Analog Synthesizer: Functional Description

Documentation and Technical Information

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Abstract

This analog audio synthesizer consists of a keyboard controller paired with several modules including a voltage controlled oscillator (VCO), low frequency oscillator (LFO), attack-decay-sustain-release (ADSR), voltage controlled filter (VCF) and voltage controlled amplifier (VCA). The device was shown to be capable of processing a variety of sounds using several control voltages which interface with the different modules. The modular devices were housed in a 15”x9”x3” aluminum case with a +15/-15 V power supply. External potentiometers allow a user to modulate different parameters of the modules. The synthesizer shows full functionality and is capable of producing a variety of interactive sounds.

Introduction

Analog synthesizers play an important role in a variety of contemporary music applications. While much of new music technology is devoted to digital signal processing and computer based applications, analog synthesizers still maintain a strong presence in contemporary music due to the aesthetic characteristics of analog sound. Therefore, there is still a sizable, consumer market for such devices.

The device examined in this paper focuses of the modularity of synthesizer design. This modular approach allows a user to generate a variety of audio signals, expanding the sonic potential for musical expression. At the heart of analog synthesizer design is the presence of control voltages. These voltages allow the modules to communicate with one another and enable the synth to generate several different types of modulation (including amplitude modulation (AM) and frequency modulation (FM)). For the most part, this control voltage is normalized to be within a -5 to 5 V_{pp} range. Furthermore, modules either produce a control voltage or process an input control voltage to send to another module. Control voltage can also be processed and *fedback* to earlier modules in the signal chain form feedback systems.

There were several project objectives for the design of the synthesizer as a whole. Most importantly, the keyboard controller, VCO, LFO, ADSR, VCF and VCA must be capable of interfacing with one another. The synthesizer should be compatible with standard keyboard speakers (e.g. LINE level, powered speakers). Lastly, the keyboard should be capable of maintaining an accurate pitch relative to a standard, western-music tuning. Additionally, each of the individual modules contains their own specific design objectives.

This paper examines the technical considerations involved in the design of such a device. The report begins with a *Methodology* section that describes the design process and general operation of the devices. Following the methodology, a *Results* section presents the outcomes of the project in terms of technical criteria and project goals. Lastly, A *conclusion* section interprets the experimental results and relates them to the design criteria.

Methodology

Due to the modularity of the devices, each device was designed independently from the others. Once the input and output voltage characteristics could be established, the modules could be designed to interface with one another. Similarly, each module could be tested independently (using waveform generators or voltage sources as signal inputs) and then re-tested while connected to one another. In general, each module was constructed and simulated with PSPICE software before proceeding to the implementation stage. Therefore, this section will first examine the synthesizer design on a macro scale and then proceed to a more in-depth discussion of each module independently. This will include commentary relating to the engineering design, construction, operation and technical considerations relative to each module.

Figure 1 shows a high-level block diagram for the synthesizer system.

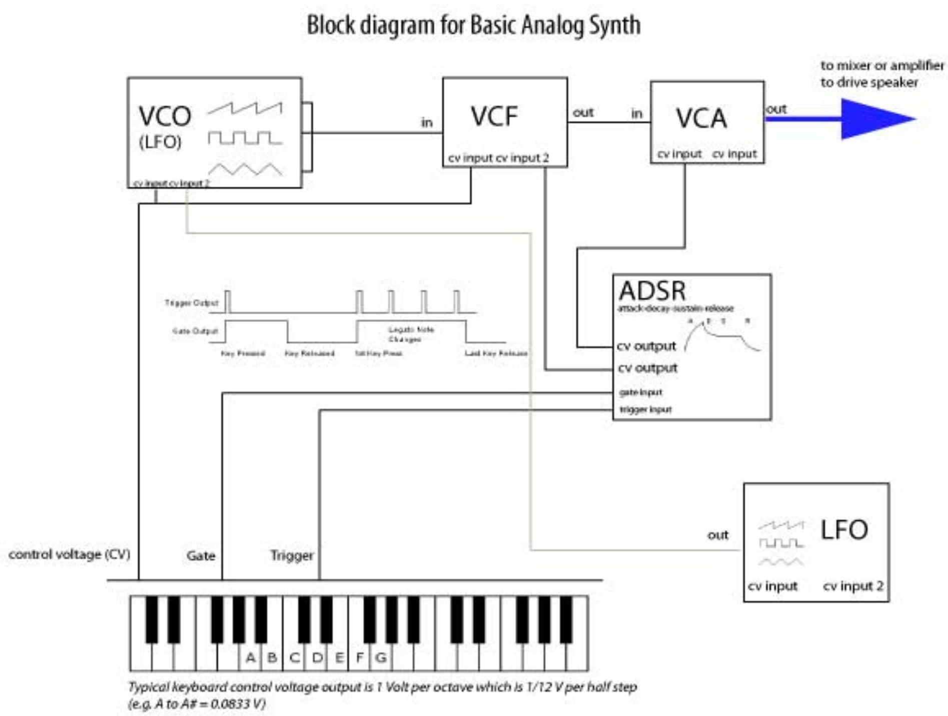

Figure 1 - Synth Block Diagram

This block diagram shows a basic module-inclusive signal path for producing sound from user input. More importantly, this diagram shows the output of the gate and trigger signals and their connections to the other modules. This will be further explored in the keyboard controller commentary. Additionally, the ADSR block illustrates the control voltage contour of its output. This module is generally connected to the VCF or VCA to modulate one of their parameters. The LFO is included in the VCO block because it performs the same type of function as the VCO. Figure 2 shows the functional decomposition of the synthesizer.

