ESET 350 Analog Electronics

Final Project Report

Analog Square-Wave Synthesizer

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Overview

Music is an extraordinary thing that I'm sure everyone enjoys, so in an effort to combine a passion for music with analog electronics the idea for a very simple, but fully analog synthesizer came to mind. In order to make this synthesizer as immersive as possible, it must at least be capable of playing a wide enough range of musical notes (each with different frequencies) to mimic the keys one might find on a piano. In order to produce different musical pitch for different keys, the synthesizer utilizes properties of op-amp relaxation oscillators to produce wave-like signals of different frequencies. Operating this very simple synthesizer only requires a bi-polar supply voltage of at least ±9V (or two isolated power supplies) and someone to press the keys.

Principles of Operation

In order to completely understand how this circuit operates, one must first be comfortable with the concepts behind an astable multivibrator circuit. The astable multivibrator is also known as an op-amp oscillator, and it is the only reason why the synthesizer is even able to create an output signal. The exact oscillator being used is known as a square wave relaxation oscillator that incorporates a schmitt trigger using positive feedback at the non-inverting terminal. It operates by supplying voltage to the capacitor at the inverting input via feedback, slowing charging or discharging it depending on the given saturation state of the op-amp. The saturation state switches as a result of the capacitor reaching a threshold voltage that is determined by the voltage divider formed from resistors R1 and R2 in figure 1. Overall, it can be shown that the period of the of the switching is a direct result of the RC time constant formed at the inverting terminal and the feedback ratio established by the non-inverting resistors R1 and R2 as such:

$$T = 2RCln(\frac{1+\beta}{1-\beta}) \ where \ R = (2fCln(\frac{1+\beta}{1-\beta})) \ given \ \beta = \frac{R_1}{R_1+R_2} \qquad Equation\ 1$$

Where T is the wave period, R is the feedback resistor at inverting terminal, C is the capacitor, R_1 and R_2 are the feedback resistors at the non-inverting terminal, and f is the wave frequency. Setting R1 and R2 to be an equivalent value of 220 kΩ and using a 100nF capacitor, the Resistor values were found using this equation:

Table 1: Measured Values of Resistance for Every Synthesizer Button (Frequency).

Key/Note	C4	C#4	D4	D#4	E4	F4	F#4	G4	G#4	A5	A#5	B5	C5
Known Frequency (Hz)	262	277	294	311	330	349	370	392	415	440	466	494	523
Resistor Value (kΩ)	17.4	16.4	15.5	14.6	13.8	13.0	12.3	11.6	11.0	10.3	9.76	9.22	8.70

The schematic for the synthesizer circuit is given in figure 1, below. The potentiometer, R3, and the resistor, R4, are meant to represent the resistance of the individual buttons found in table 1, with the potentiometer being used as an adjustable resistor. During soldering, the button outputs were all connected to a single node and the resistor branch inputs were all connected to a separate node in order to simplify the signal transmission. It is very important that a voltage follower is used at the output of the oscillator because any imposed impedance from other circuit components will have detrimental effects on the frequency that is output. At the voltage follower output, a potentiometer that is connected to ground can be used to adjust the volume of the speaker because the voltage at the middle terminal is the input voltage to an AB class amplifier. The output of the class AB amplifier is used to directly power the speaker depending on the voltage supplied by the potentiometer voltage divider network. In order for everything to work correctly, the circuit requires a bi-polar supply voltage of at least ±9V and for someone to press a key to complete the connection between the inverting terminal feedback loop.

