Electric Piano

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6.101 Final Project Report

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I. Introduction

Musical instruments have amused people around the world throughout the history. One of the most common instruments that is enjoyed by people today is the piano. Playing the piano is very intuitive; players can make notes simply by pressing keys, and the notes ascend from left to right.

In our project, we decided to build an electric piano with analog circuits. The user interface was inspired by a circuit that we built in 6.101 which lights up an LED for 30 seconds after the user touches two electrodes. We thought that the idea behind this circuit was a clever one, but we wanted to do something more interesting than just turning on a light. Turning on the circuit by touching electrodes resembles playing notes by pressing keys on the piano. The electric piano, therefore, enables players to play music in a similar way to a real piano.

The features of the electric piano were inspired by those of a real piano. The electric piano can play three octaves in total, and has a soft pedal to decrease the volume. The waveshapes can be changed to several different shapes to better mimic the sounds of the piano, if not quite perfectly.

II. Abstract

The electric piano consists of one octave of keys with an octave switch, a timbre switch, and one pedals, mimicking the soft pedal on a piano. Three different octaves can be played by using the octave switch. Each key consists of two electrodes laid on an acrylic board. When the key is touched, it changes the voltage from 0 V to some value (usually about 10 V) by using the resistance in the user's finger to create a voltage divider. This voltage triggers a tone to be played. For tone generation, a voltage controlled oscillator is used. The generated wave is a triangle wave. To mimic the timbre of a piano better, the timbre can be changed by the timbre switches. The electric piano can generate a triangle wave, sine wave, a rounded square wave, and any combination of the three. The soft pedal lowers the volume.

III. Block Diagram

Figure 1 shows the block diagram of the electric piano. Each key is a switch that is made of a pair of electrodes, and turns a MOSFET switch on or off. When the MOSFET switch is on, a voltage corresponding to the frequency of the note is sent to the voltage controlled oscillator (VCO). A triangle wave is generated and amplified so that a speaker can play the notes. The triangle wave goes through timbre changers to create a sine wave and a rounded square wave. Each component will be discussed in the later sections.

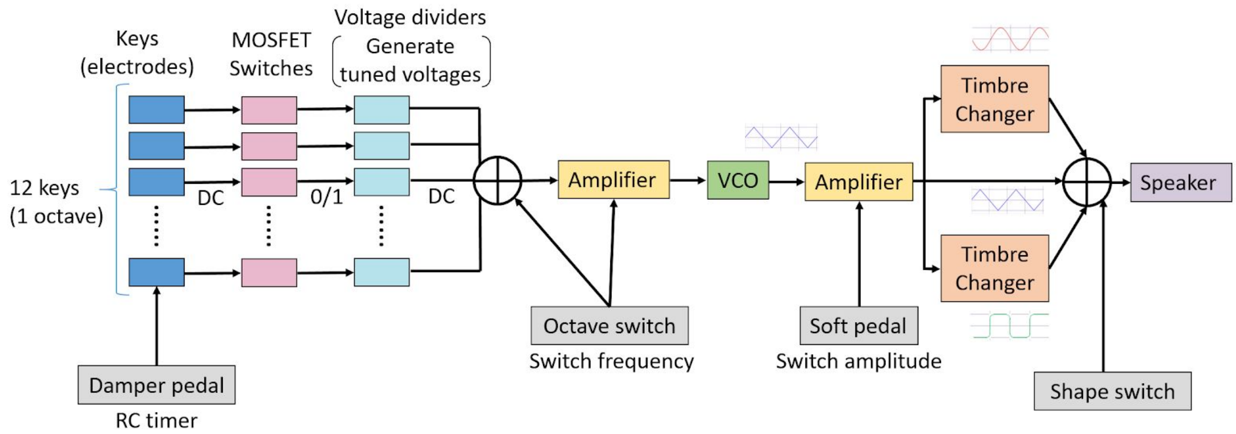

Figure 1. Block diagram of the system

IV. Synthesizer

A. Touch Sensor -Yukimi

Touch sensors are used for the 12 keys and the soft pedal. The purpose is to sense a finger (or hand) touching, and send the information as a voltage change. Figure 2 shows the schematic of a key. The key consists of two electrodes made of a copper tape. When a finger is not touching the key, the electrodes are open and sends 0 V to the switch. When a finger is touching the key, the electrodes are connected through a resistor (the finger) and the circuit works as a simple voltage divider. It sends some positive voltage to the switch. The value of this positive voltage varies from about 0.5 V to 10 V since the resistance of the finger varies between 5 kΩ ~ 20 MΩ depending on multiple factors such as moisture and how hard the user presses the keys.

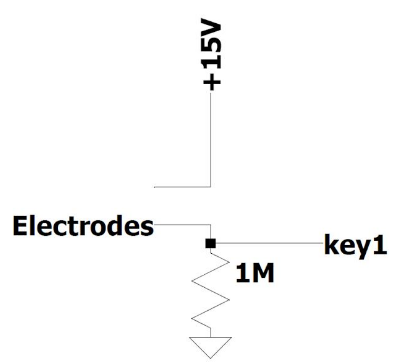

Figure 2. Schematics of the key

Figure 3 shows the implementation of the two electrodes. Each electrode was laid out in a tooth shape so that the finger is sensed no matter where it is touching on the key.

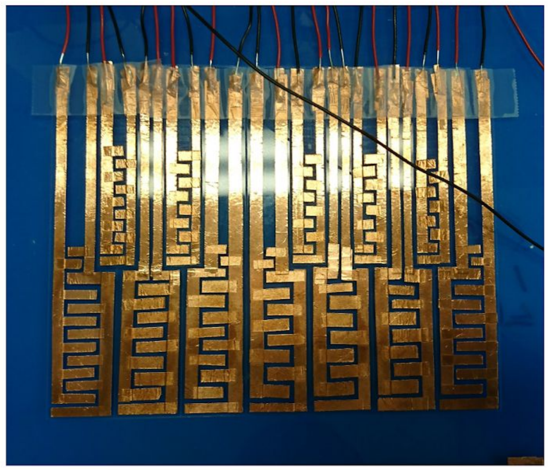

Figure 3. Implementation of keys

B. MOSFET Switch - Adam

When a user presses a key, a MOSFET switch corresponding to that key is turned on. This switch connects a voltage from a voltage divider, via a voltage buffer, to the input of the adder. This setup for key 1 is pictured below.

