Analog Function Generator

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1 Motivation

The purpose of this project is to make a function generator that has the capability to generate three different kinds of waveforms - a square wave, a triangle wave, and a sinusoidal wave using only analog circuitry. The user should be able to control the frequency of the wave as well as the amplitude of the wave (within limits).

A function generator has many practical electrical engineering applications. It is often necessary to produce different kinds of waveforms to test and debug various circuits and devices.

2 Method

The core generation of waveforms is through a relaxation oscillator which generates a square wave and a triangle wave through hysteresis. The way this works is simple - an operational ampifier basically functions as a comparator and keeps flipping its output high and low due to hysteresis. The triangle wave is generated at one of the inputs to the op-amp due to the charging and discharging of the capacitor that is part of the hysteresis loop. It is important to note that the charging and discharging of the capacitor is exponential but is reasonably linear in a small approximation.

The sine wave generation is done through an integrator circuit, which takes the triangle wave as input and outputs a quadratic waveform that is a reasonable approximation of a sine wave. The integrator introduces gain that is inversely proportional to the input frequency, and therefore this gain must be accounted for.

The user controls the frequency of the desired waveform through a dual-gang potentiometer. One of the potentiometers is hooked up to the relaxation oscillator, allowing the user to control the frequency of the generated waveform. The other is wired to a gain stage that follows the integrator circuit. This gain stage is necessary to compensate for the gain of the integrator in order to produce a sinusoid whose amplitude does not change with the frequency control.

There are a couple of other inverting op-amp gain stages to try to make the 3 waveforms have the same amplitude. All three signal are fed into a switch, which can be controlled by the user to select the desired waveform. This signal then goes into an inverting op-amp gain stage whose gain is controlled by a potentiometer. This is so the user can control the amplitude of the waveform.

3 Specifications

1. The function generator must be plugged in to a wall outlet to receive power.
2. The function generator can generate a square wave, a triangle wave, and a sine wave. The user can select between these waves using the central switch. The left most position corresponds to no signal, while the next positions correspond to square wave, triangle wave, and sine wave respectively.

3. The user can control the frequency of the generated signal using the left knob on the front panel. The frequency ranges from about 2.5 kHz to 100 kHz. The amplitude of the waveforms do not change with frequency.
4. The user can control the amplitude of the generated signal using the right knob on the front panel. The amplitude can range from about +2V to +12V.

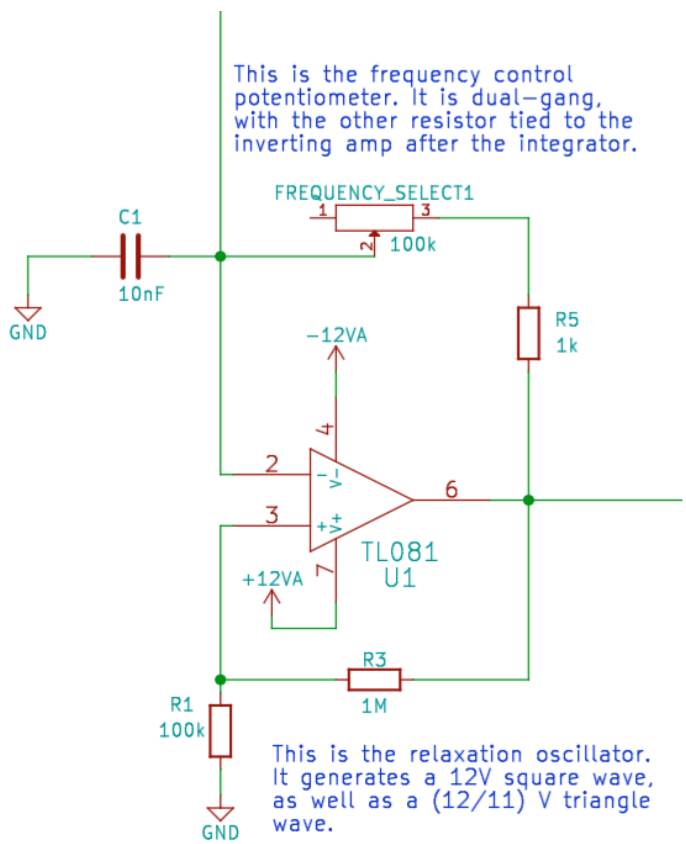
4 Characterization

The following is an analysis of how well my project handles signal generation.

