Phys219_2017 - Ryan Kaufmann/Exp. 4 (OpAmps)/Exp 4 Op-Amps

SIGNED by Ryan Kaufmann Nov 20, 2017 @09:34 AM PST

Ryan Kaufmann Nov 19, 2017 @04:17 PM PST

Experiment 4: Operational Amplifiers

Partner: Eric Brock

Ryan Kaufmann Nov 19, 2017 @04:17 PM PST

4.2 Objective

Ryan Kaufmann Nov 19, 2017 @04:23 PM PST

In this experiment, we are building on the last one with further exploration of other types of circuit components. However, this time we will be looking at one that has smaller circuits inside it. In this experiment, we plan to look at an integrated circuit called an operational amplifier, or op amp. We will explore the voltage gain of the circuit as well as explore any interesting behavior, such as bandwidth frequencies and non-ideal phenomena. We hope this lab will give us a better understanding of how integrated circuits, especially op amps, rely on outside conditions.

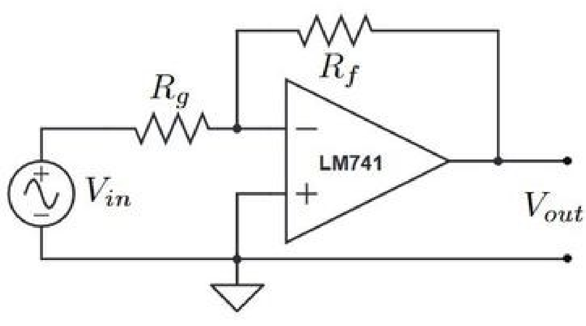
Ryan Kaufmann Nov 19, 2017 @04:22 PM PST

4.3 Introduction

Ryan Kaufmann Nov 19, 2017 @07:04 PM PST

The operational amplifier is an integrated circuit, meaning that component consists of smaller pieces hooked up inside of the component. The only access we have to the inside of the circuit is through the various number of pins on the side, which each correspond to a different part of the circuit. The op amp has a very basic property that allows it to take in an input voltage and output an amplified inverted signal. This circuit relies on a negative feedback loop and can be set up as so:

Ryan Kaufmann Nov 19, 2017 @06:57 PM PST



CircuitDiagram.jpg(21 KB)

Ryan Kaufmann Nov 19, 2017 @06:58 PM PST

Then the op amp both inverts and amplifies the input signal, giving an output signal that satisfies the following:

Ryan Kaufmann Nov 19, 2017 @07:00 PM PST

$$V_{out} = G * V_{in}$$

$$G = -\frac{R_f}{R_g}$$

Ryan Kaufmann Nov 19, 2017 @07:20 PM PST

The op amp has a few key parameters that need to be taken into account, namely the open loop voltage gain and the impedance. In an ideal op amp, the impedance in infinite and the open loop voltage gain is infinite and frequency independent. When we take into account the non ideal behavior of our op amp, our gain equation becomes a little more interesting:

Ryan Kaufmann Nov 19, 2017 @07:24 PM PST

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{G}{\sqrt{1 + (\frac{fG}{f_C A_0})^2}}$$

Ryan Kaufmann Nov 19, 2017 @07:28 PM PST

In this equation, G still denotes our gain, however, f represents our frequency, fc the cutoff frequency, and A0 the open loop gain at zero frequency. In this lab, we will explore this circuit and its equation. We wish to check the gain and how it relates to frequency and resistance in the circuit, by recording Vout under conditions where we keep frequency constant first, then voltage constant, and finally doing the same with different resistors.

Ryan Kaufmann Nov 19, 2017 @07:29 PM PST

4.4.1 Amplification and Linearity

Ryan Kaufmann Nov 19, 2017 @07:37 PM PST

Let us start by setting up our circuit as so:

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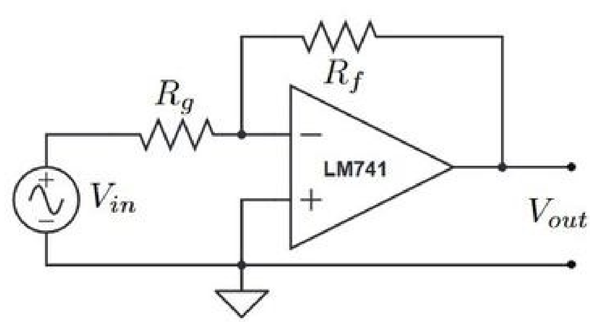