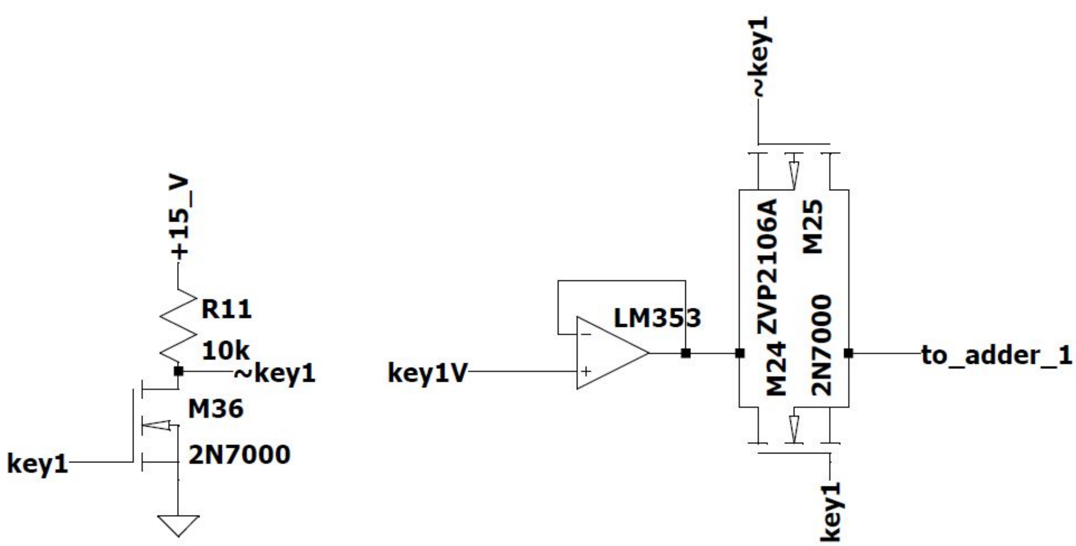

Figure 4. Schematic of MOSFET Switch and Inverter

Pictured above is the configuration for key 1, but the configuration for each key is the same with appropriate voltage label changes (i.e. key1 to key2, key3, etc.; ~key1 to ~key2,, etc.; key1V to key2V, etc.).

The label “key1V” represents the voltage created by a voltage divider to create the desired frequency for that key. The LM353 op-amp[1] acts as a voltage buffer feeding into the MOSFET switch. The MOSFET switch is turned on by the voltage created by pressing a key, represented by the label “key1.” When key1 is high, then the gate-source voltage of the 2N7000 is high, thus turning on the MOSFET. Key1 is also passed through an inverter (left), which outputs the voltage “~key1,” a voltage that is 0V when key1 is high and 15 V when key1 is low. Thus, when key1 is high, ~key1 is low, which turns on the ZVP2106A PMOS. When key1 is low, the 2N7000 NMOS remains off and ~key1 is high, thus turning off the ZVP2106A PMOS. This allows the PMOS and NMOS in parallel to act as a switch, connecting the output of the buffer to the node labeled “to_adder_1” when key1 is high and disconnecting them when key1 is low.

Both an NMOS and a PMOS were used, rather than a single NMOS, for the switch to ensure that the switch remained on throughout the entire time that the key was pressed. If only an NMOS was used, then if a voltage similar in magnitude to key1 was used as key1V, to_adder_1 would charge up to the voltage of key1V as well. This would cause the gate-source voltage of the NMOS to decrease, possibly causing the gate-source voltage to drop below the MOSFET threshold, thus turning it off. With the PMOS in parallel with the NMOS, the low voltage on the PMOS gate when key1 is high creates a negative gate-source voltage on the PMOS, which keeps it turned on. The output of this system, labeled “to_adder_1” is then fed into an adder.

The system was confirmed to work properly by observing that the voltage of key1V appeared at to_adder_1 when a high voltage (> 5 V) was supplied to key1 and that to_adder_1 was at 0 V when key1 was at 0 V.

C. Adder and Inverting Amplifier -Adam

The purpose of the adder is to allow the voltages created by each key each to be fed into the input of the voltage controlled oscillator (VCO) through a single node, without interference from the other switches. Because pressing two keys would cause the two voltages to be added together then fed into the VCO, only one key can be pressed at a time for proper operation. The schematic of the adder is pictured below.

[1] All IC’s are powered by +15 and -15V unless otherwise stated.