- The frequency of each signal can indeed be changed from 2.5 kHz to 100 kHz. The amplitude of the generated signals are all nearly equal, but the triangle wave and sine wave exhibit some minor variations with frequency when the frequency change is large. This is not a huge problem - the user can just set frequency first and then adjust the amplitude.
- The sine wave quality is good in general but it is not great for certain settings of frequency (it sometimes looks quadratic and skewed), and there is also some noise introduced by the dual-gang potentiometer. This is an issue that should be improved in future iterations of the project.
- The amplitude control works fine. However, the signals can rail slightly if the amplitude control is maxed out.

5 System Components

5.1 Relaxation Oscillator



This circuit is where the core signal generation occurs. The op-amp acts like a comparator, and keeps flipping its output between high and low, thus generating a square wave. This is due to the hysteresis loop. The op-amp V_+ node is the output divided down by a factor of 11. This sets a threshold voltage that flips between +12/11 V and -12/11 V depending on the output. The capacitor linked to V_- keeps charging and discharging periodically, which keeps flipping the output and the threshold. As an example, if the output is initially at +12 V, the capacitor charges up until V_- is pulled to +12/11 V, at which point the output flips to -12 V, and the capacitor starts to discharge until it reaches the new threshold of -12/11 V. At this point the output flips once more, and the cycle repeats. The rate at which the capacitor charges and discharges is controlled by the frequency select potentiometer, which therefore controls the frequency of the generated waveforms.

The V_- pin has a triangle wave (approximately, since the capacitor charging and discharging is really exponential) while the output pin has the square wave, which is fed into an inverting op-amp amplifier to divide its level down to the level of the triangle wave. Note that the resistive divider was chosen to set the threshold at a factor of 1/11 of the output in order to make the charging and discharging of the capacitor approximately linear. An analysis of the theoretical frequency as a function of the resistance from pin 2 to pin 6 follows.

The capacitor is charging and discharging so we write

$$V_- = A + Be^{-t/RC}$$

since this is the general solution to the differential equation that governs the charging and discharging of a capacitor. Let us assume that at $t = 0$ our output V_{out} is $-V_{dd}$ (-12 V) and thus

$$V_-(0) = A + B = -\frac{R_3}{R_1 + R_3}$$

If the capacitor is allowed to charge indefinitely, it charges to V_{dd}, thus $A = V_{dd}$ and $B = -(1 + \frac{R_3}{R_1+R_3})V_{dd}$. Then the equation for V_- becomes

$$V_- = V_{dd} - (1 + \frac{R_3}{R_1 + R_3})V_{dd}e^{-t/RC}$$

We know that at $t = T/2$, V_- must rise to $\frac{R_3}{R_1+R_3}$ in order to flip the output. Plugging this into the equation above and solving for T, we obtain