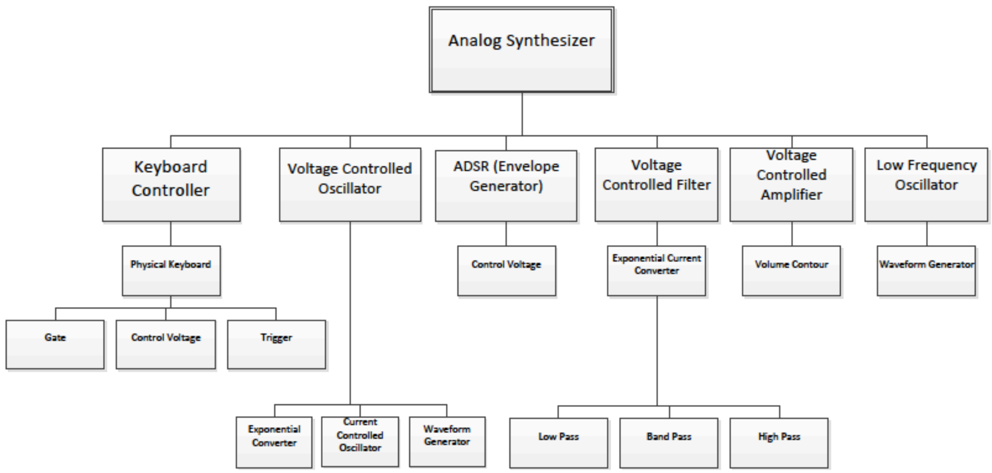

Figure 2 - Functional Decomposition

This diagram illustrates several more of the modules' parameters.

Keyboard Controller Description

Each key that is hit closes a different switch in the resistor chain, thus providing a different voltage control voltage from the voltage divider. A 5 V pulse with a period of 2.5 ms is generated from the 555 to act as a trigger output, which is sent to the ADSR. A gate voltage is also generated and outputs a constant 5 V while any key is held down. When the gate ends, it signals the ADSR to go into decay mode.

The voltage controlled oscillator (VCO) is the main tone generating module of the synthesizer. It will generate three output waveforms at a frequency controlled by the voltage sent from the keyboard controller. Along with the control voltage, the VCO contains three additional inputs that permit frequency modulation of the output waveforms. The final waveforms are sent to other modules to modify amplitude and harmonic content. The VCO also offers initial frequency adjustment from the coarse and fine tuning potentiometers. The control voltage, along with the fine, coarse, and exponential FM signals are all mixed using a voltage summing circuit. The voltage accumulated at the output of this summer is used to drive a pair of emitter tied PNP transistors. These transistors are used to produce a current that is exponentially related to the control voltage. This portion of the VCO is known as the exponential converter. The reason for this circuit is to accomplish a doubling of frequency for every 1V increment of the control voltage. **Figure 4** illustrates the exponential conversion portion of the VCO. The trimmer potentiometer connected to the base of the second transistor is used to control the voltage seen at the base. It is used to adjust the voltage increment per octave. The schematic below also shows a second modulation input, which provides a linear frequency modulation to the output waveforms. This signal is mixed in at the second op-amp, which is used in this configuration to set reference levels for the current converter. The following equations define the reference and maximum current levels for the converter.

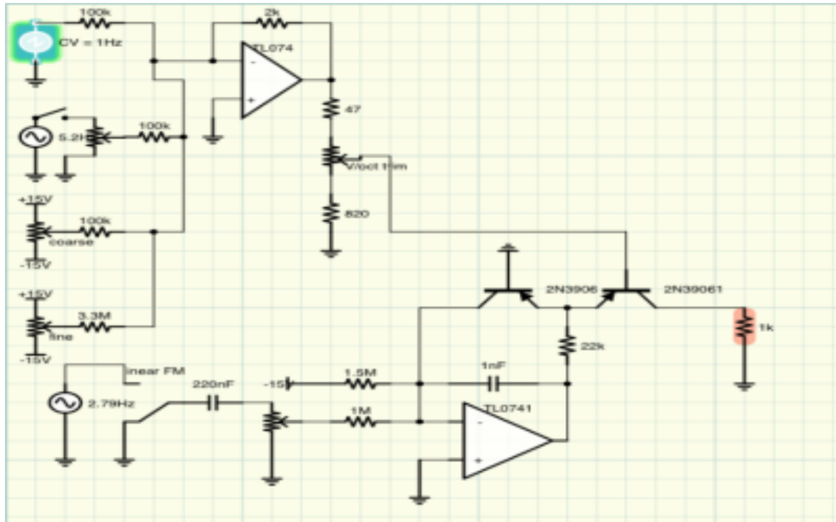

Figure 3 - Exponential converter

The simulation of the exponential converter is shown in *Figure 5* below. Here, the control voltage input is fed with a 0V to 4V ramp wave at 300Hz (green). The red waveform is the current at the collector of the second PNP transistor. Though the CV will be a DC voltage, this simulation illustrates the exponential rise in current compared to the linearly increasing control voltage.

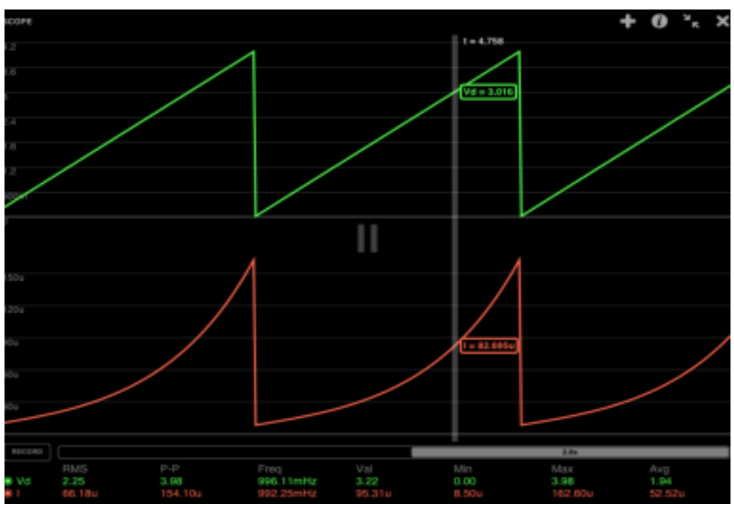

Figure 4 - Exponential Converter Simulation

The current generated in the exponential conversion portion of the VCO is sent to bias an operational transconductance amplifier (OTA). The OTA is used as a controllable resistor that varies the current flowing into an integrator. The output of the integrator is produces the triangle wave for the VCO.