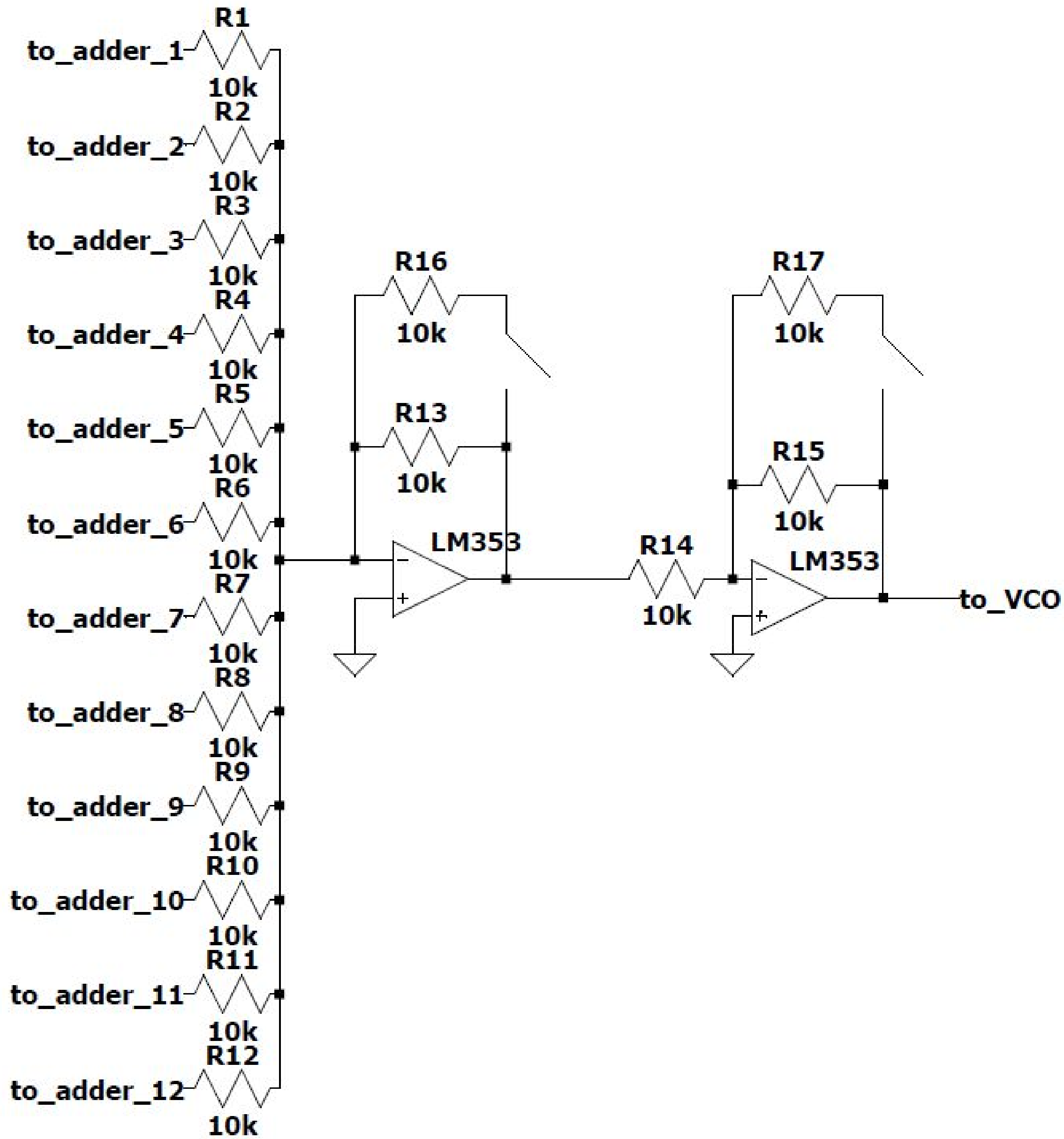

Figure 5. Schematic of Adder and Inverting Amplifier

10 kΩ resistors were chosen for all resistors to ensure unity gain in the adder. Because the adder is in an inverting configuration, however, the output of the adder was fed through another inverting amplifier of unity gain to obtain a positive voltage for the VCO. Thus, when a single key is pressed, its voltage is added to the voltage of the other inputs (which should be zero when only one key is pressed). This voltage is multiplied by -1 by the adder, then again multiplied by -1 by the inverting amplifier and fed into the input of the VCO.

The system was confirmed to work by turning on each key and measuring the voltage at to_VCO. It was confirmed that when each key was individually turned on, the correct voltage expected from to_adder_N, where N is the key number, was observed at to_VCO. For example, when key 1 was on, the voltage at to_VCO was the voltage of key1V. This check was done for every key.

The resistors connected with switches are used to change the octave of the piano, which will be discussed later.

D. Voltage Controlled Oscillator -Adam

The basic structure of the voltage controlled oscillator is a voltage to current converter followed by a comparator in a Schmitt trigger configuration. This configuration is pictured below. The design is adapted from Franco's *Design with Operational Amplifiers and Analog Integrated Circuits, Second Edition* (p. 473-474) [1].

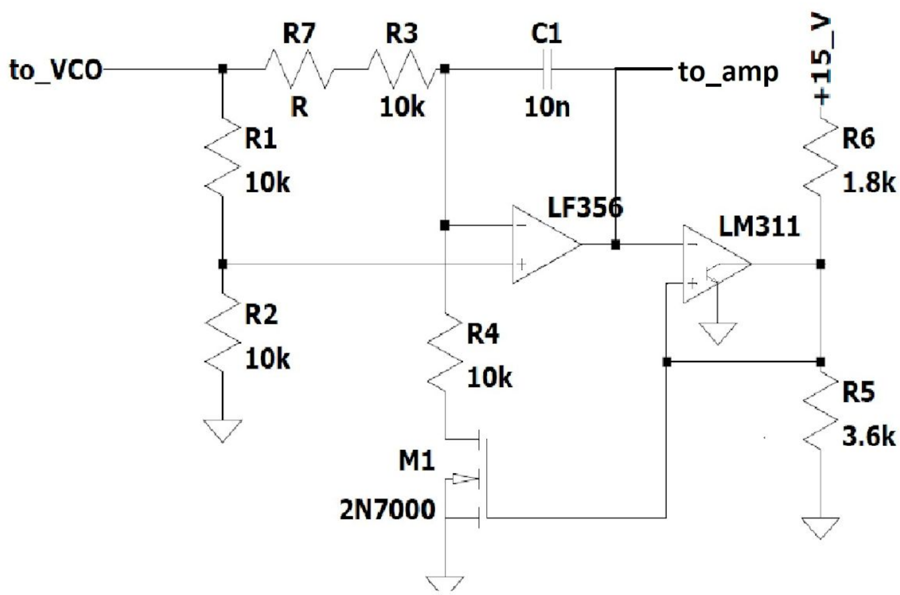

Figure 6. Schematic of Voltage Controlled Oscillator

R7 is a 10 kΩ potentiometer, set up to act as an adjustable resistor between 0 and 10 kΩ. Using a potentiometer allows for tuning the VCO to compensate for variability in resistor values. For the sake of analysis, we will treat the potentiometer as if it is simply a 10 kΩ resistor.

R1 and R2 act as a voltage divider, providing half of the input voltage to the non-inverting input of the LF356. The LM311 is used in a Schmitt trigger configuration, with output and threshold voltages of $V_{OL} \approx V_{TL} = 0$ V and $V_{OH} = V_{TH} = 10$ V. The lower output level is set by the voltage of the LM311 output when the BJT in the LM311 is saturated, in which case it acts like a short to ground. The upper level output is set by the case when the BJT is completely off, in which case, R6 and R5 simply act as a voltage divider, providing 3.6*15/(3.6+1.8) V = 10 V to the LM311 output.

If the output of the Schmitt trigger is at 0 V, then the gate voltage of the MOSFET is 0. Thus the MOSFET is turned off. Because the non-inverting input of the LM356 is set to half the input voltage (“to_VCO” = Vi), so is the inverting input as well. The current going through R7 and R3 is thus i = Vi/(40 kΩ). Because M1 is off, no current flows through R4. Therefore, i current must flow through C1. Because the voltage of the inverting input of the LM356 cannot change, the voltage of the node connected to the output of the LM356 changes. This voltage (Vo) at the node labeled “to_amp” decreases linearly while the LM311 output is low until Vo reaches 0 V. When Vo reaches 0 V, the Schmitt trigger switches its output to 10 V. When this happens, M1 turns on, allowing current to flow through R4. The current flowing through R3 and R7 is still i = Vi/(40 kΩ), but the current through R4 is i4 = Vi/(20 kΩ). Thus the current flowing through C1 must be ic = Vi/(40 kΩ), but in the opposite direction as before. Thus the capacitor begins to charge up, and Vo increases linearly. This happens until Vo = 10 V, at which time the Schmitt trigger switches its output to 0 V and the cycle proceeds in the way described above. Thus a triangle wave is produced at the node labeled “to_amp” and a square wave is produced at the output of the Schmitt trigger. The frequency of the VCO, in the ideal case, is determined by the equation [1]:

$$f = Vi/(8*R*C*(V_{TH}-V_{TL})) = Vi/(8*10*10^3*10*10^9*10)$$

The system was confirmed to work by inputting voltages to the VCO between 0 and 15 V. While this was done, the node to_amp and the output of the LM311 were observed with an oscilloscope to confirm that they outputted triangle and square waves respectively. It was also confirmed in this same process that the VCO could produce waves with frequencies ranging from about 100 Hz to about 1000 Hz, as was necessary to produce waves for three octaves. The VCO was able to produce frequencies between about 50 Hz and about 2000 Hz

