ECE 137B Analog Lab

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Theremin: An electronic gesture controlled musical instrument

Due June 1, 2010

The goal of this lab for the quarter is to design a musical instrument called the Theremin invented by the Russian inventor Prof. Leon Theremin. This instrument uses many concepts that one should be familiar with as an electrical engineer. To ensure that you are making progress in this lab, we will monitor the progress every week. Unless otherwise stated use a $\pm 5V$ supply. The over-

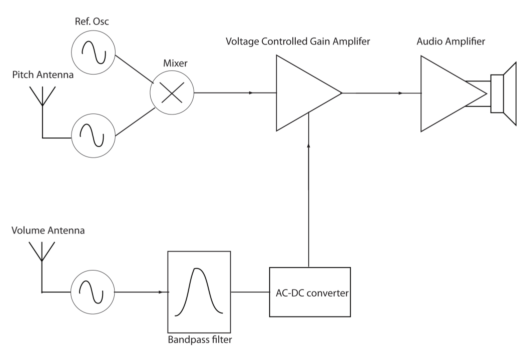

Figure 1: Block diagram of the Theremin

all block diagram of the Theremin is shown in figure 1. The principle of the theremin is one of beat frequencies. Consider two sine waves with frequencies ω_1 and ω_2, if the two sine waves are mixed (multiplied) it will produce two tones one at the sum and the other at the difference.

$$V_{mix} = \frac{1}{V_o}\left(V_1 Cos\omega_1 t\right) \times \left(V_2 Cos\omega_2 t\right) \tag{1}$$

$$2CosACosB = Cos(A+B) + Cos(A-B) \tag{2}$$

$$V_{mix} = \frac{V_1 V_2}{2V_o} Cos(\omega_1 - \omega_2)t + \frac{V_1 V_2}{2V_o} Cos(\omega_1 + \omega_2)t \tag{3}$$

By placing a low pass filter at the output of the mixer only the difference component can be obtained. If this difference is in the audible range of 20Hz-20kHz it will produce an audible tone.

The Theremin uses the above principle to implement a musical instrument using the movement of the hand. The basic idea is to implement two oscillators. One oscillator serves as the reference, while the other is a tunable oscillator based on the proximity of the hand to the sensor. The multiplication of these two signal after low pass filtering is fed to a audio amplifier that generates a sound.

The same principle can be used to also control the volume, here the output is converted to an equivalent voltage and used to control the gain of the audio amplifier.

1 Prelab 1: Due April 9, 2010

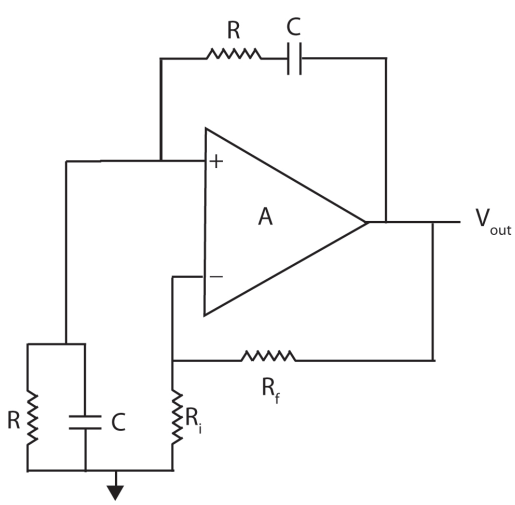

Figure 2: A Wien Bridge Oscillator

The first part of this lab will be to implement the oscillator. We will use a Wien bridge oscillator, shown in figure 2 as an example. The frequency of oscillation is given by $\omega = \frac{1}{RC}$. NOTE: You can use other op-amp oscillators (see attached note from TI) though you might have to think about how to place the antenna for the most effective variation with hand position.

A typical antenna, say a 4 inch copper plate, gives a capacitance of $\cong 0.6pF$ when the hand is 6 inches away, since your hand acts a plate that is grounded.

(a) Calculate the dimensions of a rod or loop antenna so that it generates a capacitance of 2pF when the hand is 4 inches away.

(b) Plot the capacitance of the antenna as function of the distance of the hand.

(c) A typical low pass filter has a first order roll-off of -20dB/dec, to effectively filter the sum frequencies from the difference the sum has to be at least 2 decades away. Given that the audio range from 20Hz-20kHz, design an oscillator such that the frequency of oscillation is high enough so that the sum frequencies can be effectively be filtered.

