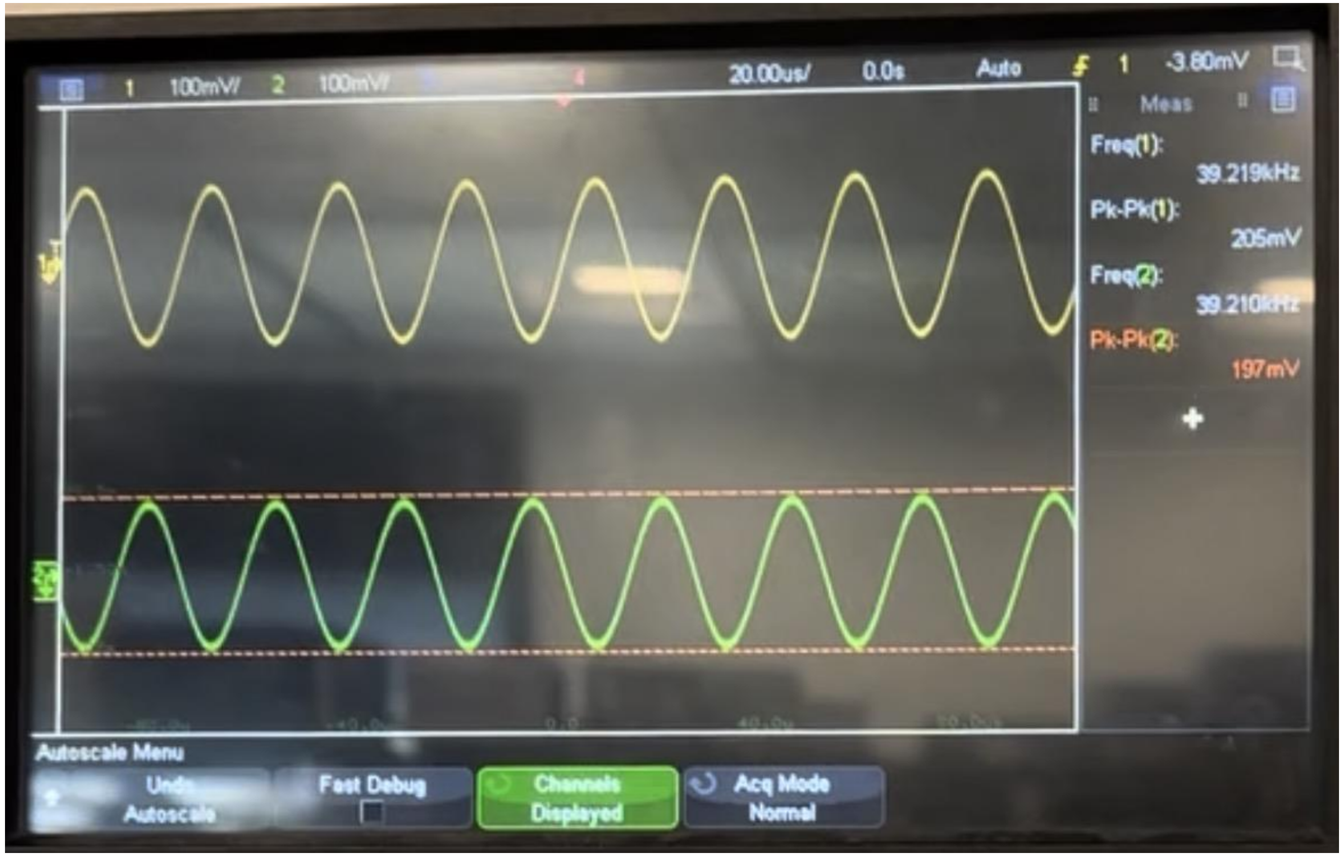
Verifications and Requirements

Requirements

- Filters out noise and frequencies outside of the bandwidth
- Amplifies the signal (if needed)
- It keeps the signal centered around the specific frequency

Verifications

- Different signals with various frequencies are sent through the filter
- The signal is amplified a necessary amount, and the difference can be seen through the output peak to peak voltage
- The output signal is still centered near the 40kHz



