Operational Amplifiers and Spectral Analysis

Sameh AMMARI Jason OYUGI

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Introduction

An operational amplifier is a high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output. The amplifier's differential inputs consist of a non-inverting input with voltage V^+ and an inverting input with voltage V^-; ideally the op amp amplifies only the difference in voltage between the two, which is called the differential input voltage. In this configuration, an op amp will typically produce an output potential (relative to circuit ground) 100,000 times larger than the potential difference between its input terminals. The output voltage of the op amp V_{out} is given by the equation $V_{\text{out}} = A(V_{\text{in}}^+ - V_{\text{in}}^-)$, where A is called the open-loop gain of the amplifier. In this lab, we integrated the operational amplifier in different circuits and studied its behaviour.

Operational amplifier

To begin the experiment, we studied the operational amplifier, or op-amp. This circuit, shown below in Figure 1, acts as a comparator, the output voltage saturating at a constant value which depends on which input value is bigger.

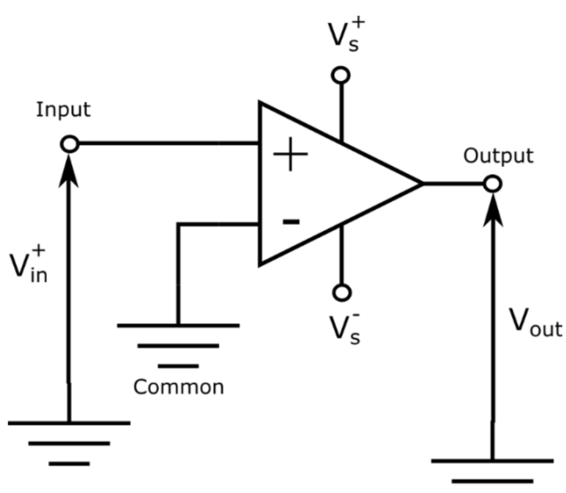

Figure 1: Differential amplifier circuit in comparator mount[1]

After setting up the comparator op-amp with V_{in}^+ connected to a square wave function generator with a $10V$ amplitude and with V_{out} connected to an oscilloscope, we indeed

[1] Taken from the lab instructions

observed that as the input voltage from the function generator changed to be positive or negative $10V$, the output voltage changed to be much larger (in magnitude) and constant, and it changed parity depending on the parity of the input voltage. A screenshot of our oscilloscope is shown below in Figure 2.

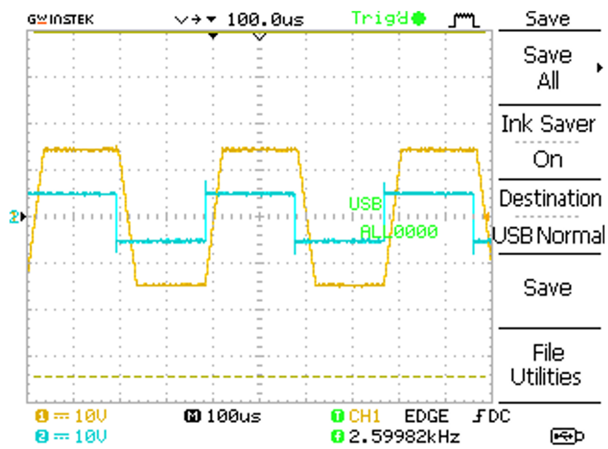

Figure 2: Comparator mount showing function generator (blue trace) and V_{out} (yellow trace)

We then set the op-amp to be in the negative feedback mount, shown below in Figure 3, which causes the difference between the input and output voltages across the resistors to go to zero and avoids fast saturation.