(d) Given your calculation of capacitance variation, choose the value of the RC network so that when the proximity based capacitance is added in parallel the frequency variation is form 20-20KHz.

(e) Add a circuit so that both oscillators start in the same state.

2 Lab 1: Due April 16, 2010

In this lab you will implement the proximity capacitance antenna and ***two*** oscillators. One oscillator will serve as your reference and the other will have the proximity detector connected in parallel with your RC.

1. Does your oscillator function as a sine wave generator or a square wave generator? Capture the various waveforms as a function of the negative feedback fraction. From this analysis would you make the feedback resistor variable or fixed in your design?
2. Plot the frequency as the hand is brought closer to the antenna. Does it change by the amount you would like? From this analysis calculate the capacitance between your hand and the proximity detector as a function of distance. Does this agree with the theoretical calculation that you did in your Prelab?

3 Prelab 2: Due April 23, 2010

Now that we have the oscillator our next job is to multiply them. These multipliers are generally termed mixers. One can build mixers from diodes or transistors. We will build a transistor mixer called a Gilbert cell shown in figure 3,

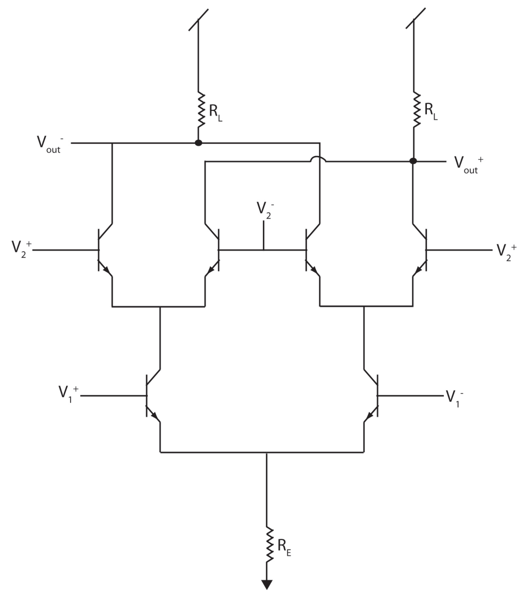

Figure 3: Circuit diagram of the Gilbert Multiplier

named after its inventor the great analog designer Barrie Gilbert. The Gilbert cell is based on the principle that the current through the branches of a differential pair is proportional to the product of the tail current source and the input voltage. This, of course, is a consequence of the fact the $g_m = \frac{qI_c}{kT} = \frac{qI_{tail}}{2kT}$ and that $i_{out} = g_m V_{in}$. If $I_{tail} = G_m V_1$ then we can multiply the two voltages from the two oscillators that we designed earlier.

1. Calculate the differential output voltage of the simple Gilbert cell shown in figure 3.

2. From the earlier calculation what is the maximum input voltage that you can tolerate before your assumptions breakdown? Do both inputs have to be in the valid region for the Mixer to work as designed?

3. Draw the output of the mixer in the frequency domain, given that both inputs are cosine waves i.e $V_1 = V_a Cos\omega_1 t$ and $V_1 = V_b Cos\omega_1 t$. What if V_2 is a square wave, how does the frequency response change?.

4. If V_2 was a square wave can the low pass filter still be a first order filter? If yes why and if not, why not?

5. If you wanted to use a larger amplitude, the voltage to current conversion needs to have a larger dynamic range. Design a multiplier that can tolerate the amplitude of $\pm 750mV$ at the input V_1.

6. There are two requirements your multiplier imposes on the input, One is that the input be differential and the other is that it has limited output range. Design a block such that the output from your oscillator is converted to a $\pm 750mV$ range and is differential.
7. Design a low pass filter such that the output of the multiplier contains only frequencies in the audible range.
8. The output of the Gilbert cell must not saturate, design the load network such that this does not happen.

4 Lab 2: Due May 7, 2010

In this lab you will implement the mixer that you designed earlier. For the following do not implement the low pass filter until instructed to do so.

1. Plot the ***DC*** transfer curve of your mixer, does it have the dynamic range you expected?
2. Design your block that converters a single ended signal and converts it to a differential and also converts the signal range to lie within $\pm 750mV$. Capture the output demonstrating this operation.
3. Using the function generator as inputs plot the frequency domain response of the mixer for frequency inputs you would expect from your two oscillators. Does the mixer work as intended? Is the output a sinusoidal waveform?
4. Add the low-pass filter to the output of the mixer, does the output give you what you expect?
5. Now connect the output of the oscillators to the mixer, capture several waveforms from the output of the mixer as you move your hand towards the proximity detector. Plot the output frequency versus the distance of the hand form the detector. What should the slope of this line represent?