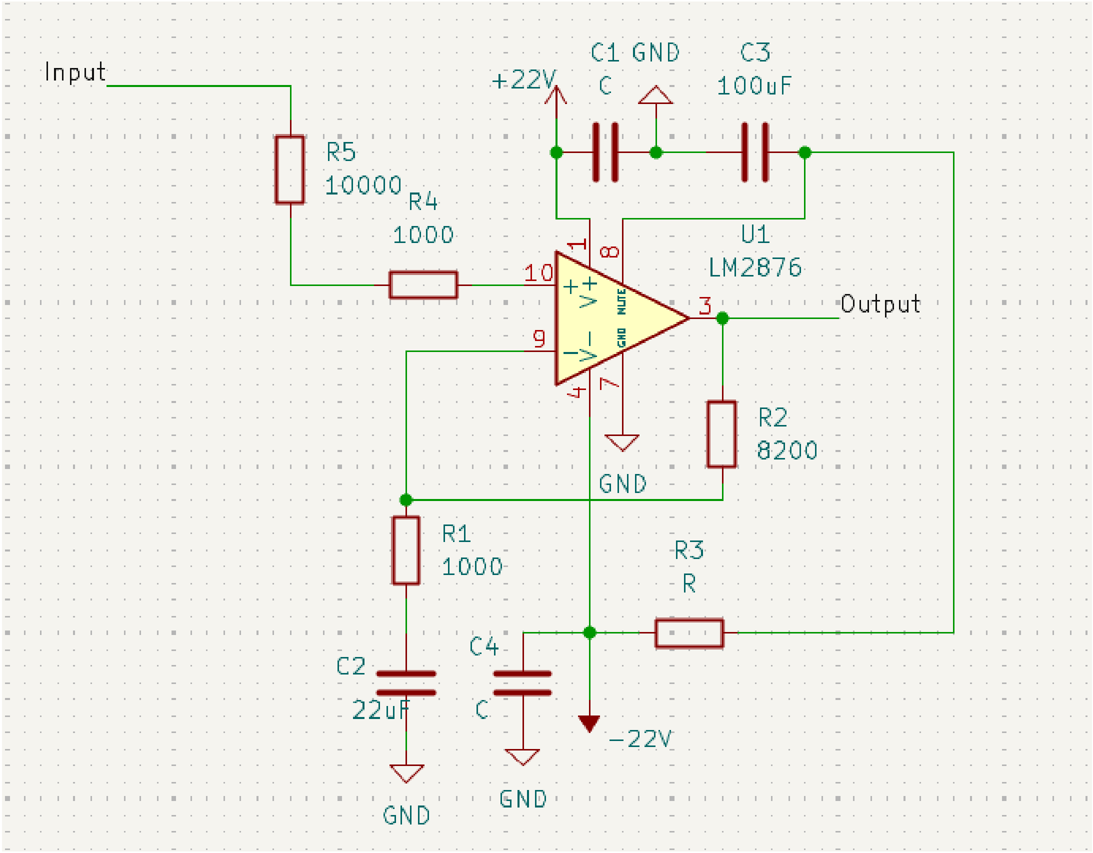
Input Freq [kHz]	Input Vpp [mV]	Freq Out [kHz]	Vpp Out [mV]
20.001	213	20.068	169
39.219	205	39.210	197
100.16	205	99.59	133

Amplifier

- LM2876T chip [2]
- Signal was successfully amplified to 39.1Vpp
- Successfully surpassed the 110 dB threshold
- Gain is currently 9.2

Key features:

- Potentiometer (R5) as volume control
- R4 as an input protection
- R1 and R2 as the feedback loop
- Mute resistor R3
- C3 as control for the mute timing
- Supply capacitors keeping rail voltage high
- C2 feedback capacitor helps block DC