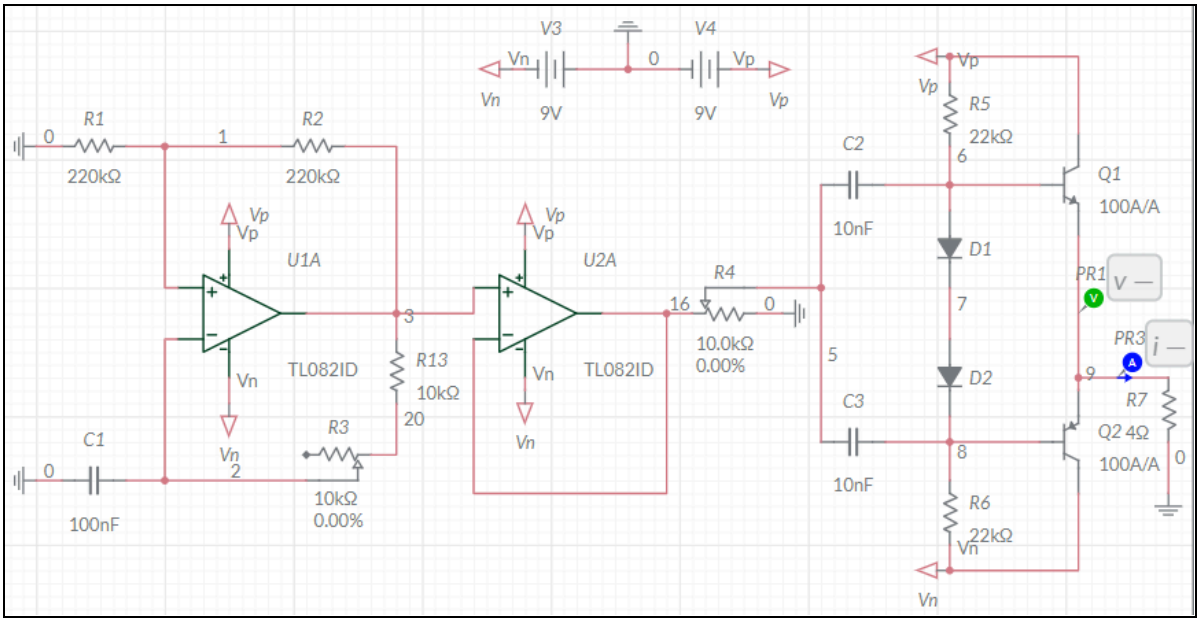

Figure 1: Synthesizer Circuit Schematic.

For a more intuitive understanding of the signal transmission inside of the synthesizer, the block diagram of figure 2 describes the relationship each component has with the other components involved. The diagram breaks down the synthesizer into different stages that correspond to different components that are shown in figure 1. The block diagram makes it much more obvious that the only external factors that contribute to the synthesizer operation are the power supply and user input. Likewise, the block diagram gives a more logical interpretation of the signal as it is transmitted from one stage to another and the effects of each stage on the final output. It should be much more obvious from the block diagram that the choice of resistor branch for the oscillator's feedback is a direct determinant of the music pitch played by the speaker as no other stages have any effect on the signal frequency.

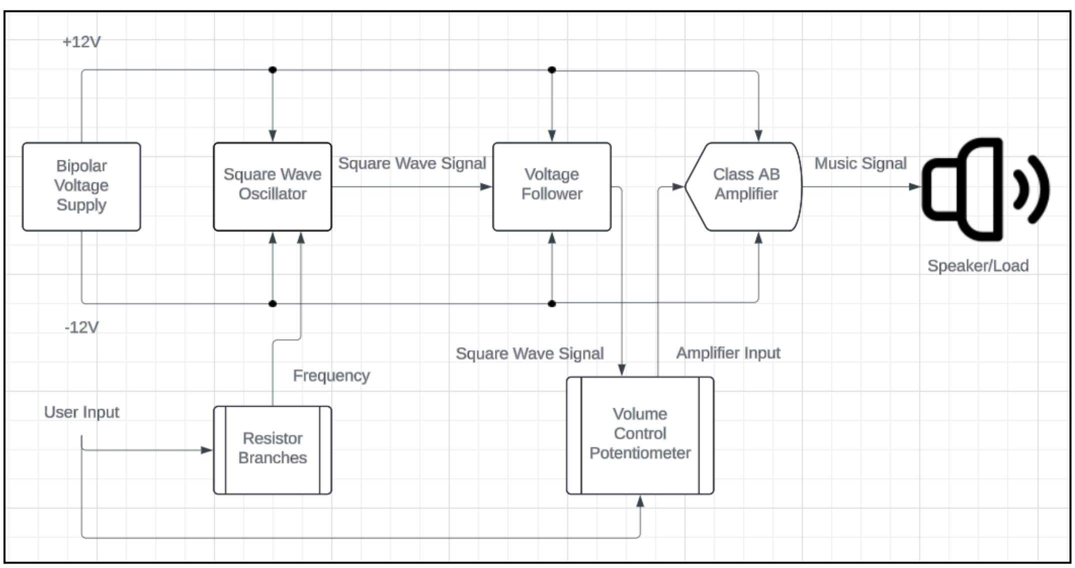

Figure 2: Synthesizer Block Diagram.