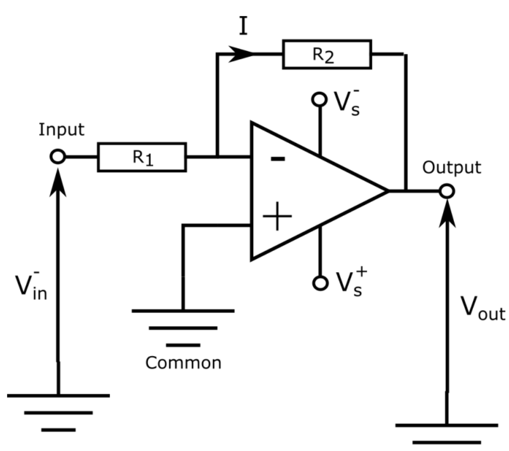

Figure 3: Negative feedback mount circuit [2]

By connecting the R_2 resistor to a variable decade resistor, we were able to collect V_{out} as

[2]Taken from the lab instructions

a function of R_2 and thus plot the gain G as a function of R_2. Our data is plotted below in Figure 4.

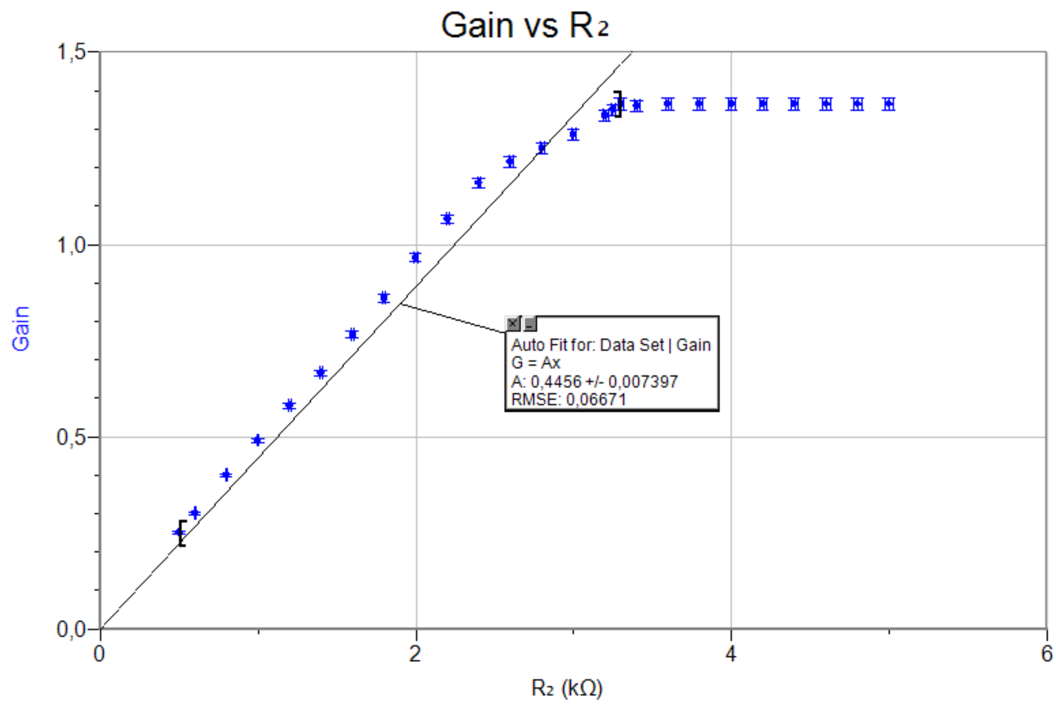

Figure 4: Gain as a function of R_2

We notice that the gain increases linearly with R_2 until a certain point, after which it levels off and remains constant. Using the definition of the gain parameter and equation 4 from the lab instructions, we have that the gain is $G = \frac{V_{out}}{V_{in}^{+} - V_{in}^{-}} = \frac{-V_{in}^{-}}{R_1(V_{in}^{+} - V_{in}^{-})} R_2$. Thus we expect G to increase linearly with R_2. However, we also expect the circuit to saturate, at which point the output voltage will not change, so the gain will be constant as R_2 increases, which is indeed what is shown in our data in Figure 4. Thus, we set our data to a linear fit passing through the origin (since with zero resistance there should theoretically be no voltage), excluding the data which showed clear circuit saturation (the included data is shown by the black brackets on the graph. The resulting linear fit showed that our gain had a coefficient of $0.4456 k\Omega^{-1}$ and since the fit has a root mean square error of 0.067, we see that our data is indeed linear.