CircuitDiagram.jpg(21 KB)

Ryan Kaufmann Nov 19, 2017 @08:50 PM PST

In this diagram, Vout will go into the oscilloscope and then to ground. To start off with, we will try a Rf resistor of 100 kilOhms and Rg of 1kilOhms. Then we set up our function generator to output a sinusoidal with peak-to-peak amplitude of 25mV and frequency of 100Hz. By varying the amplitude and offset, we found the saturation points of the op amp. We found that the op amp saturated around an output of -14V and at 15V, giving a flat value once we got to those points. The on-screen distortion could be seen as so, with the first having no distortion, then lower distortion and finally upper distortion:

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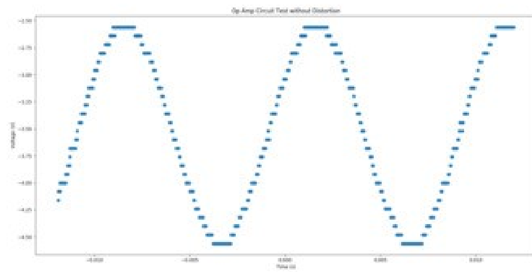
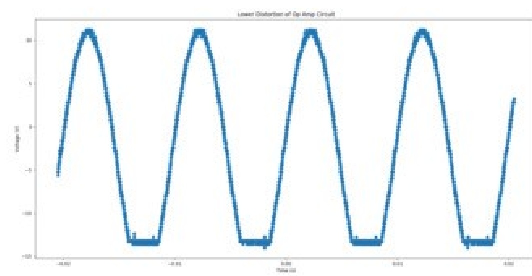


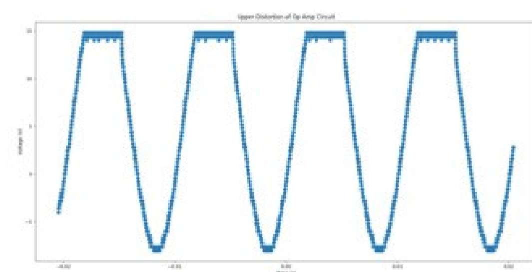
NoDistortion.png(46.6 KB)

Ryan Kaufmann Nov 19, 2017 @08:50 PM PST



LowerDistortion.png(98.8 KB)

Ryan Kaufmann Nov 19, 2017 @08:50 PM PST



UpperDistortion.png(98.8 KB)

Ryan Kaufmann Nov 19, 2017 @09:45 PM PST

With this knowledge, we wanted to explore the linearity of the amplifier. We first set our function generator to output a sinusoidal of the same amplitude but now at a frequency of 50Hz. Then we took values of various input amplitudes of the sinusoidal function. We set our sinusoidal to output at 0.005 rms voltage and took measurements at 0.005 voltage intervals. We decided the rms voltage would be best since we were using the digital multimeters to measure the output voltage. We measured the output voltage from 0.005 volts to 0.06 volts, giving us the following data:

Ryan Kaufmann Nov 19, 2017 @09:46 PM PST

LowFreqGain.csv(323 Bytes)

Ryan Kaufmann Nov 19, 2017 @09:55 PM PST

We then fit the data using the linear fit script. The fit was fair, giving us a small pattern in the residuals and a chi-squared of 1.904. While this isn't the best fit, it shows that the fit is still fairly linear. Thus data gives us the following parameters and graphs:

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$$G = 96.8000 \pm 0.0997$$

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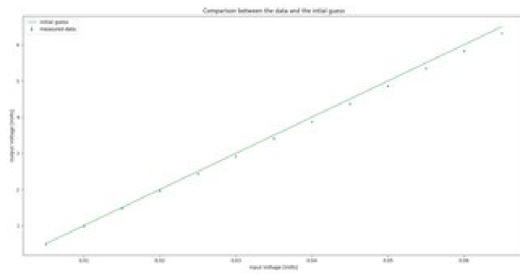

InitialLowFreq.png(52.9 KB)