Testing and Measurements

To begin testing the synthesizer, the voltage waveforms of the non-inverting, inverting, and output terminals of the op-amp were all measured simultaneously for every single button option. A few examples of the oscillator output can be seen in figures 3, 4, and 5, with figures 3 and 5 being the lowest and highest frequencies the oscillator can produce, respectively. As the oscillator produces a waveform as a result of op-amp saturation from a feedback loop, one should expect to find the values of the output terminal to always be either the minimum or maximum saturation voltage of the op-amp depending on the state it is in. Note: The yellow waves represent the non inverting input, the green waves represent the inverting input, and the blue wave represents the op-amp output.

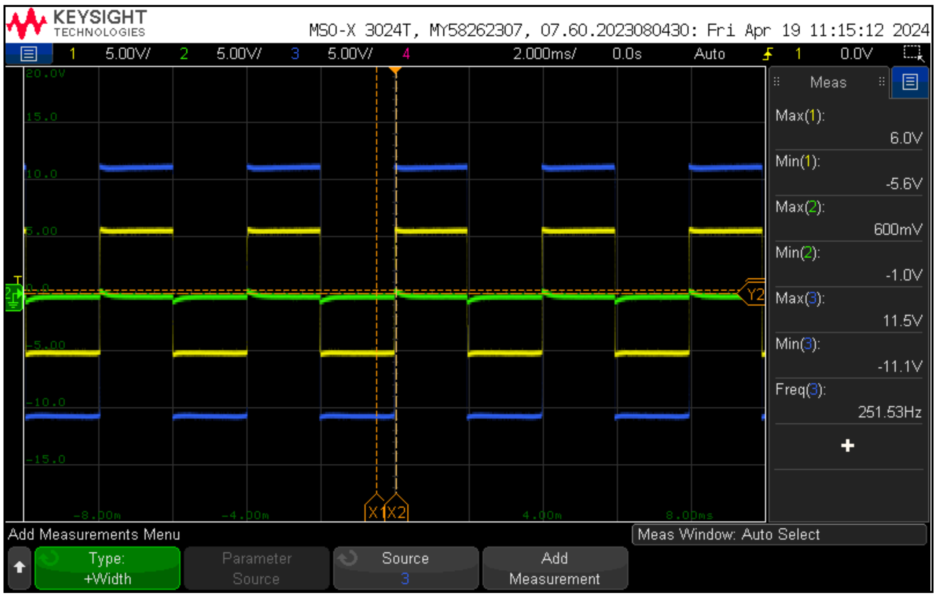

Figure 3: Oscillator Input and Output Terminal Waveforms (C4).

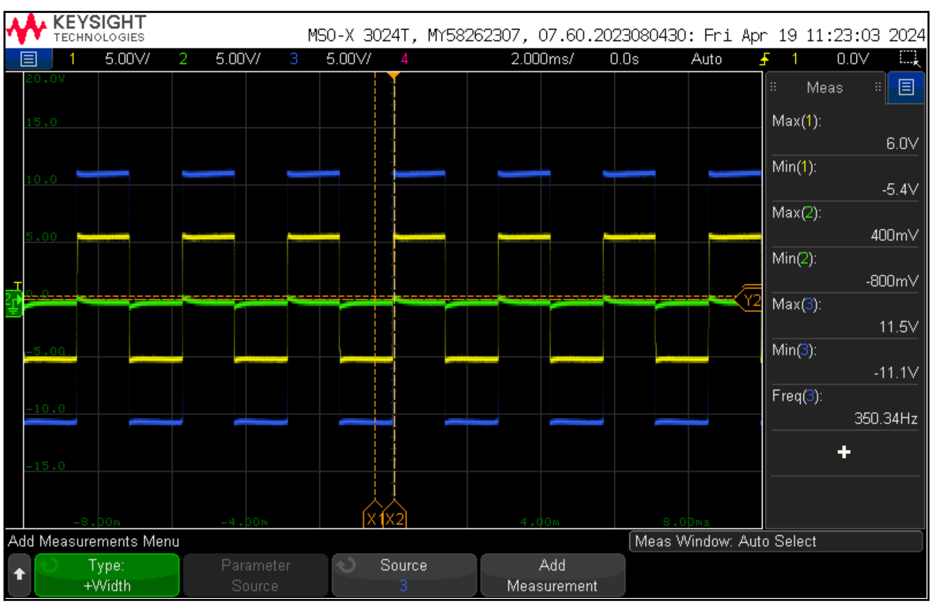

Figure 4: Oscillator Input and Output Terminal Waveforms (E4).