$$Gain = 1 + \frac{R2}{R1}$$

Subsystem #5: Amplifier

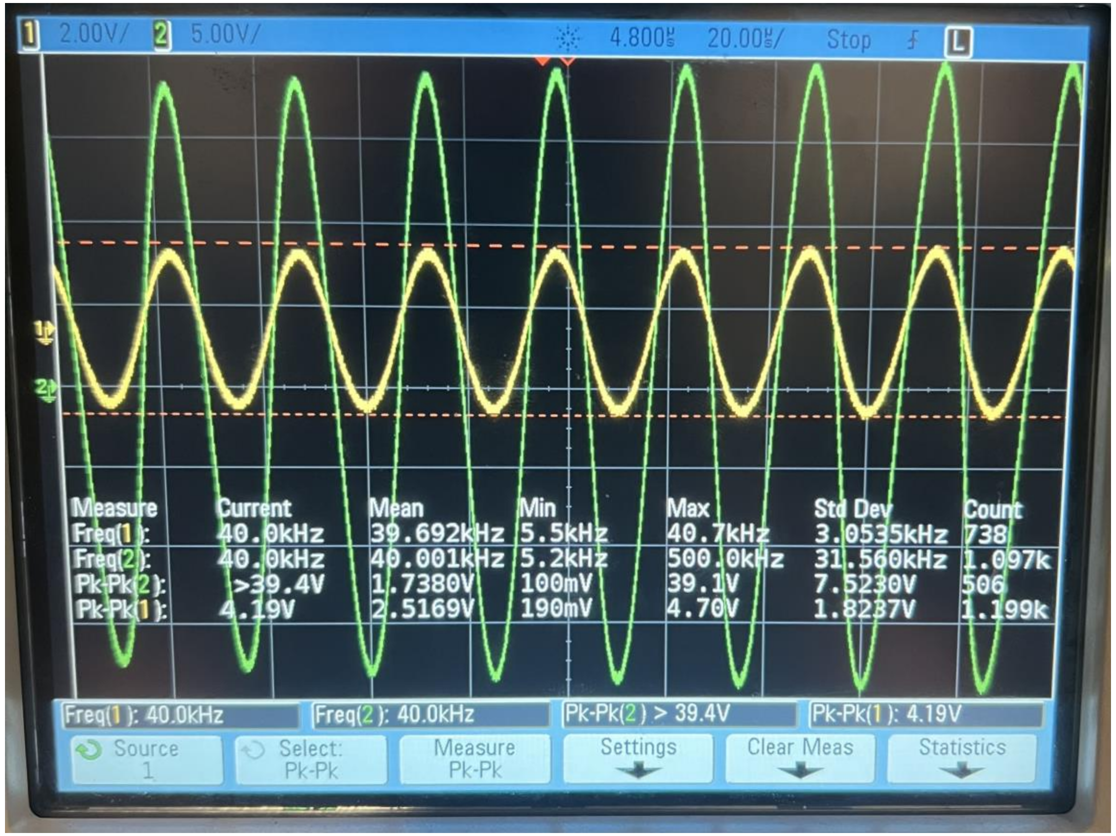
Requirements and Verifications

Requirements:

- Amplifies the signal to the necessary dB so that the signal is audible
- The amplifier can run without overheating and melting
- It does not create too much noise and distort the signal making the audio illegible

Verifications:

- Through hearing the audible noise and displaying on the oscilloscope the peak-to-peak voltage
- Running the encoded audio the entire way through and not overheating
- Output of the signal keeps the initial shape, and the code is clear



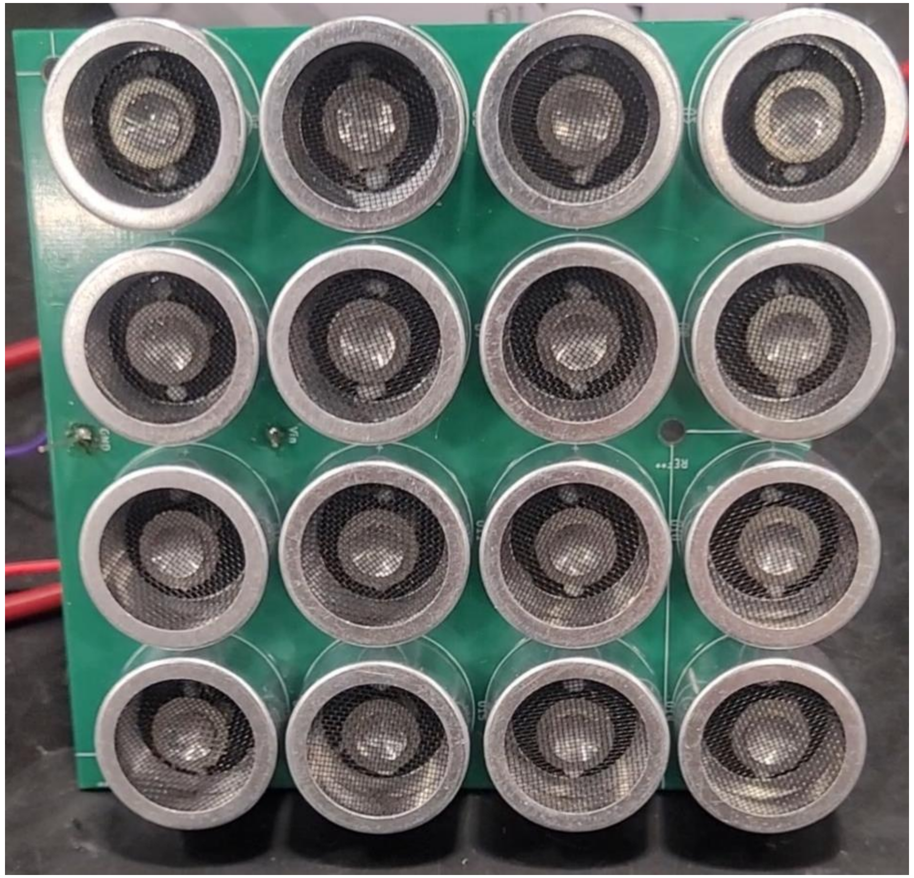
- **4-by-4 array of ultrasonic transducers in parallel on PCB**