E. Push-Pull Amplifier -Adam

The design for the push pull amplifier was adapted from the amplifier used in Lab 5 of 6.101 Spring 2019. The basic design of the amplifier is an inverting amplifier with a high pass filter, followed by a stage with two BJT’s to provide sufficient current to the output. The RC network at the inverting input of the op-amp acts as a high pass filter with cutoff frequency of 1/(2*π*R*C) = 1/(2*π*100k*940n) ≈ 1.7 Hz. This high pass filter serves to eliminate any DC offset that was introduced by the VCO. The 5.1 kΩ resistor at the non-inverting input of the op-amp that is connected to ground serves to better match the impedances between the inputs of the op amp. The 26 kΩ feedback resistor makes the amplifier have a gain of -26/100 ≈ -0.25. The amplifier actually reduces the amplitude of the output because it was found that the 10 V peak to peak waveform produced by the oscillator was too loud for reasonable listening.

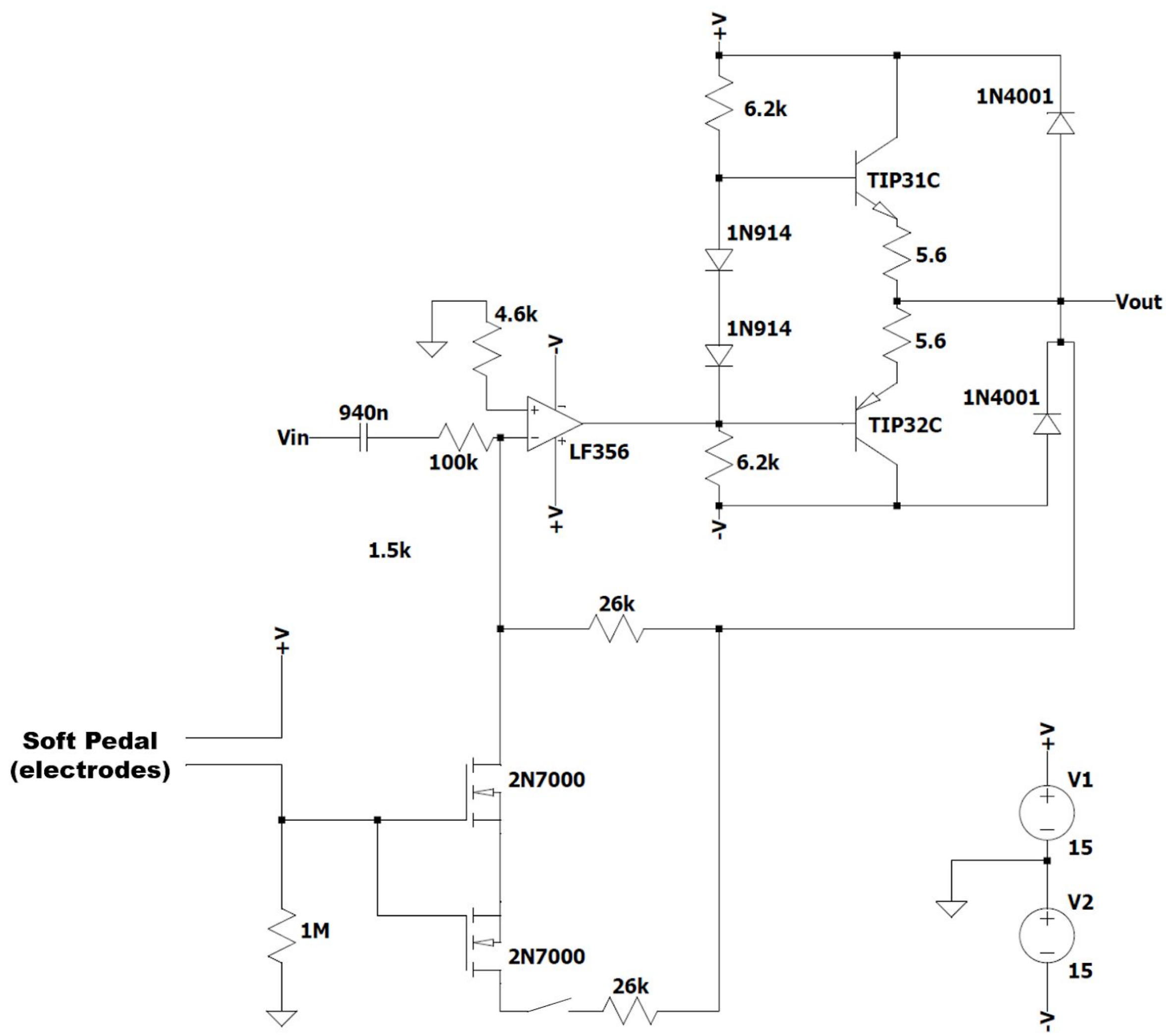

Figure 7. Push-pull amplifier

The Figure 6 shows the schematics of the push-pull amplifier. The bottom part that consists of 2N7000 is a damper pedal and will be explained later. The 6.2 kΩ resistors connected to +V and -V control the bias current of the amplifier. The two 1N914 diodes help to reduce crossover distortion by artificially creating a 2 diode drop (approximately 1.2 V) between the bases of the two BJT's. The BJT's allow for more current to be drawn from the power supplies than would be able to be drawn from the op-amp alone. The 5.6 Ω emitter resistors control the amount of current that can flow through the BJT's.

Correct functionality was determined by inputting a triangle wave to the system of a known frequency and amplitude and observing on an oscilloscope that a triangle wave was produced at Vout with 0.25 times that input amplitude and the same frequency.

Pictured below is the output of the push-pull amplifier.

Figure 8. Output of Push-Pull Amplifier

V. Audio Effects

A. Timbre Changer -Yukimi

The timbre changer changes the triangle wave input into a sine wave and a rounded square wave. The motivation for changing the timbre is to make the notes sound more like a real piano. The waveshapes of a real piano varies depends on the frequency as shown in Figure 9. The waveshape is almost a rounded square for low tones, almost a triangle for middle tones, and almost a sine for high tones. Since it is too complicated to produce the waveshapes that perfectly resemble a real piano, we decided to have three different waveshapes (a triangle, a sine, and a rounded square). In addition to those three shapes, the electric piano can produce any combination of those three shapes.