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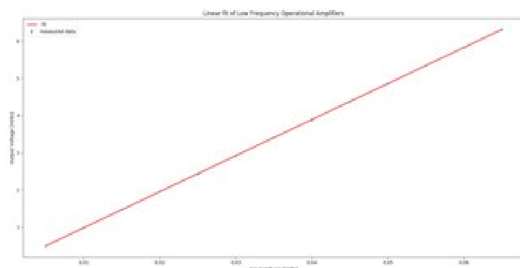
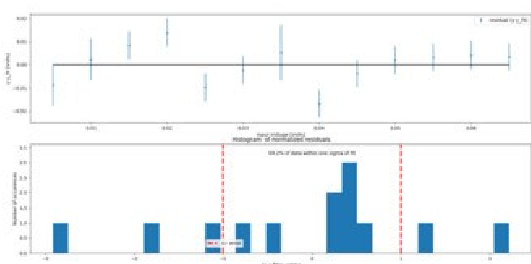


FittedLowFreq.png(49.1 KB)

Ryan Kaufmann Nov 19, 2017 @09:57 PM PST



ResidsLowFreq.png(48.8 KB)

Ryan Kaufmann Nov 19, 2017 @09:58 PM PST

This gain is fairly similar to the gain we expect. After measuring the resistors we used we got the following values and theoretical gain:

Ryan Kaufmann Nov 19, 2017 @10:05 PM PST

$$R_f = 98870 \pm 20 Ohms$$

$$R_g = 987.6 \pm 2 Ohms$$

$$G = \frac{R_f}{R_g} = 100.11$$

$$\sigma_G = G * \sqrt{(\frac{\sigma_{R_f}}{R_f})^2 + (\frac{\sigma_{R_g}}{R_g})^2} = 0.000414655$$

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which gives us a T-score of approximately:

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$$T = \frac{|G_{data} - G_{theory}|}{\sqrt{\sigma_{data}^2 + \sigma_{theory}^2}} = \frac{|96.8 - 100.11|}{\sqrt{0.0997^2 + 0.000414655^2}} = 33.1993$$

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Which is a pretty high T-score, much higher than our defined cutoff of 3. However, we can see that the values are quite close, so there might be a problem with our uncertainties being too low. There other option might be that there is an uncertainty that we didn't take into account when measuring the resistances.

Now, let us try a different frequency to see if we get the same results. We decided to look at the high frequency of 100kHz, using the same procedure, we measured the output versus the input voltage of the system, now going from an input voltage of 0.005V rms to 0.075V rms. We got the following data:

Ryan Kaufmann Nov 19, 2017 @10:16 PM PST

HighFreqGain.csv(397 Bytes)

Ryan Kaufmann Nov 19, 2017 @10:30 PM PST

The fit we got was both better and worse. On one hand, our chi-squared was much better for this plot, having a value of 1.16323, showing a fair fit. However, our residuals showed a pattern that was clearly not linear. There is a large bow in the residual plot, giving the impression that the data is better fit to an exponential or polynomial of some sort. This matches our theory as well, showing us that the frequency can affect the linearity of the gain. The data is as follows:

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$$G = 6.355 \pm 0.09812$$

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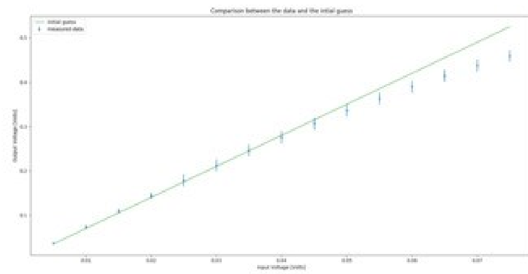
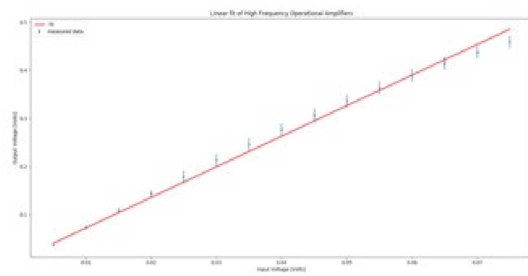


InitialHighFreq.png(54.6 KB)

Ryan Kaufmann Nov 19, 2017 @10:31 PM PST



FittedHighFreq.png(51.2 KB)

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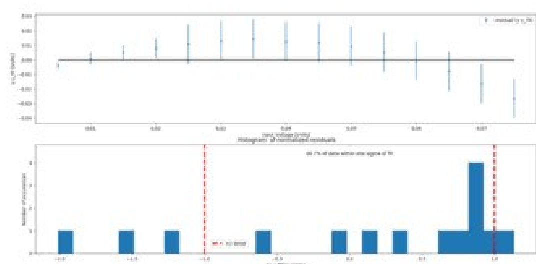