Oscillator

We then proceeded to study the operational amplifier to obtain negative resistance. To do this, we set up the circuit shown below in Figure 5

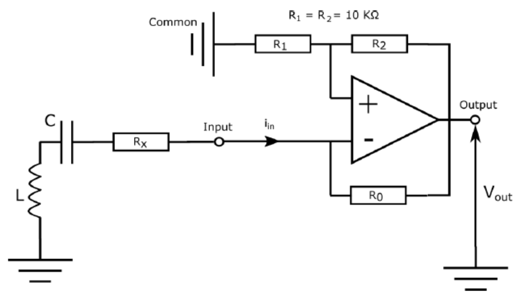

Figure 5: Negative resistance circuit [3]

For R_0, we used a decade resistor and the output voltage was attached to the oscilloscope. To begin, we had several issues as the output of our circuit showed a non-sinusoidal shape that was not expected (according to the professor who was guiding this lab), and furthermore it did not varied very little with the resistance, requiring hundreds of kilo-ohms in order to make a change. After much reworking and attempting to fix our circuit, we were finally able to get a proper sinusoidal shape appearing. When we decreased R_0 to 0, the output voltage was 0, but as we increased the resistance, we saw that the output voltage followed a sinusoidal shape, shown below in Figure 6.[4] These oscillations were very low amplitude.

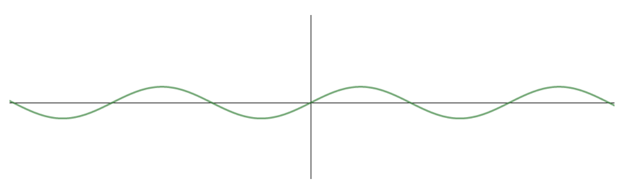

Figure 6: Shape of threshold oscillations [5]

[3]Taken from the lab instructions

[4]Unfortunately, after we completed this section of the lab, we discovered that all of the screenshots that we had taken during this part of the session did not save to our USB drive. However, due to the complications with the threshold resistance, we had already rewired our circuit several times. We then spent a long time trying to rebuild our circuit to recollect the data and try to save new screenshots, however we ran out of time during the session. We did make sketches in our notes of the shapes and we recorded the relevant values and we will include digital reproductions of those sketches in our report.

[5]Generated using GeoGebra.org

In order to find the threshold voltage at which the sinusoidal oscillations began to appear, we first set R_0 to clearly show oscillations. We then slowly decreased R_0 until there were no oscillations visible, and then we adjusted the scale of the oscilloscope to increase the resolution of the display. If, with this new "zoomed in" display, we saw oscillations, we continued to decrease the resistance and adjust the scale of the oscilloscope. We continued this pattern until we could not discern the oscillations from the noise and then we slowly increased the resistance until oscillations just appeared. The characterization of the oscillations at the threshold resistance are shown below in Table 1.

Table 1: Characterization of oscillations at threshold resistance

Threshold resistance	$6.638k\Omega \pm 0.5\%$
Frequency	$277.8 \pm 10kHz$
Amplitude	$17.6 \pm 0.8mV$

The LC circuit connected across the operational amplifier stores energy in the form of electronic oscillations. These oscillations are not damped and do not decay to 0 from electric resistance. This is because, the negative resistance from the op-amp cancels the internal loss resistance in the circuit, generating spontaneous continuous oscillations at its resonant frequency.