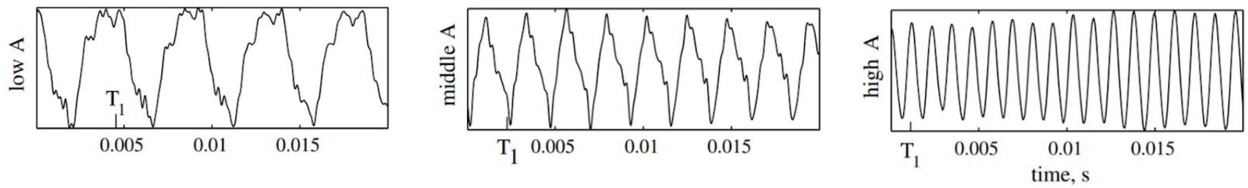

Figure 9. Waveshapes of a real piano [2]

A triangle wave is changed to a sine wave using a low pass filter shown in Figure 10. Only the acute angles (or the part with the highest local frequency) are rejected by a low pass filter, and the resulting wave is a sine wave. The cutoff frequency is set high enough not to reject the entire wave but low enough to reject the edges of the triangle wave. In reality, the filter doesn’t have a perfect cutoff because the first-order low pass filter has a gradual roll off of 20 dB/ dec. Therefore, simply choosing the cutoff frequency based on 1/(2π*R*C) produces a wave more like a triangle than a perfect sine wave. The resistor value was tuned carefully by checking the output waveform with the oscilloscope.

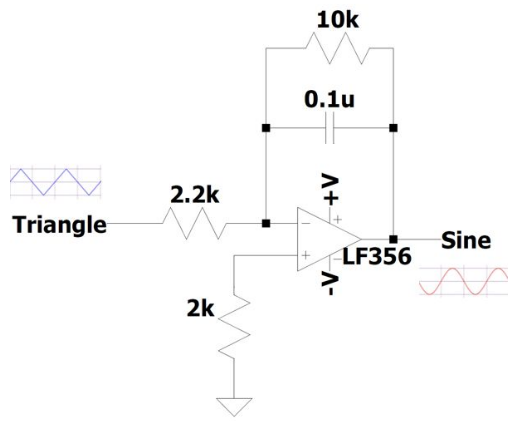

Figure 10. Low pass filter

Figure 11 shows the sine wave output of the low pass filter.

Figure 11. Sine wave output of the low pass filter

A triangle wave is changed to a rounded square wave using a logarithmic wave shaper shown in Figure 12. The idea is based on a circuit for triangular-to-sine wave conversion that is discussed in Sergio Franco's *Design with Operational Amplifiers and Analog Integrated Circuits, Second Edition* (p. 480) [1].

The top half of the circuit that consists of two 2N3906s and resistors works as a current mirror, and both BJTs supply the same current. V_{CE} of Q3 is same as V_{BE} (~0.6 V) since the base is connected to the collector. Since V_{BC} is 0 for both Q3 and Q4 and the bases are connected, I_B for Q3 and Q4 are the same as long as they operate in the active region. Therefore, I_C of Q4 is the same as I_C of Q3 no matter the difference of V_{CE} between Q3 and Q4.

The bottom half, which consists of an LM394 supermatch pair, works as a logarithmic wave shaper. When the input is nearly zero, I_C has a linear relationship with V_{BE}. This changes I_C of Q3 linearly depending on the input voltage. When the amplitude of the input is large, I_C of Q1 or Q2 has a logarithmic relationship with V_{BE}. This changes I_C of Q3 logarithmically depending on the input voltage. Therefore, the wave is rounded only in the part with a large magnitude and not in the part with a small magnitude. Tuning the potentiometer changes the overall roundness of the shape and the flatness of the edges of the wave so that this circuit can create a sine wave, a square wave and anything in between them. For the electric piano, the potentiometer was tuned to create a rounded square wave.

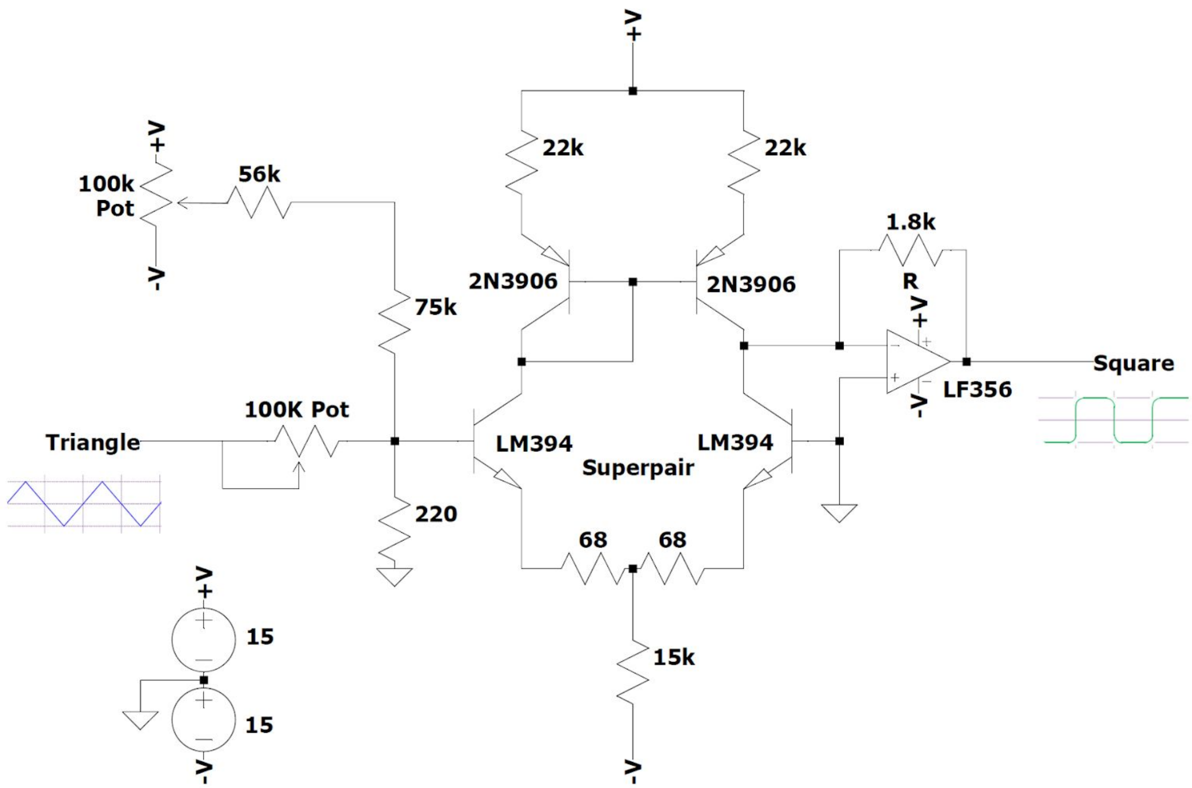

Figure 12. Logarithmic wave shaper

The current is converted to a voltage by a transimpedance amplifier. The generated rounded square wave is shown in Figure 13. Because the rounded square wave is phase-shifted by π, it creates interesting waveshapes when added to a sine or a triangle wave.