This portion of the VCO is called the current controlled oscillator. The oscillation is generated by the emitter-coupled Schmitt trigger in the right half of the circuit in **Figure 6.**

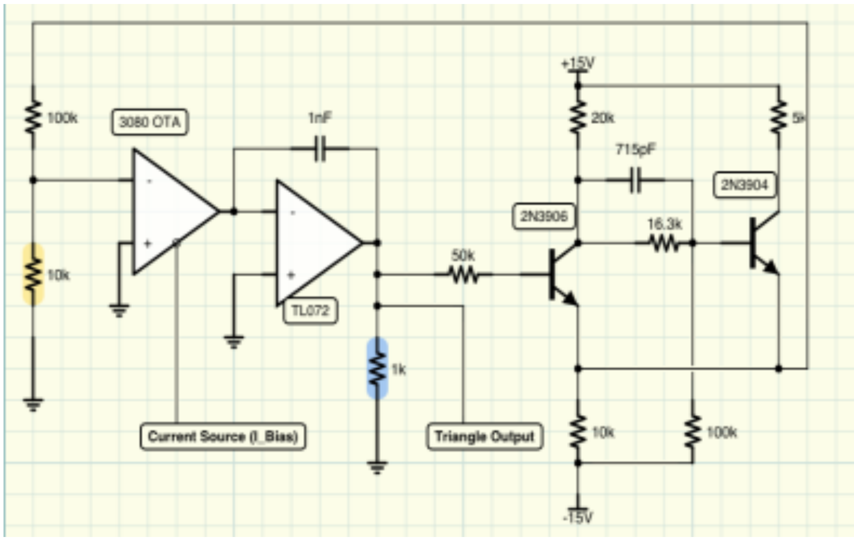

Figure 5 - Schmitt Trigger

This is a bistable oscillator circuit that changes between to states based on the input threshold level. These threshold levels are determined by the following equations.

$$V_{HT} = \frac{R_E}{R_E + R_{C2}} V_+ \qquad [3]$$

$$V_{LT} = \frac{R_E}{R_E + R_{C1}} V_- \qquad [4]$$

The Schmitt trigger circuit produces a square wave that is feed back to the integrator to produce the triangle waveform. The threshold levels were calculated to be +/- 5V. The current controlled oscillator portion of the VCO generates an oscillatory wave that is then converted to a sine and pulse waveform output. **Figure 7** shows the simulation results of the current controlled oscillator portion of the VCO. The yellow square wave shows the output of the Schmitt Trigger that is feed back to the integrator, which produces the triangle output waveform.

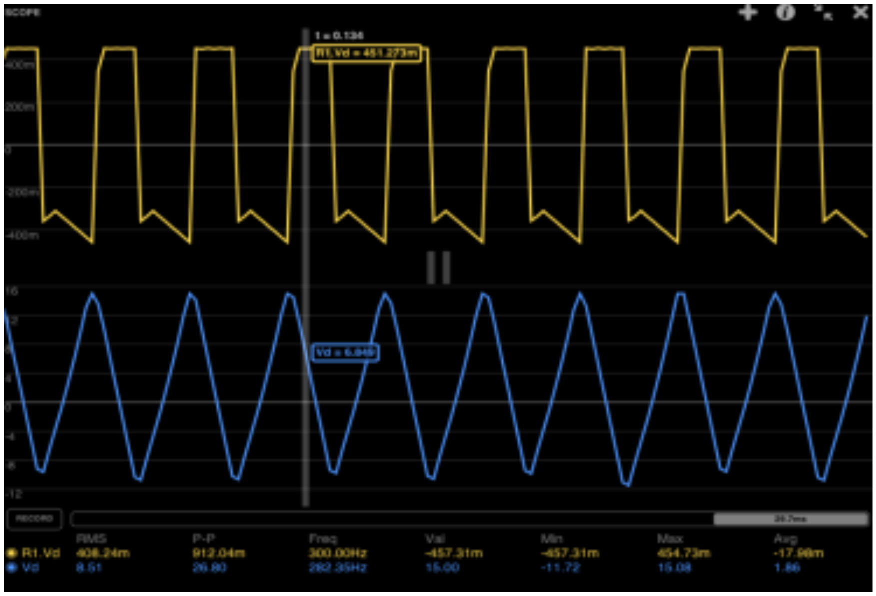

Figure 6 - Current Controlled Oscillator Simulation

The op-amps used for these circuits were generic LM741s. The OTA used was a 16-pin LM13700, which provided dual OTAs. The final portion of the VCO consists of the waveform conversion circuitry. The triangle output was feed to the base of the 2N3904 NPN transistor. These transistors are purposefully overdriven into the nonlinear operation region. This circuit approximates a sine wave, which also includes potentiometers for peak roundness and symmetry trim.

The collectors of the differential transistor pair are sent to another LM741 differential amplifier. This produces a better approximation to the desired sine wave output. The sine wave is then sent to a comparator op-amp configuration. The sine wave is feed into the non-inverting terminal of the op-amp, while the inverting terminal is held at a constant DC voltage. This causes the output to switch between high and low level outputs. The pulse width modulation input is also summed into the comparator using another LM741 op-amp. **Figure 8** illustrated the waveform conversion circuitry described here. This circuit also contains a potentiometer to adjust the initial pulse width of the pulse wave output. It ranges between 10% and 90% duty cycle. The final outputs of these three waveforms were 10 V peak to peak at a frequency dependent on the control voltage. **Figure 9** illustrates the simulation results of the waveform conversion portion of the VCO. It shows all three output waveforms, with the pulse wave output being modulated by a low frequency sine wave. The signals used to modulate the VCO will come from a secondary oscillator with a frequency range of 1Hz to 20Hz.