To determine the theoretical value of the frequency of the threshold oscillations, we can return to the lab S3 from last semester, titled "Analogy between mechanical oscillators and electrical circuits: Study of RLC circuits", we see that the oscillations have a threshold frequency described by

$$f = \frac{1}{2\pi\sqrt{LC}}$$

With the values indicated in this lab instructions, $L = 10.5mH$ and $C = 45nF$, we have a theoretical threshold frequency of

$$f_{theo} = 7.322kHz$$

However, we immediately noticed that our experimental threshold frequency is two orders of magnitude greater than the theoretical threshold frequency. We recomputed the theoretical threshold frequency and attempted to find the experimental threshold frequency several times more, yet each time we had the same result within just a few kHz of our first experimental threshold frequency. Our method was confirmed by the guiding professor, and we also checked our circuit several times, yet we could not determine why the experimental and theoretical values were so different. We attempted to build another circuit based off a photo of another group's circuit which gave them good values, but we were not able to get it to function since the photo was low quality and we could not see all of the components. In the end, we decided to move on, but it was at this point that we noticed that none of our oscilloscope screenshots had saved, and we attempted to rebuild our original circuit but we did not have enough time to finish rebuilding the circuit since we encountered several problems whilst doing so.

As a result, we could not see any clear relationship between the threshold value for R_0 and the resistances of the circuit. We do suspect that they should be equal. In this case, the net resistance will be zero, and so the damping is zero. Explicitly, if we analyse the circuit using Kirchhoff's law, we arrive at a the differential equation for a damped harmonic oscillator. However, in the case when R_0 and the resistances of the circuit are equal, the damping term is 0, and so there are only sinusoidal oscillations

We then progressively increased the value of R_0 to observe the output voltage V_{out} far from the threshold. At $R_0 = 10k\Omega$ and its neighborhood, we observed the same sinusoidal shape as we did at the threshold frequency (see Figure 6), although the amplitude was greatly increased. At $R_0 = 17k\Omega$, the shape began to appear more like a triangular wave with rounded peaks, similar to that shown below in Figure 7

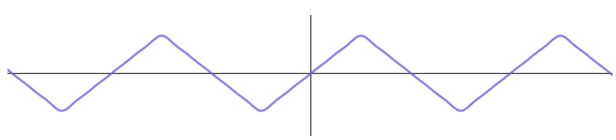

Figure 7: Shape of oscillations at $R_0 = 17k\Omega$, slightly far from threshold[6]

Then, at approximately $R_0 = 200k\Omega$ we saw a very sharp triangular wave, similar to that shown below in Figure 8

We increased the resistance of R_0 even farther, and extremely far from the threshold resis-

[6]Generated using GeoGebra.org

[7]Generated using GeoGebra.org

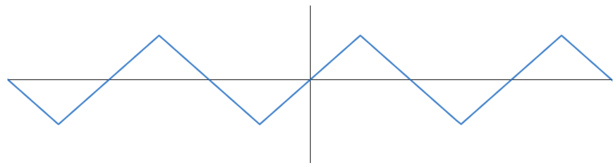

Figure 8: Shape of oscillations at $R_0 = 200k\Omega$, very far from threshold[7]

tance, at approximately $R_0 = 500k\Omega$, we saw that the peaks began to be flat on the top, similar to that shown below in Figure 9. This is most likely a result of the circuit reaching saturation and only outputting a constant voltage, the parity of which depends on the parity of the input voltage.

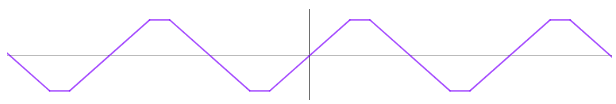

Figure 9: Shape of oscillations at $R_0 = 500k\Omega$, extremely far from threshold[8]

Unfortunately, our data was lost since the screenshots of the oscilloscope did not save and since the frequency of the oscillations of each shape were written on the screenshots, we did not write it down, so we can not compare the frequency of the oscillations of each shape to the threshold frequency oscillations. Additionally, since we spent so long building, rebuilding, and troubleshooting, we did not have time to begin the second part of the lab.

[8]Generated using GeoGebra.org