5 PreLab 3: Due May 14, 2010

Now that we have signal tone proportional to the distance of the hand to the proximity detector, we need to output this signal to an 8Ω speaker. The goal is to design an amplifier that can deliver 2W to an 8Ω speaker.

1. Given the output of your mixer what is the output voltage that you would have to deliver to an 8Ω speaker to generate a peak power of 2W.

2. From this calculate the gain of you amplifier

3. Loudspeakers are generally modelled as inductors to isolate this from the output of the amplifier you need to use DC isolation, what is the value of this DC isolation cap. What happens if you do not use DC isolation.

4. To transfer maximum power you need to match the output impedance of your amplifier to the load, given that the load is 8Ω and knowing the gain of an amplifier is $g_m r_{out}$ even a gain of 10 requires large amounts of bias currents. This indicates that you will need a high-gain amplifier with low output impedance, which are of course opposing requirements. The best way to solve this problem is to follow a high gain stage with a unity gain buffer stage with a low output impedance. Design an amplifier that meets the gain and impedance requirements.

6 Lab 3: Due May 21, 2010

In this lab you will implement the audio amplifier that you designed in prelab 3.

1. Build only the gain stage of your design. Input a waveform from the signal generator and record the output waveform, does your amplifier give the right gain?

2. Build the unity gain low output impedance buffer and test it with a signal from the function generator. Now keep the input at an appropriate DC level and find the output impedance of the amplifier.

3. Connect the speaker (ensure it is DC isolated) and input a sine tone from the function generator in the audible range and demonstrate that your buffer can drive the speaker.

4. Connect the two stages together and show functionality using a signal generator.

5. Finally connect the output of the mixer to the amplifier, does the tone at the speaker change when you move your hand?

7 PreLab 4: Due May 28, 2010

The final part is to design a volume control based on hand movement as well. The simplest way to implement this is to use an oscillator (you need only one this time) and feed the output into a bandpass filter tuned to the oscillator's frequency. Since the antenna (which can be a rod , a plate or a loop like earlier) is connected to the oscillator, moving your hand toward the plate will decrease the frequency of the oscillator, when this is fed to a tuned resonant circuit (like a bandpass) the output amplitude will vary depending on where the frequency is on the resonance curve. Once an amplitude variation is obtained it is a simple matter of converting this to a DC waveform and using it to control the gain of an amplifier.

1. Design an antenna for your volume control and calculate the change in capacitance as you hand is brought closer to the antenna. Choose your baseline capacitance for your Oscillator such that the change in frequency due to hand movement is *at most* 10% of your free-running oscillator frequency.

2. Given that the maximum change in frequency is 10% what should the bandwidth be at half-max? Given this bandwidths what should be the Q of your filter?

3. The gain of your bandpass filter depends a lot on your AC-DC converter. For example if you are using a simple diode rectifier the output of your bandpass filter at half-max must be larger that the turn on voltage for your diode. Select a design for your AC-DC converter and then choose the appropriate gain for your bandpass filter.

4. The last phase of your design is to implement a voltage controlled gain, the simplest is to use a MOSFET as a voltage controlled resistor. Design a voltage controlled gain amplifier that allows for gain control in the range that the output of the DC signal varies so that the gain varies by at least 20 over this range.

8 Lab 4: Due June 4, 2010

In this lab you will implement the volume control portion of you circuit.

1. Implement your oscillator design and antenna and ensure that your oscillator is operating at the right free running frequency. Plot the frequency of the oscillator versus the position of the hand.

2. Implement the bandpass filter and from the step-response reconstruct the filter transfer function in the frequency domain.

3. Implement the AC-DC converter and verify it with a function generator. Connect the bandpass filter to you converter and verify the operation. Following this connect the output of your oscillator. Record the voltage change at the output of the converter as a function of the position of the hand to the antenna. From this plot and the earlier frequency versus

position plot compute the frequency response of your circuit. Does this match with the response obtained from the step response.

4. Design your voltage gain controlled amplifier. Using a DC control voltage and function generator plot the gain versus controlled voltage, does the gain vary by at least 20 when the control voltage is in the range of your frequency to voltage converter?

5. Connect your volume control circuit to the pitch control circuit that you designed earlier and ensure that your audio amplifier is after the volume control amplifier. Does your whole circuit work as intended? If not, why not?