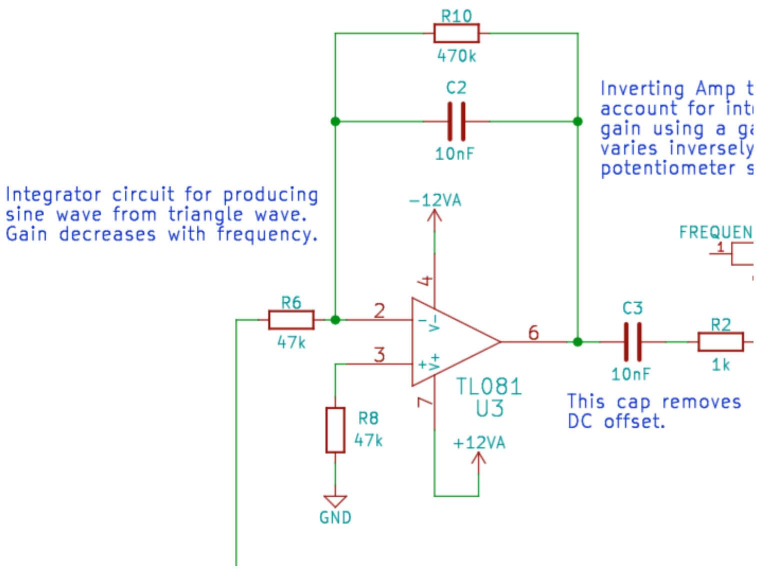
$$T = 2RC\log(1 + 2\frac{R_3}{R_1})$$

Then, solving for the frequency and plugging in our values, we obtain

$$f = \frac{1}{2\log(\frac{6}{5})RC}$$

This is why I used a base resistor of $1k\Omega$ and a $100k\Omega$ potentiometer - I wanted to get a frequency range of about 1 kHz to 100 kHz.

5.2 Integrator



The sine wave is produced from the triangle wave via a simple integrator circuit. Although the resultant waveform will be quadratic, it will be a reasonable approximation to a sine wave. The integrator transfer function is

$$H(s) = \frac{-\frac{R_{10}}{R_6}}{1 + sC_2R_{10}}$$

which as sC_2R_{10} grows sufficiently large, becomes

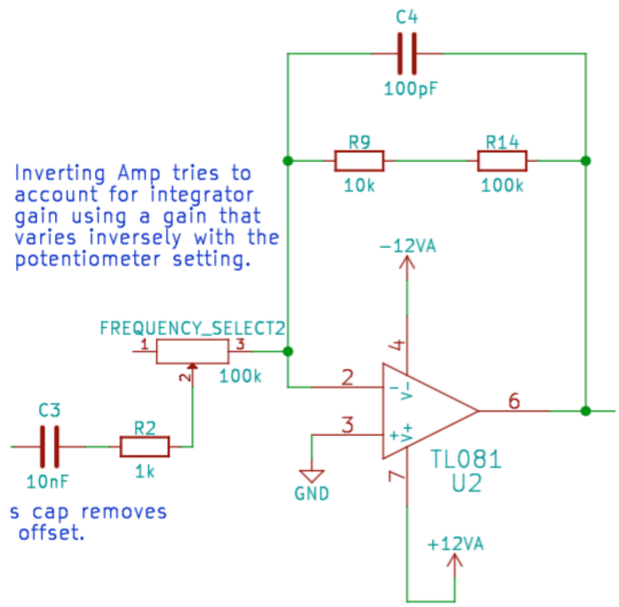
$$H(s) = -\frac{1}{R_6C_2s}$$

This limit corresponds to $\omega \gg \frac{1}{R_{10}C_2} = 213$ or $f \gg 34$ Hz. This is how the values of C_2 and R_{10} were chosen. The value of R_6 was chosen to be an order of magnitude lower than R_{10} for the DC gain characteristics of the integrator. Note that in the regime of interest

$$|H(j\omega)| = \frac{1}{R_6C_2\omega}$$

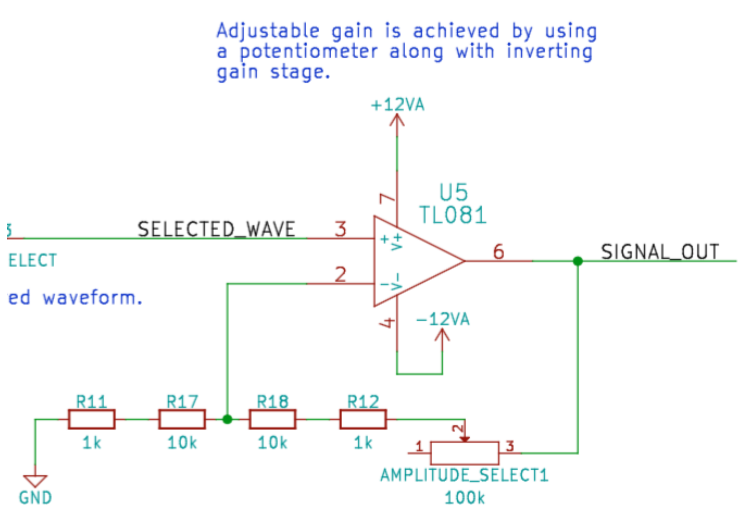
This means that the integrator gain decreases with the frequency that the user selects. The gain stage that follows the integrator attempts to correct for this. Also note that presence of C_3 which just removes the DC offset in the generated waveform.