ResidsHighFreq.png(49.4 KB)

Ryan Kaufmann Nov 19, 2017 @10:38 PM PST

Our data also gives us a gain that is much less than the theoretical gain we calculated, so much that a t-score would reveal nothing to us. However, this large change in gain was expected. As we said before, our op amp is not ideal and thus has a certain point where the gain starts to decrease as a function of frequency. This is due to the non-infinite open loop voltage gain that is a property of all operational amplifiers. How this behaves with respect to frequency is what we analyze next.

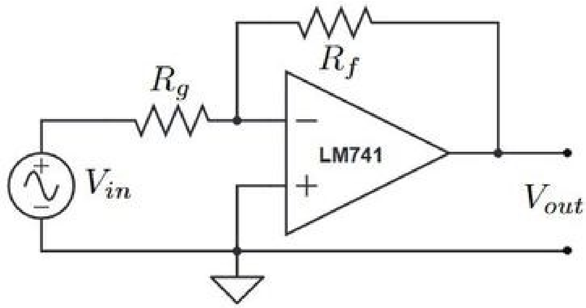
Ryan Kaufmann Nov 19, 2017 @10:39 PM PST

4.4.3 The Non-Ideal Op Amp

Ryan Kaufmann Nov 19, 2017 @10:50 PM PST

In the second part of the lab, we want to explore the behavior of the gain with respect the frequency. We will be using the same circuit setup as the previous part:

Ryan Kaufmann Nov 19, 2017 @10:51 PM PST



CircuitDiagram.jpg(21 KB)

Ryan Kaufmann Nov 19, 2017 @11:02 PM PST

For this segment we want to keep the rms voltage constant for the entire time. Meanwhile, we would change the frequency of the input voltage and see if it follows the following equation:

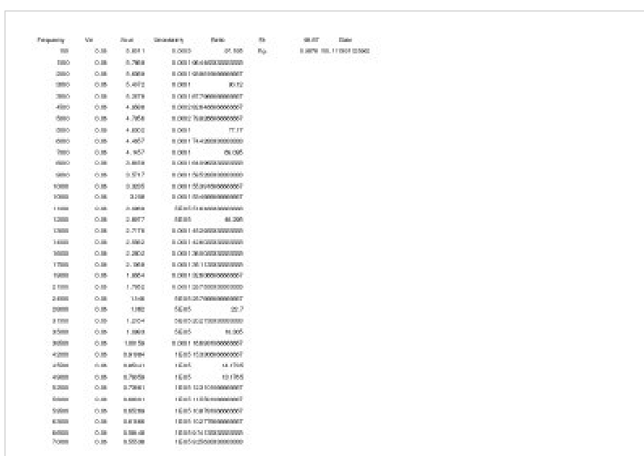
Ryan Kaufmann Nov 19, 2017 @11:05 PM PST

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{G}{\sqrt{1+(\frac{fG}{f_c A_0})^2}}$$

Ryan Kaufmann Nov 20, 2017 @12:23 AM PST

We first looked at the Rf and Rg we had in the previous equation, giving us an original gain of 100.11, approximately. We then took the input voltage to be 0.06V rms. We picked this voltage so that we could get close to clipping but still have a high voltage so that when the gain decreases as the frequency increases, the voltage out is still measurable. Thus we varied the frequencies starting from 100 Hz to 100000Hz, getting the following data:

Ryan Kaufmann Nov 20, 2017 @12:24 AM PST



Frequency-GainMeasurement.xlsx(10.7 KB)

Ryan Kaufmann Nov 20, 2017 @12:33 AM PST

We then used another python script to fit the data to a op amp frequency curve. We got a relatively good fit for the data, with a chi-squared of 1.06. However, our uncertainties are not the best. While they seem to mostly revolve around 0, there is a clear pattern in them. The pattern seems to suggest there is another element we aren't taking into account, or our fit is more or less exponential that what we actually predicted. Our first fit gave us the following parameters and fits:

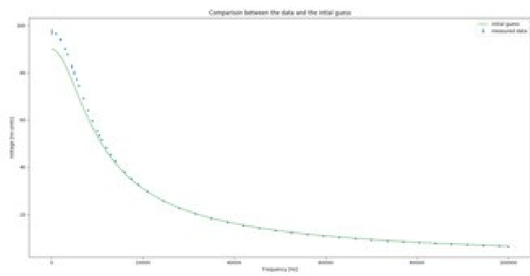
Ryan Kaufmann Nov 20, 2017 @02:35 AM PST

$$G = 99 \pm 0.2572$$

$$f_c A_0 = 662600 \pm 199Hz$$

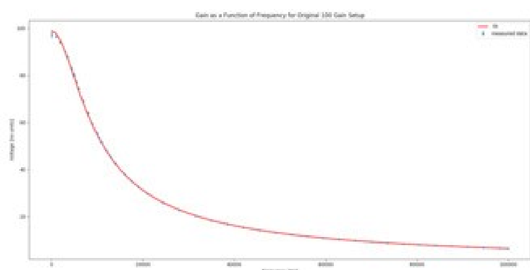
$$V_{offset} = -0.1664 \pm 0.03208V$$

Ryan Kaufmann Nov 20, 2017 @12:45 AM PST



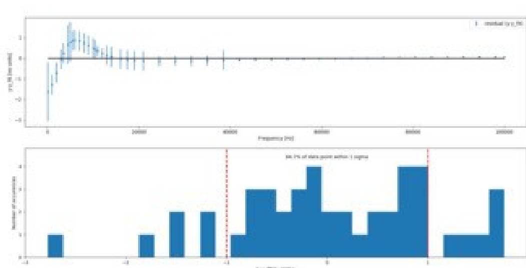
Gain100Initial.png(51.7 KB)

Ryan Kaufmann Nov 20, 2017 @12:45 AM PST



Gain100Fitted.png(50.2 KB)

Ryan Kaufmann Nov 20, 2017 @12:45 AM PST



Gain100Resids.png(38.4 KB)

Ryan Kaufmann Nov 20, 2017 @01:44 AM PST

By looking at our fits, we can estimate the bandwidth frequency. Using the numbers that we have, we can apply the gain formula to see when the voltage drops by sqrt(2):

Ryan Kaufmann Nov 20, 2017 @02:35 AM PST

$$\frac{G}{\sqrt{1+(\frac{fG}{f_c A_0})^2}} = \frac{1}{\sqrt{2}}$$

$$\sqrt{1+(\frac{fG}{f_c A_0})^2} = \sqrt{2}G$$

$$1+\frac{f^2G^2}{f_c^2A_0^2} = 2*G^2$$

$$f = \sqrt{2(f_c A_0)^2 + \frac{(f_c A_0)^2}{G^2}}$$

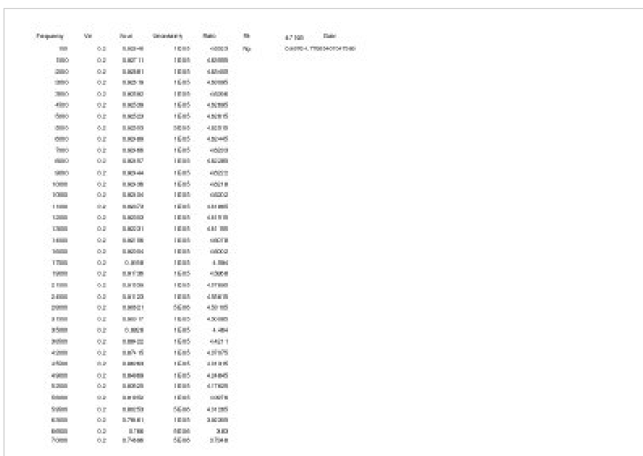
$$f = 937080Hz$$

Ryan Kaufmann Nov 20, 2017 @09:11 AM PST

We noted that this bandwidth frequency doesn't make any sens with the graphs we produced. This may be because of some mistaken data taking or error in the fit formula. We cannot say exactly what is wrong but more experimentation can reveal the answer.