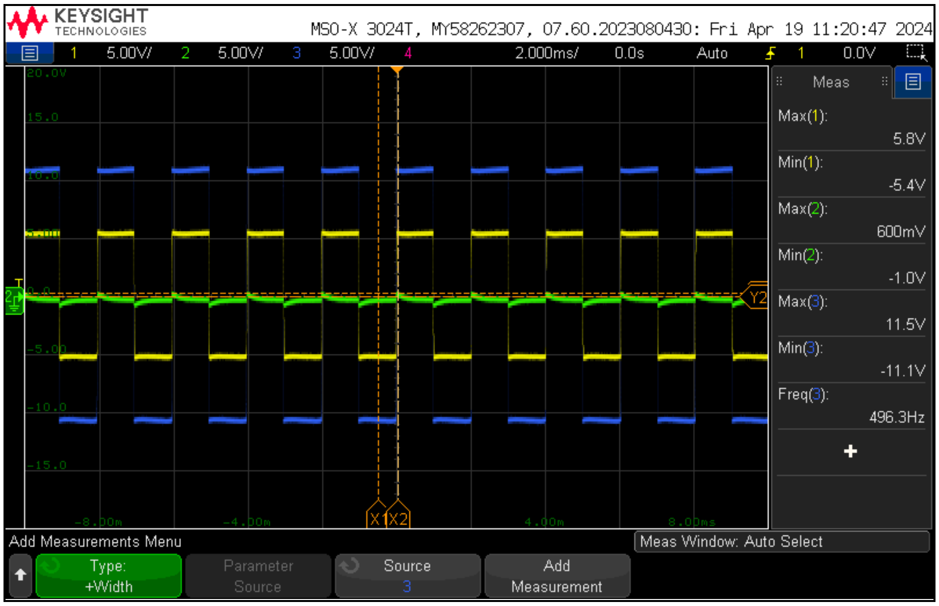

Figure 5: Oscillator Input and Output Terminal Waveforms (C5).

From the given waveforms, it is clear that the op-amp is fully capable of generating an AC signal across a set of specified frequency values as intended. Figures 3 and 5 in particular show that the frequency can be much different depending on the button that is pressed, because of the difference in resistance changing the RC time constant. The full compilation of frequencies that the synthesizer can produce based on what button (note) is pressed is given in table 2, below.

Table 2: Measured Values of Frequency for Every Synthesizer Button.

Key/Note	C4	C#4	D4	D#4	E4	F4	F#4	G4	G#4	A5	A#5	B5	C5
Known Frequency (Hz)	262	277	294	311	330	349	370	392	415	440	466	494	523
Recorded Frequency (Hz)	252	266	279	298	312	334	350	502	394	417	442	497	496

Using the values from table 2, a model of the recorded vs ideal frequencies has been plotted for a more visual representation of the synthesizer output, shown in figure 6. The model makes it obvious to see that the synthesizer unfortunately does not realize the most ideal conditions. Even though almost all frequency values fall within 5-6% error, the signal for G4 demonstrates over 28% deviation from the ideal scenario which is too great to be considered negligible. This deviation could be the result of incorrect resistor values or possibly the result of an incorrect connection in the circuit.