Figure 13. Rounded square wave output of logarithmic wave shaper

The three shapes —a triangle, a sine, and a rounded square— are added together by a simple adder using an op-amp as shown in Figure 14. The mechanical switches connect or disconnect each wave input. The output can be six different shapes -a triangle wave, a sine wave, a rounded square wave, a sum of a sine wave and a rounded square wave, a sum of a triangle wave and a rounded square wave, or a sum of all three waves.

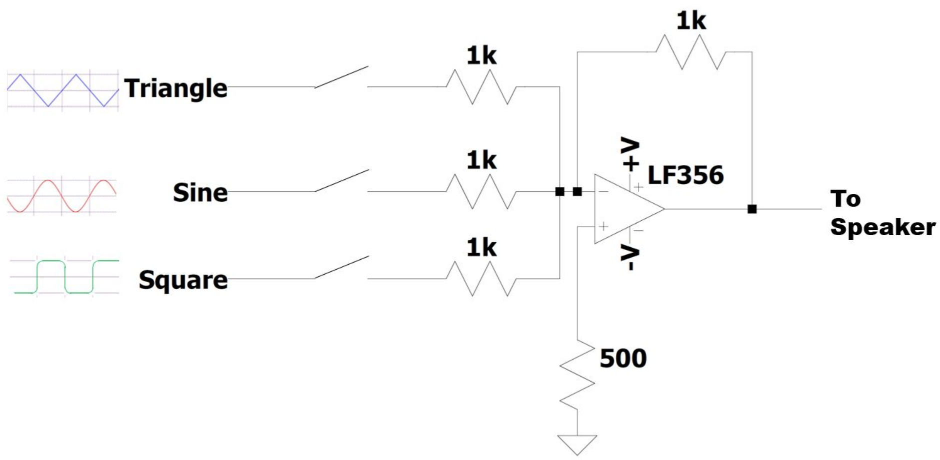

Figure 14. Adder

Figure 15 shows examples of possible outputs.

(a) (b)

Figure 15. (a) Sum of triangle and rounded square, (b) Sum of all three waves

B. Octave Switch -Yukimi

This electric piano has 12 keys (the keys for one octave), but a real piano has multiple octaves. Therefore, we implemented an octave switch to enable playing three octaves (Figure 16). To change the note, the input voltage to the VCO is changed to vary the frequency. The starting octave is C5 ~ B5 (523 Hz ~ 988 Hz). The same note that is one octave lower has half the frequency of the original note, so the input voltage to the VCO needs to be half as well. Therefore, the gain of the adder before the VCO was halved by adding a resistor (R16) of the same value in parallel. This creates the notes from C4 ~ B4 (262 Hz ~ 494 Hz). To make the note another octave lower, the gain of the amplifier is halved by connecting a resistor (R17) of the same value in parallel in addition to the resistor in the adder (R16). This creates the notes from C3 ~ B3 (131 Hz ~ 247 Hz).

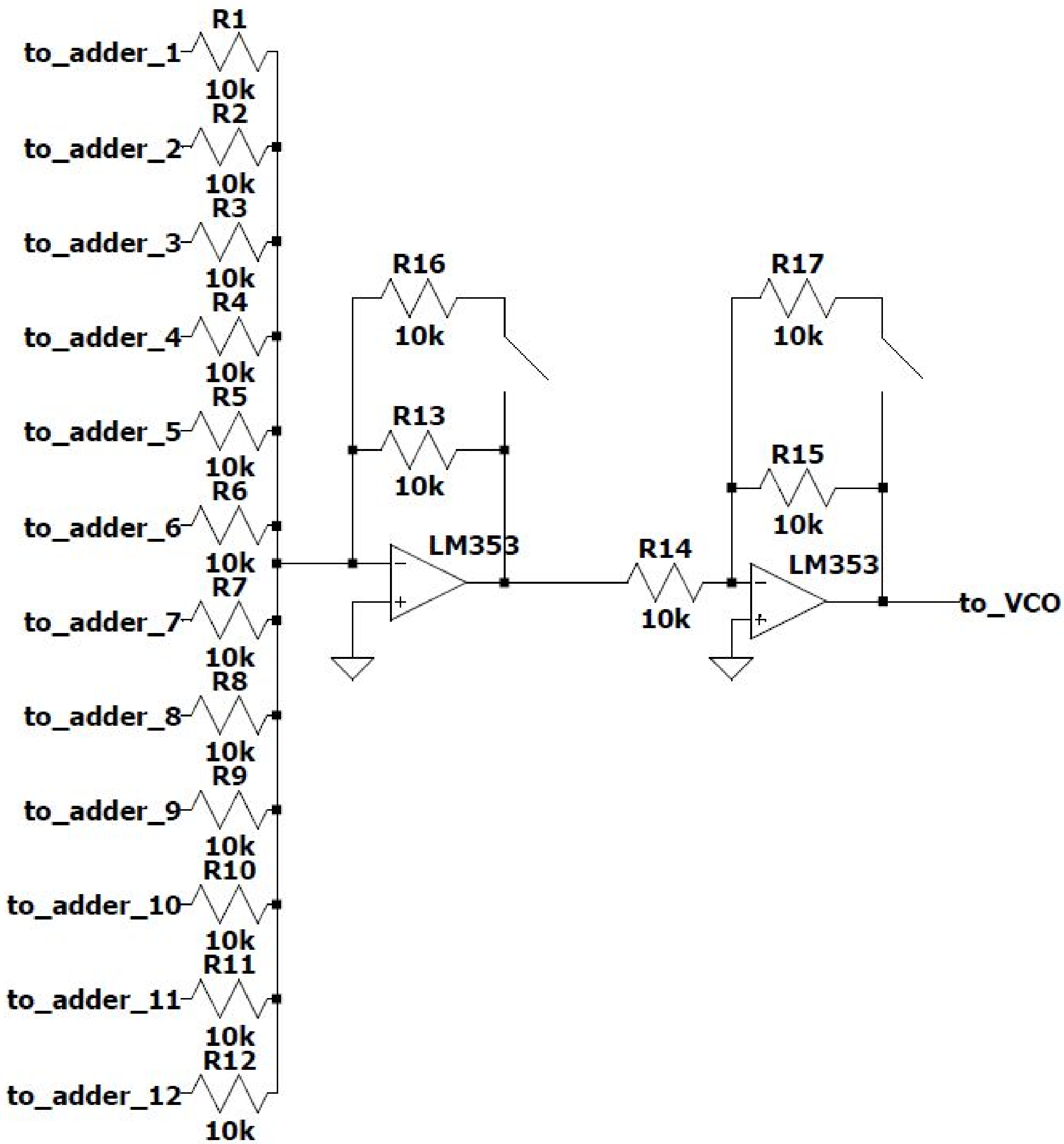

Figure 16. Octave switches on adder and inverting amplifier

Turning the octave switch allowed the notes to go one octave lower and another octave (two octaves in total) lower. The errors of notes were within 5 Hz.