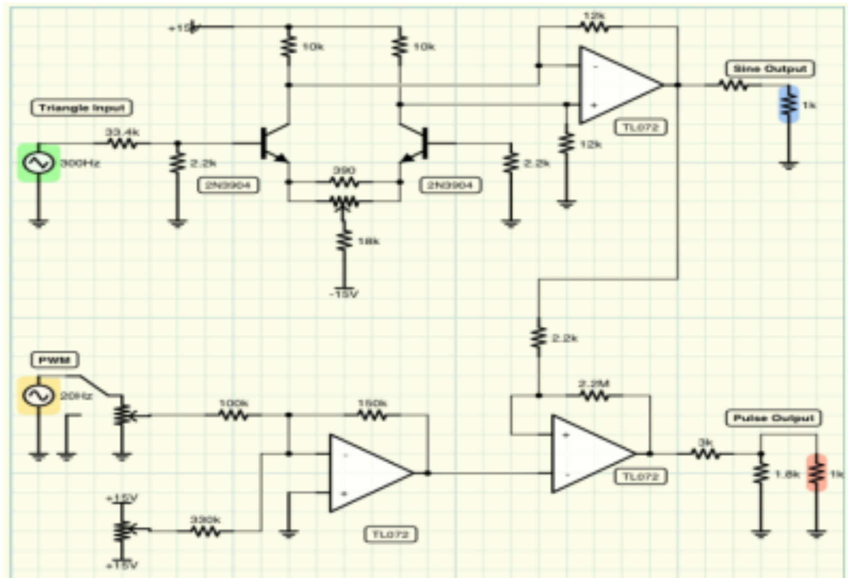

Figure 7 - Waveform Conversion Circuitry

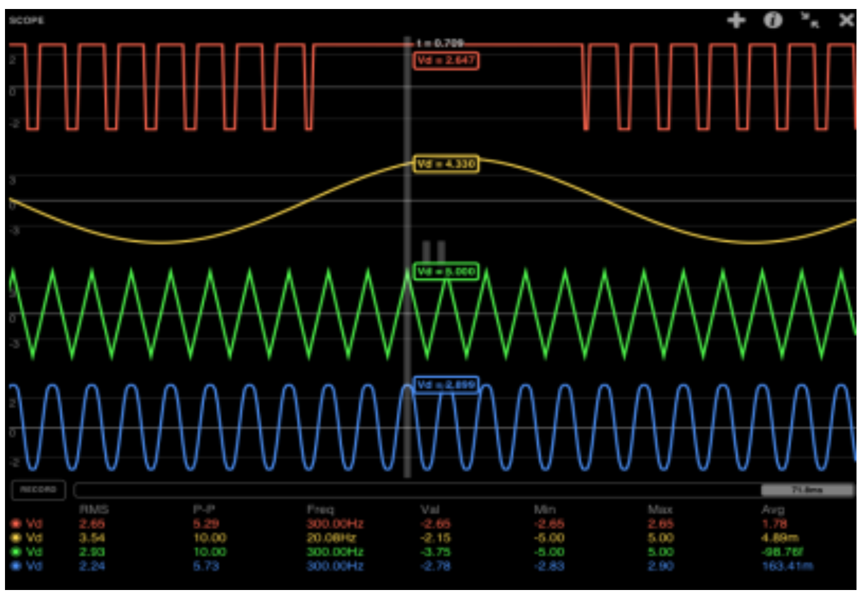

Figure 8 - Waveform Conversion Simulation

The waveform conversion circuitry of the VCO is dependent on the generation of the triangle wave from the current controlled oscillator. Without the triangle waveform, neither the sine nor pulse wave outputs will be generated. The frequency range of the VCO should span the audible range of 100 Hz to 20 kHz, though the fine and coarse frequency adjustment allow for the frequency range to extend up to 70 kHz.

The low frequency oscillator (LFO) module is the secondary oscillator used to either amplitude or frequency modulates other modules of the synthesizer. Its operation frequency range is from 1Hz to

20Hz. It has one potentiometer to adjust the frequency of the three output waveforms. This LFO is designed to output a triangle, sine, and square waveforms. This simple circuit includes three LM741 operation amplifiers, as well as two 1N914 diodes. **Figure 10** below illustrates the circuit schematic of the LFO.

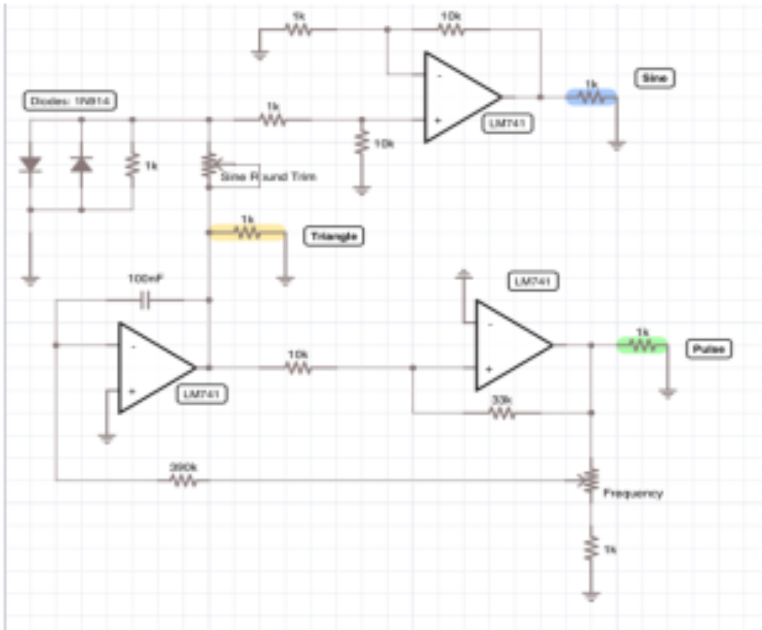

Figure 9 – LFO Circuit Schematic

The LFO circuit works in a similar fashion to the VCO oscillatory circuit only without any inputs to modulate the frequency. The op-amp with the feedback capacitor controls the frequency range of the outputs. The LM741 comparator op-amp with positive feedback is a Schmitt trigger that changes the output between high and low level outputs depending on the threshold level seen at the input. This is what generates the square wave output. The two parallel diodes are used to round the peaks of the triangle wave, which allow for the sine wave output to be generated. The third op-amp is a simple inverting amplifier that amplifies the sine wave to 10V peak to peak amplitude. The trimmer potentiometer in this configuration also allows for the roundness of the sine wave to be initially adjusted. These output wave forms can be patched to the VCO FM inputs, the VCF envelope input, or the VCA envelope input.