We can repeat these measurements with different resistors to see how these values change as a function of the resistance. The next resistor we tried was the 4.7kOhm resistor. We followed the same procedure as before, now with a gain of 4.7. We got the following data:

Ryan Kaufmann Nov 20, 2017 @02:09 AM PST



Frequency-GainMeasurement_5kOhm_.xlsx(10.6 KB)

Ryan Kaufmann Nov 20, 2017 @02:15 AM PST

This fit was much worse than the previous fit. While our residuals were not terrible, revolving around zero with minimum pattern. However, our chi-squared was extremely high, giving a value of 5.6207. Thus, our fit isn't probably the best. However, we still got the following values and graphs:

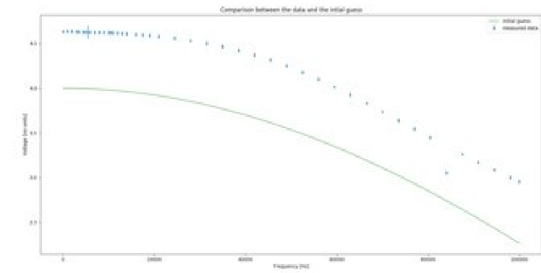
Ryan Kaufmann Nov 20, 2017 @01:25 AM PST

$$G = 29.23 \pm 6.499$$

$$f_c A_0 = 8016000 \pm 2747000Hz$$

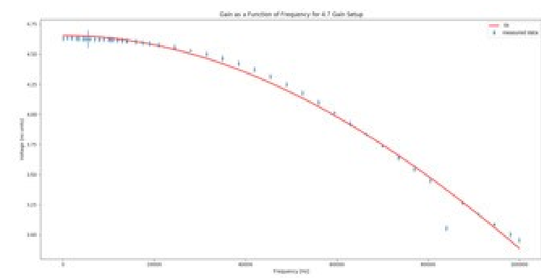
$$V_{offset} = -24.58 \pm 6.502V$$

Ryan Kaufmann Nov 20, 2017 @02:16 AM PST



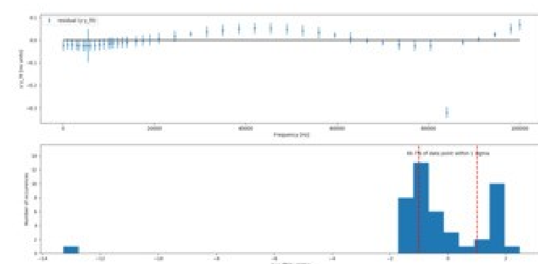
Gain4.7Initial.png(53 KB)

Ryan Kaufmann Nov 20, 2017 @02:17 AM PST



Gain4.7Fitted.png(57.2 KB)

Ryan Kaufmann Nov 20, 2017 @02:17 AM PST



Gain4.7Resids.png(42 KB)

Ryan Kaufmann Nov 20, 2017 @02:23 AM PST

Once again, we can calculate the bandwidth frequency of the circuit using the same formula:

Ryan Kaufmann Nov 20, 2017 @02:32 AM PST

$$\frac{G}{\sqrt{1+(\frac{fG}{f_cA_0})^2}} = \frac{1}{\sqrt{2}}$$

$$\sqrt{1+(\frac{fG}{f_cA_0})^2} = \sqrt{2}G$$

$$1+\frac{f^2G^2}{f_c^2A_0^2} = 2*G^2$$

$$f = \sqrt{2(f_cA_0)^2 - \frac{(f_cA_0)^2}{G^2}}$$

$$f = 10^7 Hz$$

Ryan Kaufmann Nov 20, 2017 @09:04 AM PST

And again, the bandwidth frequency from the equation does not match the bandwidth frequency that appears on the graphs.

To wrap up, let us take another resistor where the gain is 0.1. Thus, rather than a gain, we had a loss. Following the same procedure as before, we got the following data:

Ryan Kaufmann Nov 20, 2017 @02:40 AM PST

Frequency-Gain0.1.csv(1.1 KB)

Ryan Kaufmann Nov 20, 2017 @02:45 AM PST

This was a strange fit to perform. We weren't sure how the fit would react to the data. We found that the chi-squared was a reasonable number, not as high as the last set, having a value of 1.7080. However, the residuals did not fit well into our plot, showing a pattern slightly. The data gave us the following graphs and parameters:

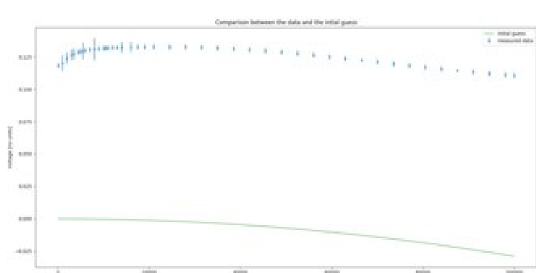
Ryan Kaufmann Nov 20, 2017 @01:35 AM PST

$$G = 11390 \pm 21840$$

$$f_cA_0 = 5.870e11 \pm 1.686e12$$

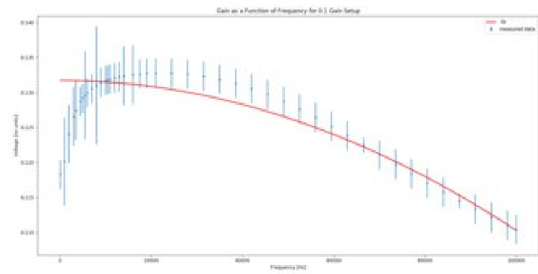
$$V_{offset} = 11390 \pm 21840V$$

Ryan Kaufmann Nov 20, 2017 @02:45 AM PST



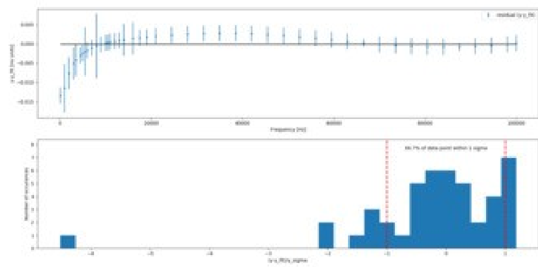
Gain0.1Initial.png(43.6 KB)

Ryan Kaufmann Nov 20, 2017 @02:45 AM PST



Gain0.1Fitted.png(54.7 KB)

Ryan Kaufmann Nov 20, 2017 @02:45 AM PST



Gain0.1Resids.png(43.4 KB)

Ryan Kaufmann Nov 20, 2017 @02:52 AM PST

From these fits, it doesn't seem as if this fit works when the gain is less than 1. Then the bandwidth and equation are meaningless.
Otherwise, the data and fits are the work well even if our values do not match well. That being said, we can calculate the t-score between the values of fcA0:

Ryan Kaufmann Nov 20, 2017 @02:56 AM PST

$$T = \frac{|fA_{100} + fA_{4.7}|}{\sqrt{\sigma_{100}^2 + \sigma_{4.7}^2}} = 2.677$$

Ryan Kaufmann Nov 20, 2017 @02:58 AM PST

Our t-score was above 1, which means that maybe the values are not the same, but it wasn't yet a 3. We concluded that the value of fcA0 needed to be explored more thoroughly for a more accurate number.

It is additionally important to note that fc and A0 cannot be separated in the fitting since we are unsure about how fc and A0 relate in the fitting.

Ryan Kaufmann Nov 20, 2017 @08:42 AM PST

4.5 Conclusion

Ryan Kaufmann Nov 20, 2017 @09:34 AM PST

In this lab, we started by testing the gain at single frequencies in both the low and high parts. What we saw was a massive difference between the gain at 50Hz and 100kHz, which can be described by the non-infinite open loop voltage gain. We received a gain of 96.8 and 6.355 with uncertainties of 0.0997 and 0.09812, respectively. However, when the first gain was compared to the theoretically calculated one, we received a t-score of 33. This may suggest that our uncertainties are too low and the data collection wasn't precise enough. We could retake data to reassure our original theory by either retaking the frequency data or remeasuring the resistors.

The second half of the lab focused on the non-ideal behavior of the operational amplifier. We wanted to compare the values for bandwidth frequency and the product of open loop voltage gain and cutoff frequency. We found that the bandwidths did not agree between the graphs and the theory with the values of the cutoff frequency and open loop voltage gain. For the original set up we had a value for the product of 662600, which seemed high, and a gain of 99, which was expected. However, when testing a circuit with a theoretical gain of 4.7, we got a value for the product of 8016000 and a gain of 29, neither of which were expected. We couldn't tell very well where our data went wrong. However, we stand by our data, believing that it is still good, and saying there may be an error in the fit function. To end this section, we also look at a circuit that had a loss instead of a gain. That is we set up a circuit with a theoretical 'gain' of 0.1. This data did not work with the theory we were present. The op amp did not do well when we attempted to make a loss and seemed to follow a completely different pattern.

In the end, we analyzed parts of a basic op amp circuit. There is still more to explore and better data collection to fully define the op amp. We think the fits could be optimized to produce better numbers but we could always collect more data for a better fit.