C. Soft Pedal -Yukimi

The soft pedal is the pedal which makes the volume softer, or smaller. When the soft pedal is pressed, a resistor of the same value is added in parallel to the push-pull amplifier to halve the gain. Connection of this parallel resistor is controlled by a voltage controlled switch using two NMOSs. The amplitude of the output also becomes half, so the volume decreases.

Figure 17 shows the push-pull amplifier and the soft pedal (the voltage controlled switch). The pedal consist of two electrodes just like the keys. When the pedal is not pressed, the circuit is open so 0 V is sent to the gates of two NMOSs. When the pedal is pressed, the circuit is connected and works as a voltage divider, and sends some positive voltage to the gates of the NMOSs. This turns off the top NMOS for the positive half of the triangle wave, and turns off the bottom NMOS for the negative half of the triangle wave.

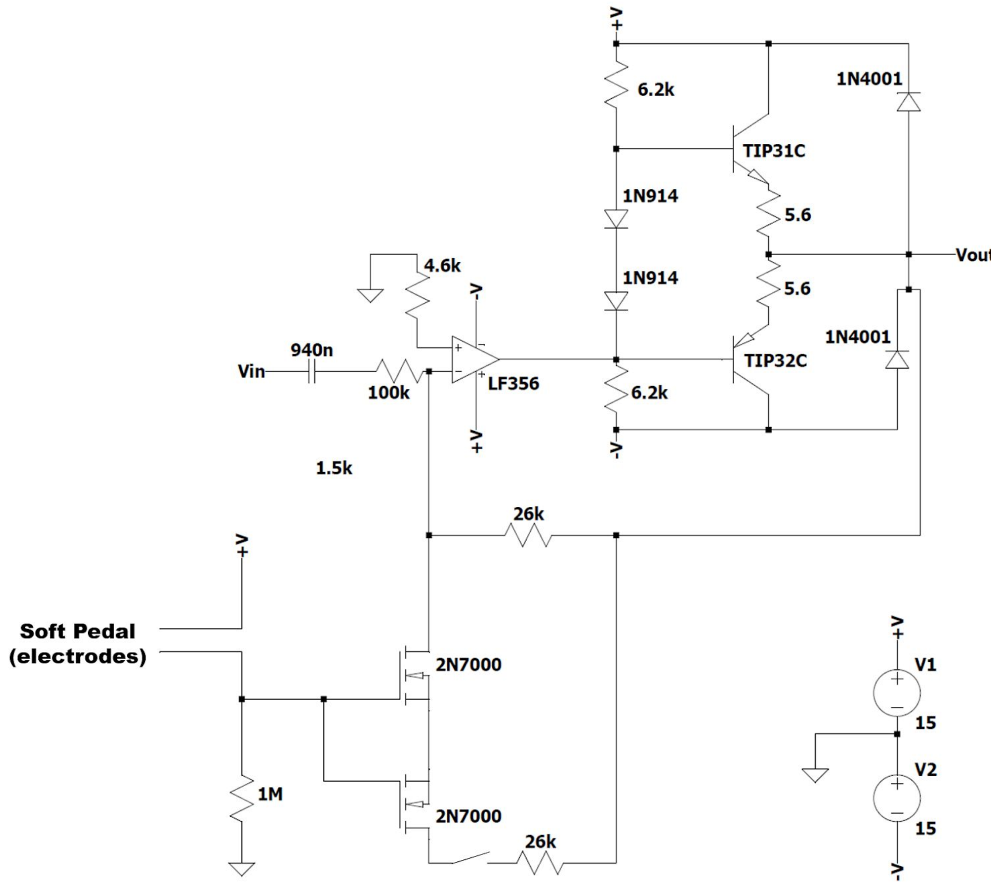

Figure 17. Push-pull amplifier and soft pedal

When the soft pedal is pressed, the oscilloscope confirmed the amplitude of the output became half of the original amplitude. The volume became noticeably smaller to the ear.

D. Damper Pedal (Attempt) -Yukimi

The damper pedal is the pedal to hold the notes for a short while after a finger leaves a key. Discharging time of a capacitor is used for holding a note. The time that a note can be held is determined by time constant (RC).

Figure 18 shows the schematics of the attempt of the damper pedal. The logic behind this schematic is as follows. When the electrodes for the damper pedal are not touched, the circuit is open. Therefore, the gate of 2N7000 is at 0 V, and it is off. Only the left half of the circuit is connected, so it doesn't have a damper effect. When the electrodes are touched, the gate of 2N7000 is at a positive voltage so 2N7000 is turned on. By connecting the capacitor in parallel with the resistor, it holds the note while the capacitor discharges. The diode is there to make sure that the current doesn't flow in the opposite way.