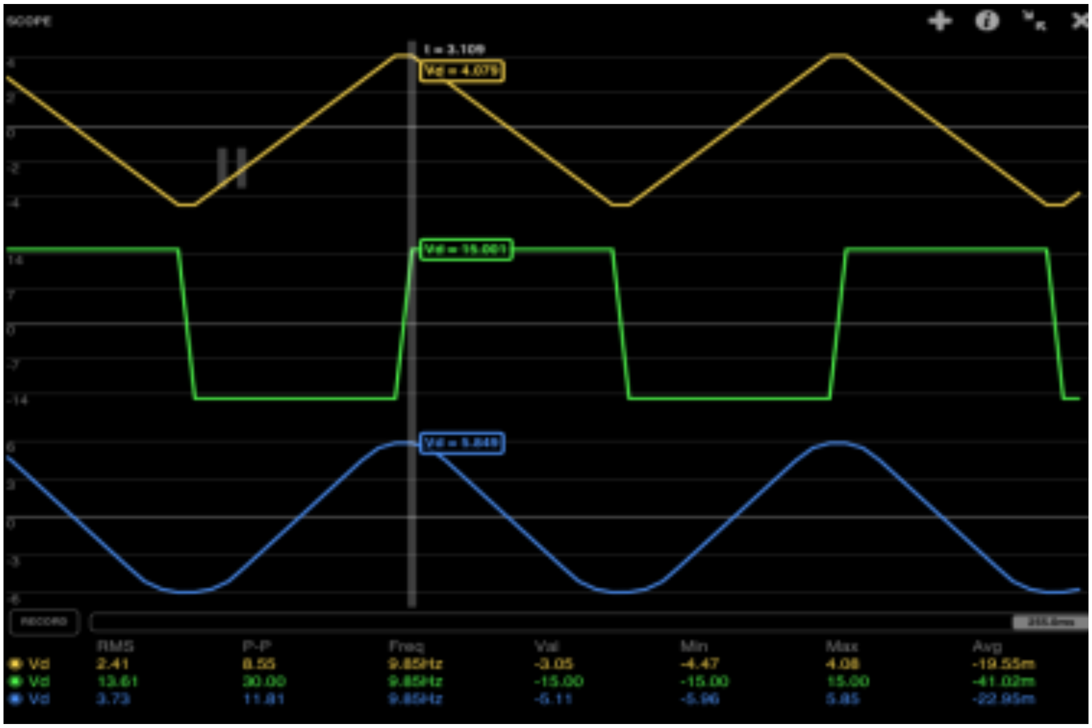

Figure 10 - LFO Waveforms

The VCF makes use of a state variable voltage controlled filter that has patchable low-pass (LP), band-pass (BP) and high pass (HP) outputs. The filters' cutoff frequency is controlled by *1V/OCT* input, an *envelope* input, and *COARSE* and *FINE* potentiometers. The cutoff frequency control converts the 1V/OCT voltage signal (via two matched npn transistors: 2N3906 Transistors) to an exponential current which is then routed to the two operational transconductance amplifiers (OTA, CA3080) in the state variable filter. Essentially, this creates a variable resistance at the OTA stages in the VCF which will adjust the cutoff frequency of the filter (or the passband in the BPF). The exponential current converter is shown in **Figure 4**.

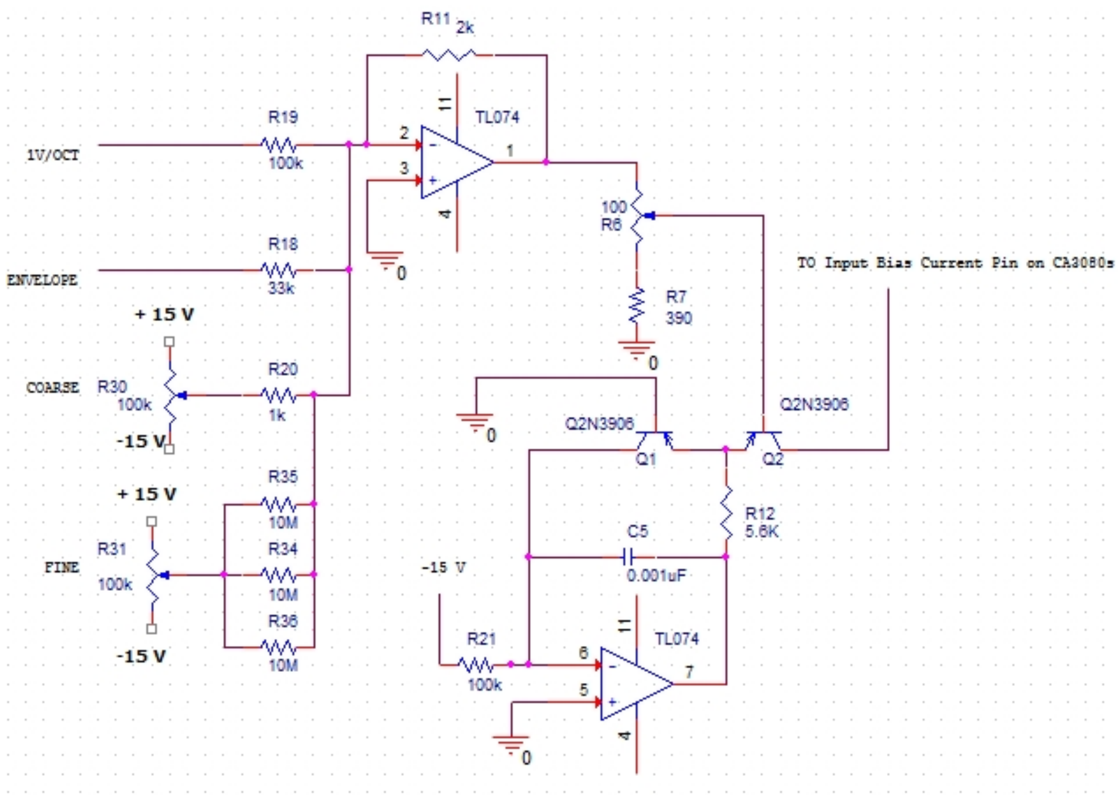

Figure 11 - Exponential Converter

**It should be noted that for the PSPICE schematics, the power pins for the ICs are not shown.*

The current can also be modulated by a time-varying control voltage using the envelope input.

The output current that is sent to the OTA in the VCF could be controlled by setting the R6 potentiometer. This part of the circuit was tested using an ammeter to register the output current and a DC power source controlling the voltage at the 1V/OCT terminal. The output current should increase exponentially with the 1V/OCT input.

VCF

The VCF makes use of a state variable voltage controlled filter that has patchable low-pass (LP), band-pass (BP) and high pass (HP) outputs. The filters' cutoff frequencies are controlled by *1V/OCT* input, an *ENVELOPE* input, and *COARSE* and *FINE* potentiometers. The cutoff frequency control converts the 1V/OCT voltage signal (via two matched npn transistors: 2N3906 Transistors) to an exponential current which is then routed to the two operational transconductance amplifiers (OTA, CA3080) in the state variable filter. Essentially, this creates a variable resistance at the OTA stages in the VCF which will adjust the cutoff frequency of the filter (or the passband in the BPF). The exponential current converter is shown in Figure 4.