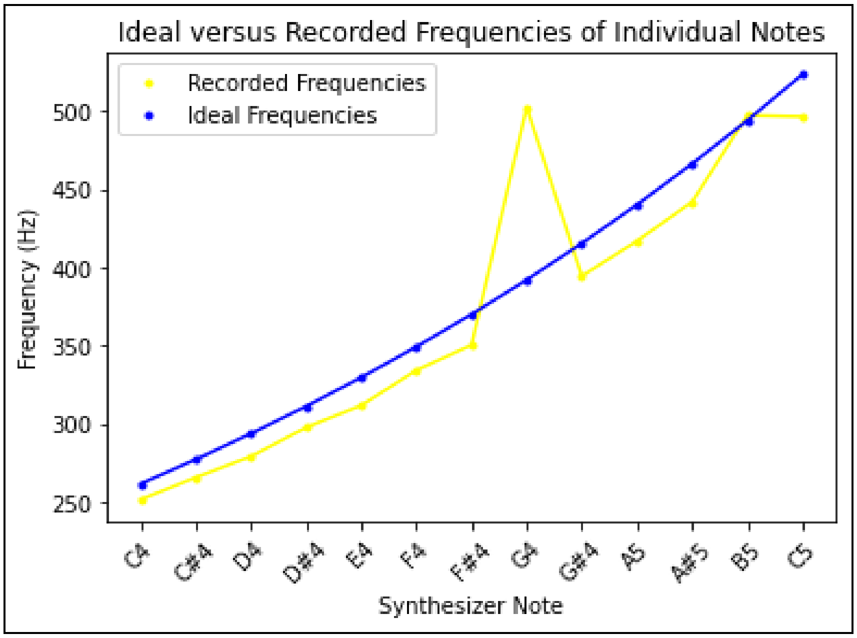

Figure 6: Oscillator Ideal vs Recorder Output Frequencies by Key.

Now, it is important to verify that the voltage follower is acting as it should, otherwise the final output could be incorrect. The voltage followers function was observed by probing the non-inverting input and output of the op-amp used. Note: The yellow waves represent the non inverting input and the blue wave represents the op-amp output.

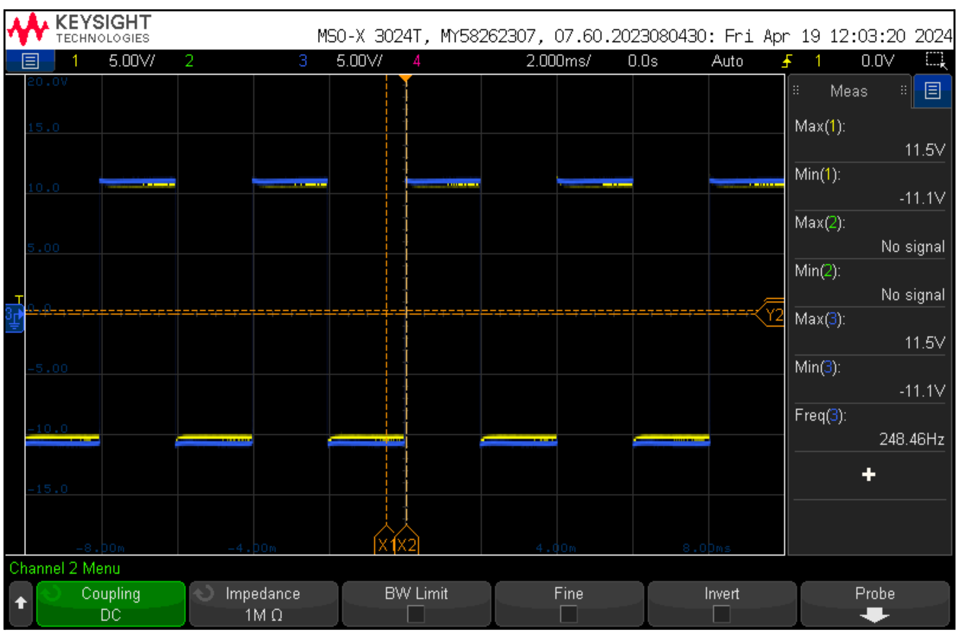

Figure 7: Voltage Follower Input and Output Waveforms.

From the given waveforms of figure 7, the non-inverting input and output of the op-amp are the exact same signal. Clearly, the voltage follower is functioning exactly as intended based on the evidence that is provided.

In order to demonstrate that the class AB amplifier is functioning, the voltage that is in the middle of the potentiometer voltage divider and the output voltage are observed. The amplifier is a crucial component in this circuit, as speakers are known to have high power draw and op-amps are not strong current sources. In order to source enough current, very strong transistors (TIP3055 - TIP2955) were used to compensate for the low saturation voltage and provide enough power. Figures 8, 9, and 10 showcase the amplifier input and output voltage waveforms. Note: The yellow waves represent the amplifier input (or voltage divider potential) and the blue wave represents the amplifier output.