5.2.1 Compensating for the Integrator gain



The design of this block started as a simple inverting op-amp gain stage with gain tied to the frequency control potentiometer setting using a dual-gang potentiometer. Since the integrator gain is inversely proportional to the frequency and the frequency is inversely proportional to the potentiometer setting, the integrator gain is proportional to the potentiometer setting. This block tries to compensate using a gain that is inversely proportional to the potentiometer setting through the standard inverting op-amp gain of $-R_2/R_1$. However, that was not enough to compensate and it turned out to be more beneficial to add the capacitor C_4 in parallel with the feedback resistance. This essentially made the circuit block another integrator, but in this case it functioned as a low-pass filter whose cutoff frequency moves along with the frequency select potentiometer. This helped clean the sine wave output as well as compensate for the gain. The design of this block turned out to be largely experimental to see what worked well and what did not.

5.3 Amplitude Control



This block simply uses a potentiometer and a non-inverting op-amp gain stage to control the amplitude of the output. It is relatively straight forward since the gain of the block is basically $1 + R_2/R_1$ and the potentiometer simply varies R_2. The values were chosen to provide a reasonable range of amplitudes (+2 V to +12 V).

6 Problems

I faced many significant problems during this project.

1. The relaxation oscillator worked perfectly on my first try, but as soon as I tried the integrator block I started running into significant issues. Getting the design of the integrator block was very tricky and even when I finally saw a sine wave output, I realized that the amplitude changed significantly with the frequency setting. Getting this amplitude to remain relatively constant without sacrificing too much of the sine wave quality was the most significant design challenge I faced. Using the compensating gain block eventually worked, but it took a long time and a lot of experimentation.

2. The packaging aspect of the project was also very challenging. I had trouble finding ways to attach my potentiometers to the protoboard. I ended up using wire wrap but the wires kept braking so I used solder and tape as well. I also had a lot of trouble exposing them to the front panel of the box. I ended up drilling holes, cleaning up the scraps of cardboard, and using hot glue, but it was a pretty messy task. The switch was by far the hardest thing to package though. It was incredibly difficult making a hole that was large enough for my switch to sit in, but not too large so that it wouldn't fit comfortably.

7 What I Learned

During the course of this project, I learned many things. I learned about how to design various analog circuit blocks to produce specific waveforms. I found the theory of how it all works beautiful - my circuit analysis classes finally came to life and helped me produce something meaningful. This project also helped me gain experience in making my work look nice and polished - it is a very useful skill to have and it is often neglected in engineering classes. In the real world, it isn't enough for a product to work. It needs to have aesthetic appeal - this is why Apple is so successful. Other than learning about the importance of packaging, I learned many other things in this class.

1. Op-amps are incredibly powerful and it is very easy to chain them together without worrying about loading effects due to high input impedance.

2. I learned from my EE90 switch fiasco and used hot glue to mount the switches in place. This helped make them much easier to turn.

3. Black box packaging makes projects looks super cool, and I get to say that the function generator that I made is literally a black box.

4. Theory is great, but in practice, you often need to try things instead of thinking too hard. Experimenting with different values for different components was very useful, especially when it came to the design of the integrator and compensating for its gain.

5. It is always a nice idea to keep a notebook. It helped me remember what I did and when, what values I used, and what I need to do next time. It also helped me write this report!

8 Future Work

There are many improvements that could be made to this project.

- The range of frequencies can be improved to accommodate some lower frequencies (on the order of Hz) and higher frequencies (on the order of MHz) by changing the potentiometer set up on the relaxation oscillator as well as the value of the capacitor.

- The quality of the sine wave could be improved some more through some careful experimentation.
- It would be nice to use a label maker to label the front panel controls to make the user interface feel more intuitive and natural. It'd be awesome if the amplitude control was exact for all three signals so that specific numbers could be labeled on the front panel.
- It also would be nice to create a better interface for connecting to the function generator than exposing two pins.