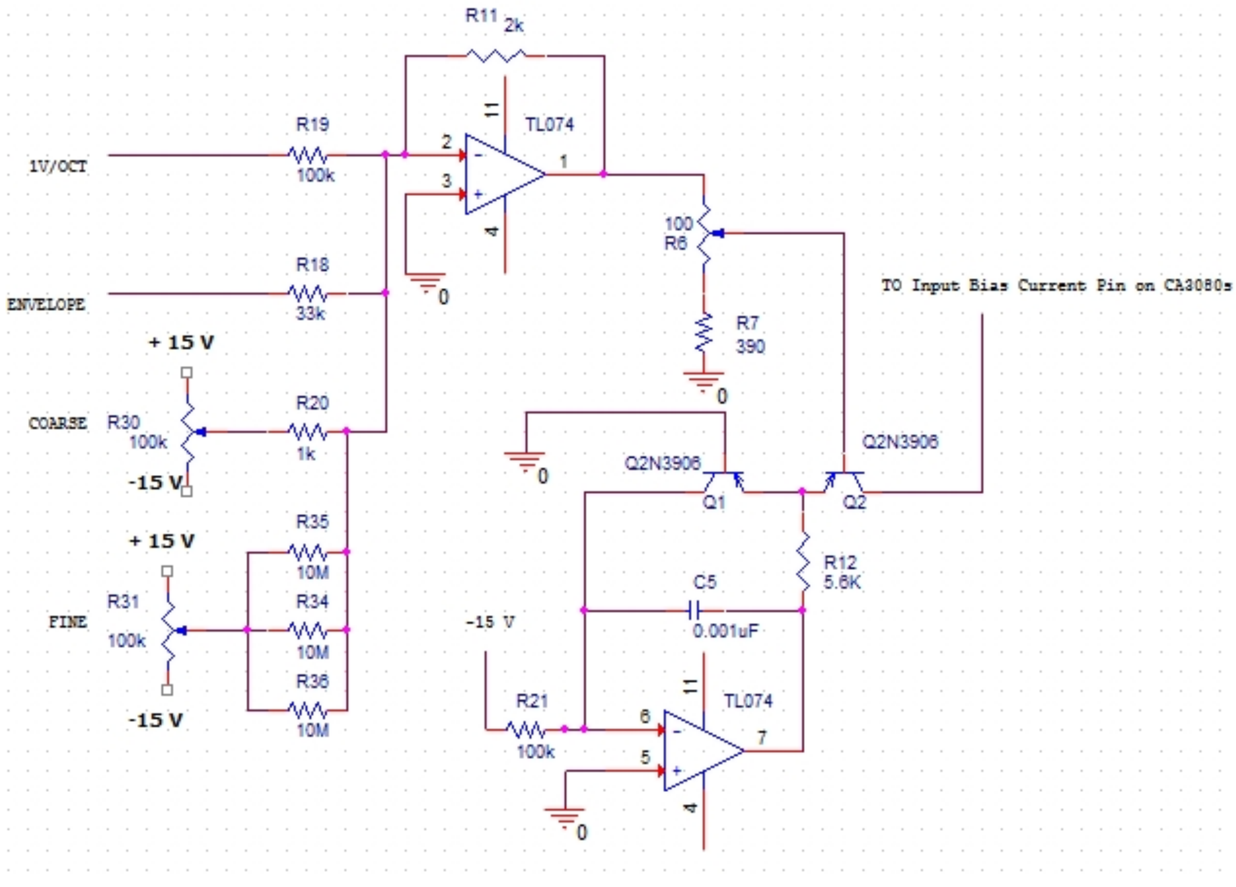

Figure 12 - Exponential Converter

**It should be noted that for the PSPICE schematics, the power pins for the ICs are not shown.*

The current can also be modulated by a time-varying control voltage using the envelope input.

The output current that is sent to the OTA in the VCF could be controlled by setting the R6 potentiometer. This part of the circuit was tested using an ammeter to register the output current and a DC power source controlling the voltage at the 1V/OCT terminal. The output current should increase exponentially with the 1V/OCT input.

Figure 5 shows the VCF portion of the circuit with inputs to the OTAs from the current converter.

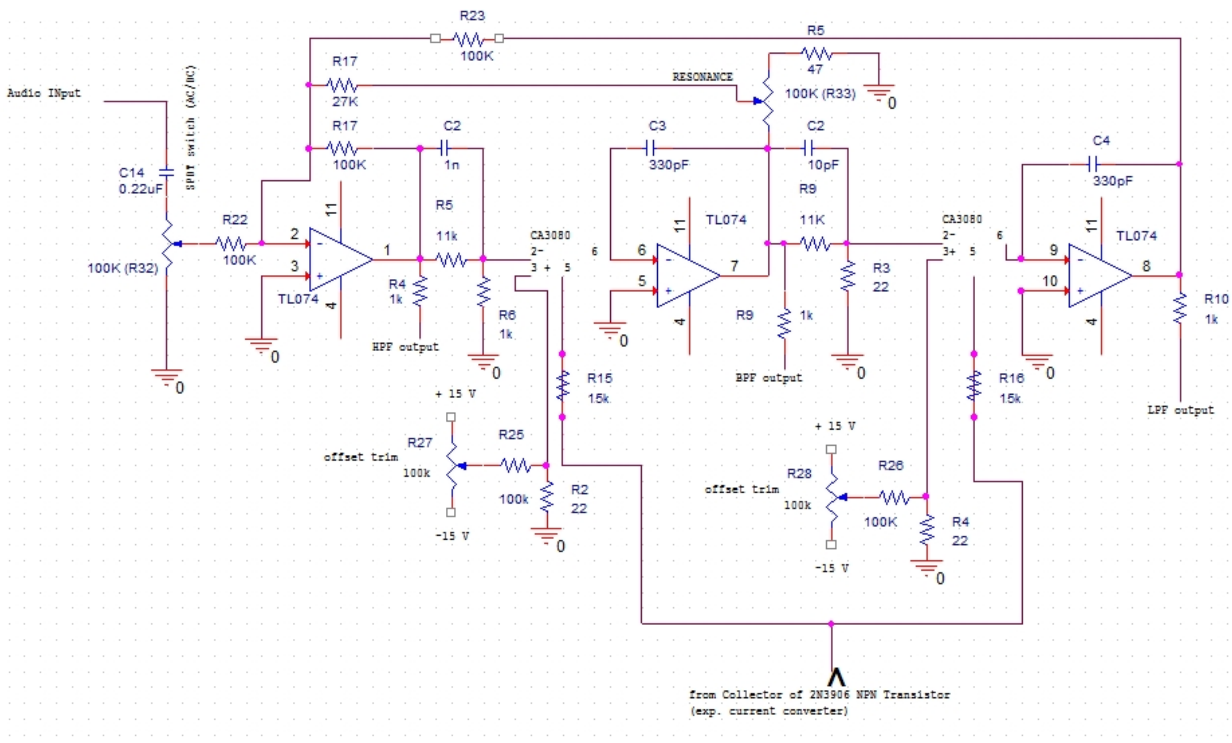

Figure 13 - VCF

The offset trim potentiometers at R27 and R28 set the reference voltage for the CA3080 OTAs. These were set manually to minimize any DC deflection at the outputs.