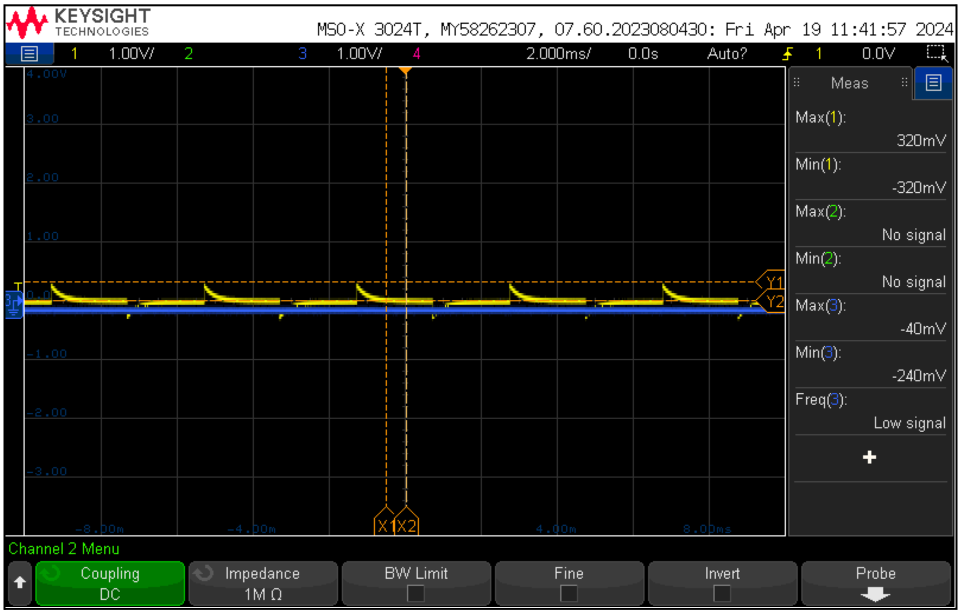

Figure 8: Class AB Amplifier Input and Output Waveforms.

Figure 8 shows that when no input is present to be amplified, the output is null or negligible. This means that when the potentiometer swiper is connected to ground, the speaker must have no output.

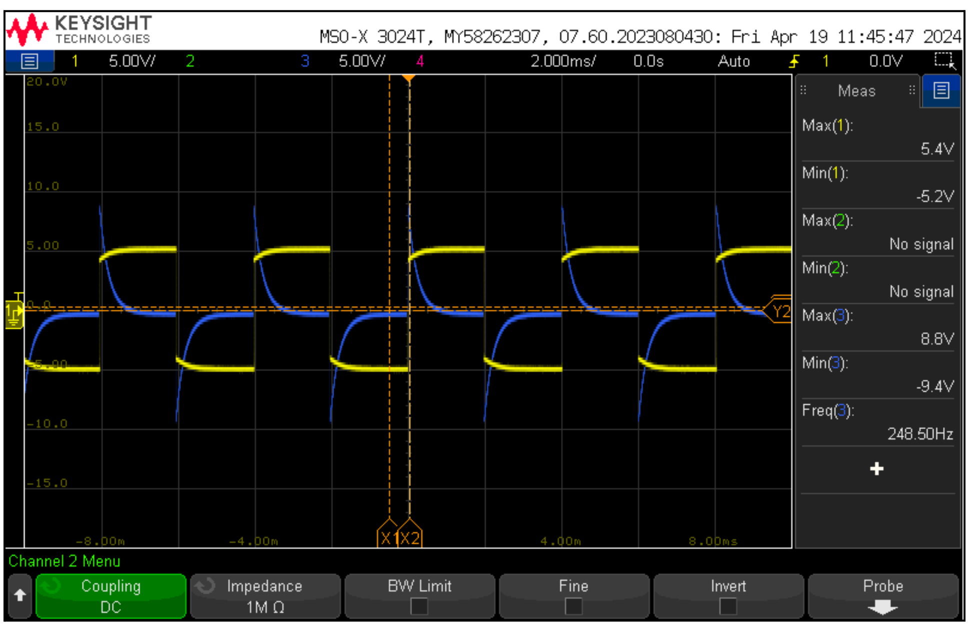

Figure 9: Class AB Amplifier Input and Output Waveforms.