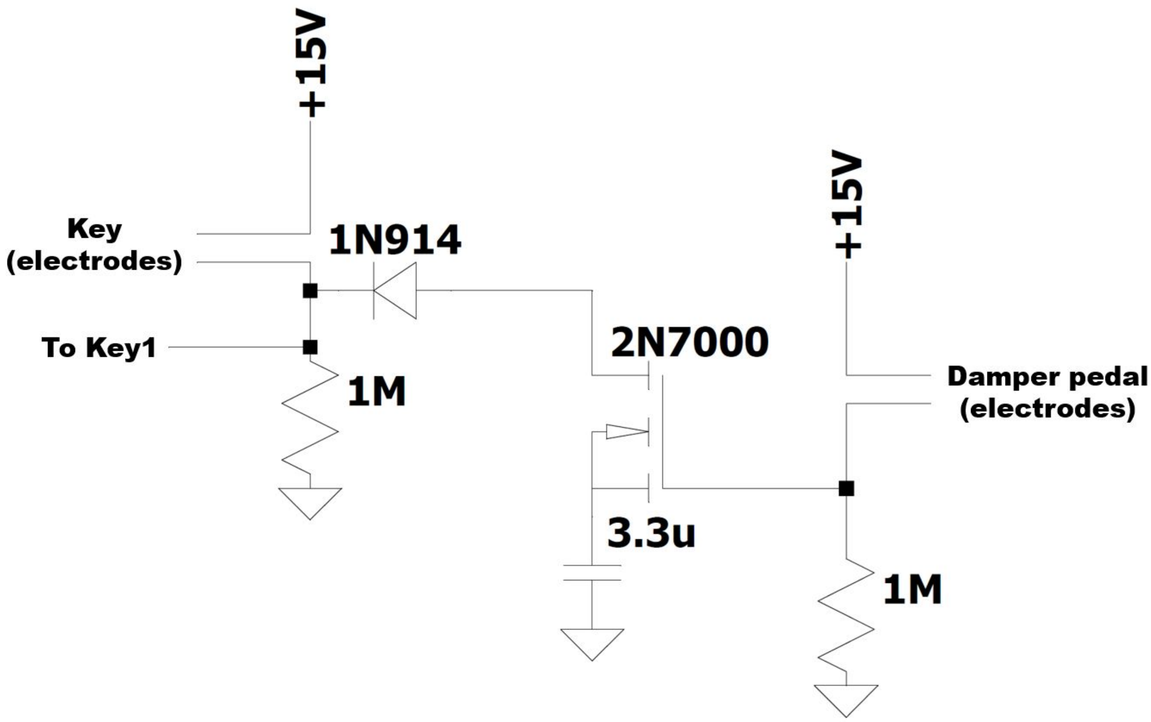

Figure 18. Key and damper pedal

Testing showed that this circuit is only half functional. When the finger is not touching the damper pedal, it works as desired; it creates notes only when the key electrodes are touched, and it does not hold notes after the finger leaves the key. When the damper pedal is touched after the key is pressed, it holds the note for about 5 seconds. The problem arises after playing a note with the damper pedal once. When the damper pedal is pressed, it creates the previous note and holds it for 5 seconds regardless of whether any key is touched. The issue could not be solved in the given time for this project. The problem may be due to the parasitic capacitance of the MOSFET.

VI. Design Analysis

The creation of each individual section of the piano went relatively smoothly, while the most time consuming challenges occurred when integrating the various modules with each other. We found that connecting many copies of the same circuit together especially did not behave as simply as we expected. Each module was designed separately, and it was assumed that one part would not interfere with the operation of another. This assumption was quickly disproven, however, which forced us to rethink how each module interacted with the others. Once each section was redesigned to minimize the interference with one another, the basic design of keys, oscillator, and amplifier came together quite smoothly. Extra modules and features that we thought would be simple to create, however, proved more difficult than expected, such as pressing two keys at once and the damper pedal.

VII. Conclusion

We were able to successfully create a keyboard of resistive touch keys that played twelve notes. We were able to tune the notes to be within a few Hz of the target note for each key. We were able to implement the ability to switch between three octaves of notes and, for each note in each octave, every note played was recognizable as the desired note by a music tuning app. We were able to do this by successfully implementing a MOSFET switch, which was activated by a resistive sensor and using this switch to input a voltage to set the frequency of a voltage controlled oscillator. We were also able to create a push pull amplifier to provide the required current for the system. The electric piano could successfully generate a triangle wave, a sine wave, a rounded square wave, and any combination of the three. Distortion of the triangle wave and the sine wave was negligible on the oscilloscope. The differences between each waveshape were recognizable by the ears. The damper pedal could hold a key that was pressed, but it had a problem where it creates the note while only pressing the damper pedal but not the key.

If we were to continue working on the electric piano we would like to improve the functionality of the damper pedal, as well as implement the ability to press more than one key at once. The ability to press more than one key, however, would require multiple oscillators; we would need either one for each key, or fewer oscillators with the ability to have only one key affecting one oscillator at a time. We would also be interested in looking into various effects that we can implement to make the timbre of the electric piano more closely match that of a real piano, particularly by introducing harmonics into the system.

VIII. References

1. Sergio Franco, *Design with Operational Amplifiers and Analog Integrated Circuits, Second Edition*, New York, NY, McGraw-Hill, p. 480
2. Mark R. Petersen, *Musical Analysis and Synthesis in MATLAB*, MAA's College Mathematics Journal Vol. 35, No. 5, p. 396-401 (2004)

IX. Appendix

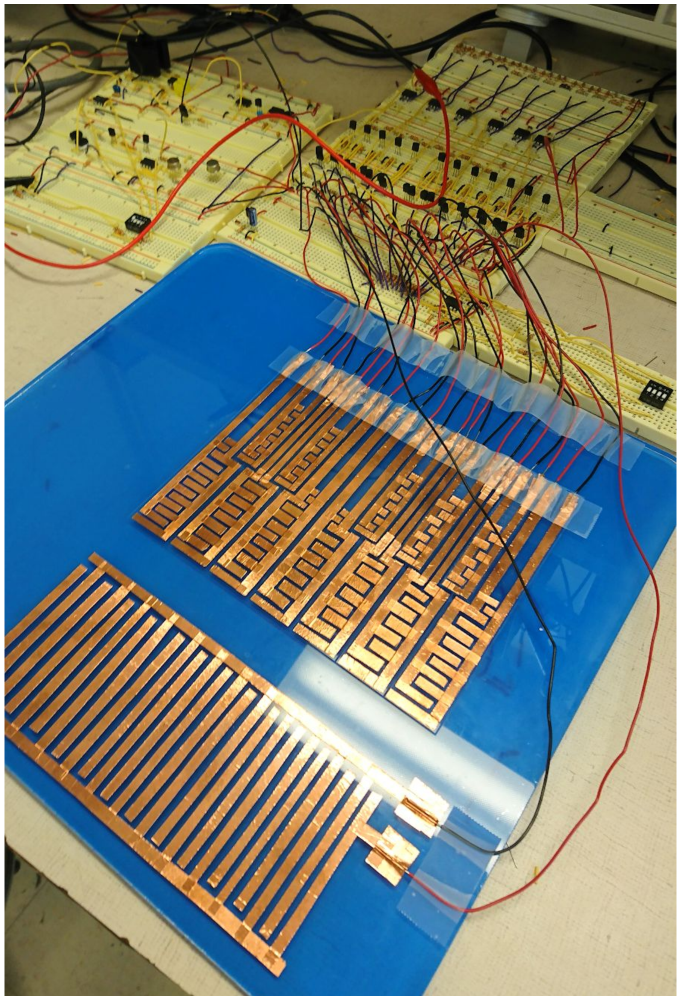

Figure 19. The completed electric piano