The main purpose of the VCA is to provide amplitude (volume) control for the synthesizer output. Figure 13 show the schematic for the VCA.

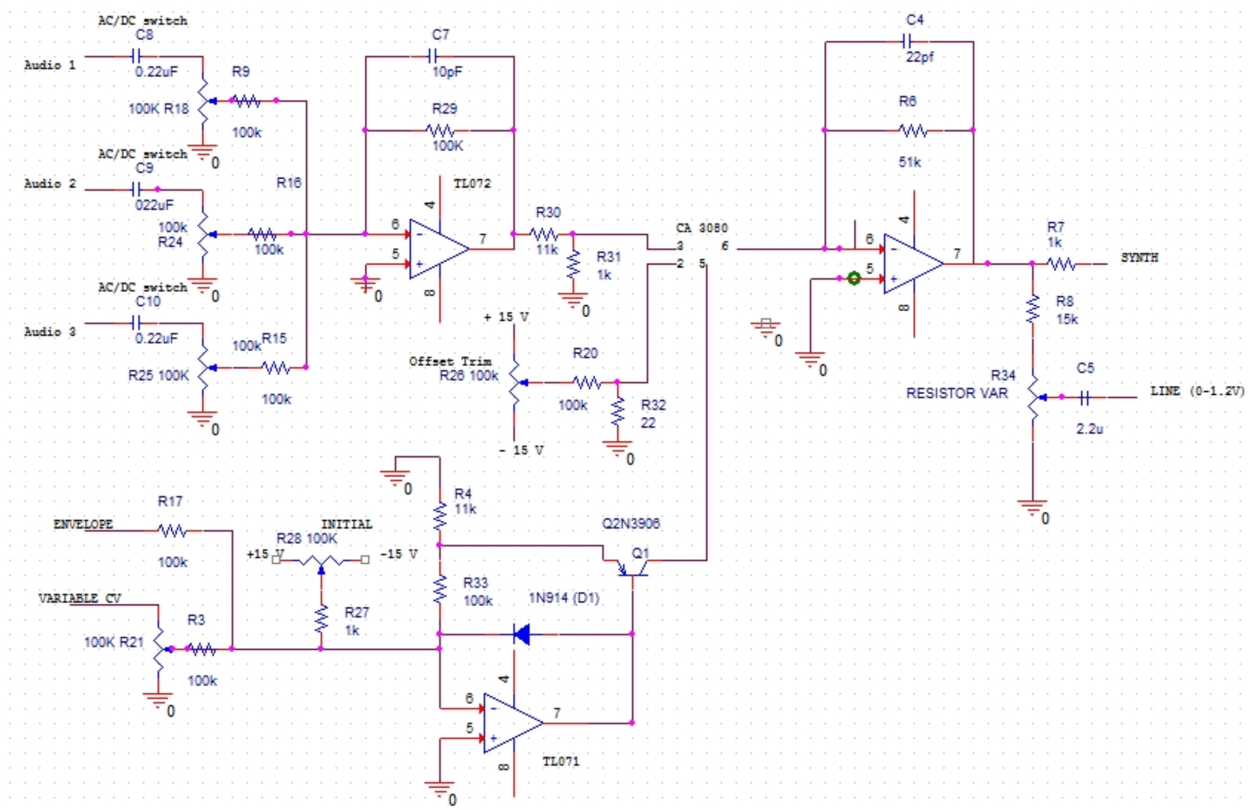

Figure 14 - VCA Schematic

The VCA uses the GATE signal from the keyboard to control when the input audio signal is let through to the output. The VCA also contains an *ENVELOPE* input and a *VARIABLE CV* input so that different waveforms (such as the LFO output) can modulate the amplitude of the output signal. Therefore, this module can amplitude modulate the input audio signal. The VCA contains two patchable output signal, *MAX* and *LINE LEVEL*. The MAX signal can provide a full 10 V_{pp} output while the LINE LEVEL signal provides a 0-1.3 V_{pp} level so that the signal can be routed to other audio equipment such as mixers, audio preamps or powered speakers. The ADSR control voltage can be supplied to the VARIABLE CV input so that the output signal will contain the appropriate attack, decay, sustain, and release time durations. The VCA contains three AUDIO inputs which serve as a simple audio mixer. The AC/DC switches (SPST type) at these inputs allow for the user to select AC or DC coupling per audio input for the signal.

Results

Each module of the synthesizer functioned as anticipated.

The VCO generated a 10 V peak to peak output with different frequencies based on the control voltage given by the keyboard controller. The sine, triangle, and square waves given a constant control voltage can be seen in the figure below.

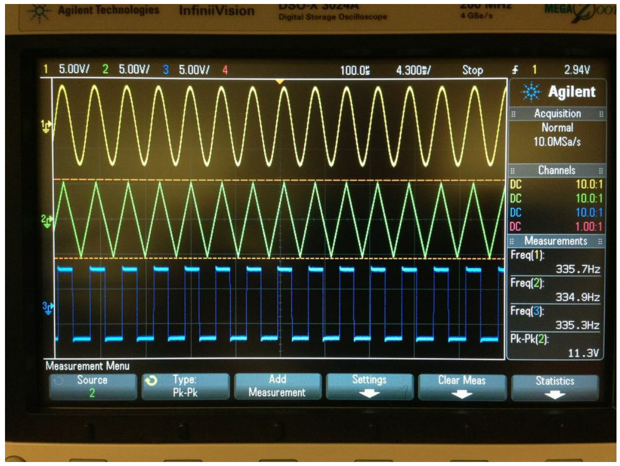

Figure 15 - VCO Waveforms

Although the ADSR did not function as expected, given the unpredictable trigger from the keyboard, it did function properly with a pulse sent from the function generator. The attack, decay, and release time is controlled by the respective potentiometers, as is the sustain level.