Figure 9 in particular shows that the input can be amplified to a much larger value as a result of the biasing voltage.

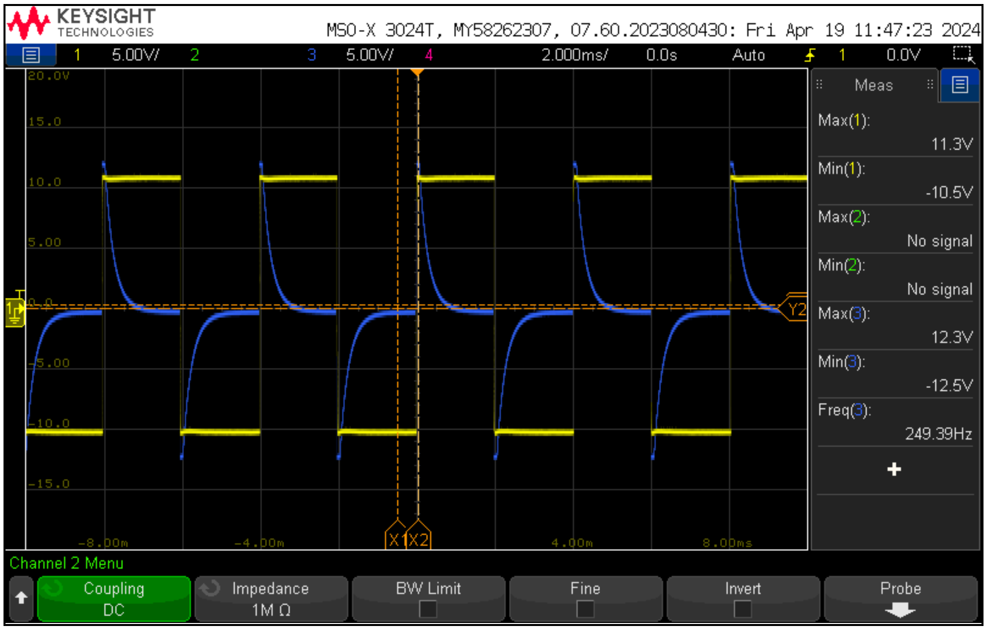

Figure 10: Class AB Amplifier Input and Output Waveforms.

Figure 10 shows that the amplifier is incapable of producing an output that is greater than the supplied biasing voltage, which makes sense. Clearly, from the given waveforms the amplifier is fully capable of amplifying an AC signal as intended. The full compilation of voltage values that the amplifier can produce based on what voltage is input is given in table 3, below.

Table 3: Measured Values of Voltage at Amplifier Input vs Amplifier output with no Speaker.

~ Resistance From Divider to ground (Ω)	0	1k	2k	3k	4k	5k
Voltage Divider - Amplifier Input without speaker (V_{pp})	0.320	1.41	3.78	5.40	8.80	11.3
Voltage At Amplifier Output without Speaker (V_{pp})	0.04	2.29	6.19	8.80	12.3	12.3
Voltage Divider - Amplifier Input with speaker (V_{pp})	0.8	1.41	3.86	5.07	8.6	11.5
Voltage At Amplifier Output with Speaker (V_{pp})	0.04	1.73	4.02	5.07	9.4	11.5

Using the values from table 3, it is obvious that the amplifier is properly amplifying signals up until the bias voltage limit is reached. It is interesting to note, that when the load is attached there seems to be less voltage amplification than when the circuit is unloaded. That is likely a direct result of the speaker being a 4 Ω load, which would mean the transistor would be sourcing a lot of current. Using Ohm's law, it can be determined that the current through the speaker at minimum and maximum input voltage would be 10 mA and 2.88 A, respectively. This would mean that at minimum and peak load the speaker would be using up 400 μW and 33.1 W respectively. Considering that the speaker used for the synthesizer is a 10W RMS speaker, these are very reasonable power ratings.

Conclusions

Overall, the project was a very successful endeavor that helped to demonstrate only a few of the concepts that were taught in class. Requiring only a bi-polar power supply to operate, the synthesizer was able to produce a very solid selection of frequencies to choose from. Each component stage that was implemented seemed to be within acceptable margins, which indicates that a sufficient knowledge of analog electronics was employed in the circuit design.