- Transducers have ~2400 pF capacitance each [3]
- **Two series 220 μH inductors in parallel with the transducer array**:

$L = 1 / [C \times (2 \times \pi \times f)^2] = 428\ \mu H \approx 2 \times 220\ \mu H$

Verification:

- Transducers maintain resonance frequency of 40 kHz (refer to previous slide image)
- Total inductance is 440 μH, charging/discharging effects removed



Power Supply

DC power supply
- Successfully provides ±22 V
- Voltage regulators regulate the voltage down

Voltage Regulators
- Simple 3 pin chip, input, output, and ground
- Positive: LM7815 & LM7805
- Negative: LM7915

Requirements
- The power supply provides the necessary voltage without any current spikes or the voltage dipping
- The regulators regulate the voltage to the necessary magnitudes

Verifications
- Using a multimeter to probe the rails where ±22 V are provided and the outputs of the regulators.

High-Level Requirement 1

“The system shall maintain a half-power beamwidth of less than 10 degrees at a distance of 1 meter.”

Figure 1: Sound Pressure Level at Various Angles

Degrees (°)	Sound Pressure Level (dB)
<< -5°	70.5
-5°	70.6
0°	81.8
5°	70.2
>> 5°	70.0

This table displays the sound pressure level measured with a decibel meter at a distance of 1 meter from the center of the transducer array at various angles, while a test 1 kHz sine wave is the input signal.

High-Level Requirement 2

“The system shall maintain an audio output frequency response flatness of ±6 dB within an operating bandwidth of 300 Hz to 1250 Hz.”

Figure 2: Sound Pressure Level at Various Frequencies

Frequency (Hz)	Sound Pressure Level (dB)
1250	83.5
1100	83.5
1000	83.4
900	83.3
750	83.3
650	83.0
500	82.9
400	82.7
300	82.6

This table displays the sound pressure level measured with a decibel meter at a distance of 1 meter from the center of the transducer array at an angle of 0°, while sine waves of various frequencies are inputted.

High-Level Requirement 3

“The transducer array must generate a minimum ultrasonic sound pressure level of 110 dB at the emitter face. If this threshold is not met, the air fails to delinearize, which is necessary for the ultrasonic signal to become audible.”

- **The signal is audible**
- Research shows that past 110 dB the signal is audible [4]

- We can estimate SPL:

Measured Vpp = 39.1 V --> Vrms = 13.82 V
From Data Sheet [3]: minimum 115 dB SPL given 10 Vrms

SPL ≈ Base SPL + Voltage Gain + Array Gain
SPL ≈ 115 + 20*log(V / Vref) + 20*log(N)
SPL ≈ 115 + 20*log(13.82 / 10) + 20*log(16)
SPL ≈ 142 dB > 110 dB

Successes

- The circuit outputs audio that can be heard and is legible
- The speaker itself is directional
- The circuit can run for multiple minutes
- Each subsystem is compatible with one another
- Successfully satisfied all high-level requirements

Challenges

- The project was only able to be completed on a breadboard due to constant back stepping to improve audio quality.
- The rail voltage limitation for the amplifier made audio quieter and with less resolution than initially hoped for.
- Budget for transducers and power subsystem were limited.

Conclusions and Future Work

Conclusions

- We confirmed 40kHz is a viable and effective carrier frequency for the AM signal.
- We confirmed that the demodulation of an AM signal in air is possible.
- We learned that ~40Vpp is just past the necessary threshold for the demodulation effect.

Future Work

- Increasing rail voltages will increase output volume and allow for greater modulation depth for greater resolution.
- Optimizing transducer placement may help reduce dead spots in audio, or perhaps even promote constructive and destructive interference.
- Further optimize the equalization of various frequencies.
- For the scope of this class, pursuing a PWM scheme may be more reasonable, powerful, and efficient

References

[1] AD633 Low Cost Analog Multiplier, datasheet, Analog Devices, 2015. Available at: https://www.analog.com/media/en/technical-documentation/data-sheets/AD633.pdf

[2] LM2876T Datasheet –Overture Audio Power Amplifier Series High-Performance 40W Audio Power Amplifier w/Mute, datasheet, Texas Instruments, 2000. Available at: https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/2135/LM2876.pdf

[3] *CUSA-T60-150-2400-TH Datasheet - Ultrasonic Transmitters*, datasheet, Same Sky, 2024. Available at: https://www.sameskydevices.com/product/resource/cusa-t60-150-2400-th.pdf

[4] Theory and Design of an Ultrasound Loudspeaker, Polytechnic University of Valencia, 2017. Available at: https://www.iteam.upv.es/wp-content/uploads/2018/10/01.pdf

Questions?