The LFO successfully modulated the amplifier and the VCO. Figure 15 below shows a triangle wave output from the LFO modulating the amplifier.

Figure 16 - LFO modulating VCA

The output wave of the amplifier clearly has a triangular envelope. The LFO can also be patched to the FM modulation envelope of the VCO. The triangle wave output of the FM modulated VCO is shown below in Figure 16.

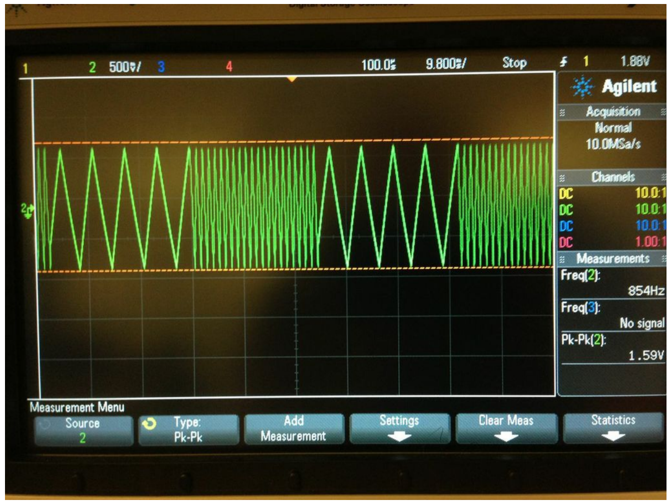

Figure 17 - LFO Modulating VCO

All of the filter outputs were capable of appropriately filtering an input signal. Figure 17 shows the 3 dB cutoff frequency point of the LPF with an 11.3 V_{pp} sine wave being fed to the audio input.

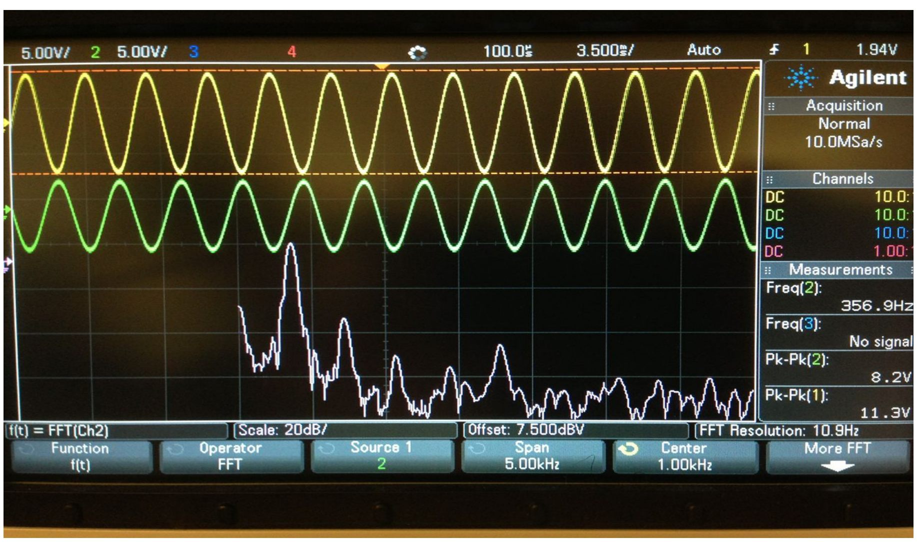

Figure 18 - Low Pass Filter of Sine Wave

The output of the LPF is approximately 0.707 of the peak-to-peak input voltage. Also, shown in this Figure is the FFT spectrum of the signal that was generated from the Agilent 3024A oscilloscope. It clearly shows a prominent spectral peak at the fundamental frequency (357 Hz). Similarly, Figure 18 shows a triangle wave being low pass filtered.

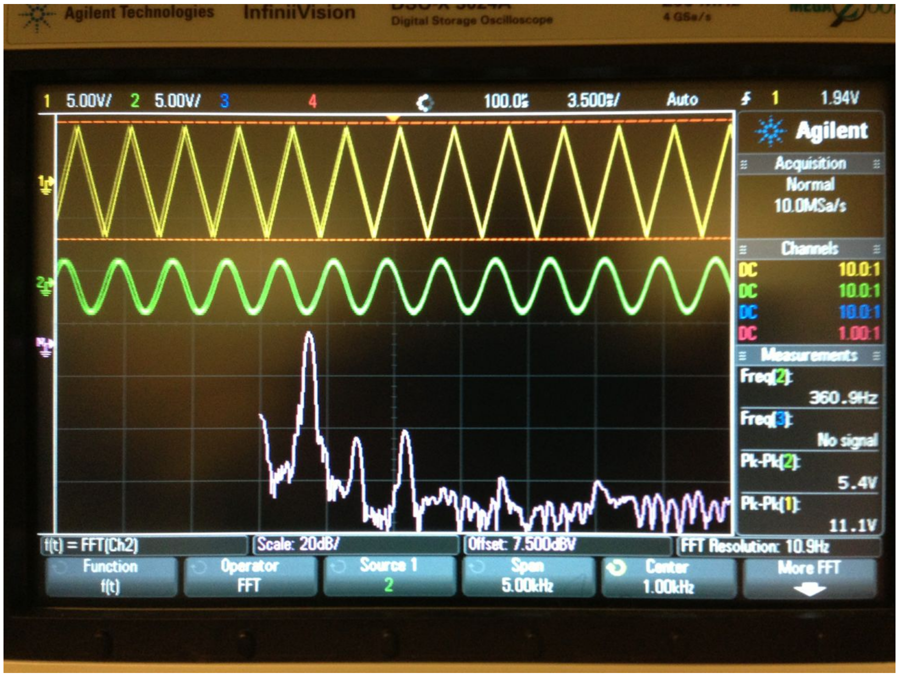

Figure 19 - Low Pass Filter of Triangle Wave

This screenshot illustrates how the triangle waveform's sharp peaks are attenuated by the low pass filter and consequently modifying the output sound to approximate a sine wave.

The amplifier line output, which is used to drive audio speakers, converts the 10 V peak-to-peak waveform to a 2 V peak-to-peak waveform.

References

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