Operational Amplifier

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In this experiment we designed a voltage divider connected to an operational amplifier. The input for the amplifier was inverted. The gain, A, measured for the open loop circuit was inversely proportional to the frequency that was increased on the alternating current input. In the closed loop circuit the normal gain, G, remained a constant value of 100 because it was based off the additional resistors added to the circuit R_a and R_b.

I. INTRODUCTION

The operational amplifier, op amp, is a unique electronic component that is used as a high gain directly coupled amplifier that is typically used for feedback setups and has been around in the earlier eras of technology in the 20Th century. The characteristics of the op-amp serve as a indicator of how well an op-amp will perform. If the statistics aren't passable then the op-amp cannot be used to control the transfer function it has to manage amplification and feedback.[1]

The op-amps original application was developed originally from being used in analog computations in circuits to do summation and integration but as time and technology improved with time then it became the modern tool it is today as a generic analog processor of data elements. In the 1950's, the earlier models of the upper end op-amps were less flexible as they are today and had very limited functions. Within 10 years, into the 1960's, the op-amp had become similar to what it is today, inexpensive, widely available, and better developed for flexibility by being able to include in modular solid state-state circuits.[1]

In this experiment we will discuss the two circuit designs for the op-amp input and outputs. The op-amp has a open loop and closed loop circuit that was built upon a breadboard, a flat multi-layered surface with holes that allows you to connect various leads and wires. By doing both the open and closed loop we can test the open loop to see how the op-amp's characteristics perform to provide us the gain and feedback. Then by setting up the circuit as a closed loop we are able to purpose the setup into reducing the amount of noise that would be present in the open-loop setup and rely on the feedback response of the circuit than the characteristics of the op-amp.[2] The op-amp has several inputs and the primary thing to be concerned with in this setup is that we are using an inverted input when putting in our voltage, meaning that the sign of the voltage input will be opposite of what it supplied, if it's positive the input will be inverted to negative. The output of the op-amp will be connected to an oscilloscope that will allow us to observe the wave-forms that are generated from the AC input power supply that generates a waveform.

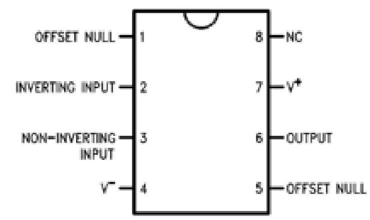

FIG. 1. Operational Amplifier and its 8 input post connections.

II. THEORETICAL BACKGROUND

A. Math and Equations: Open Loop

$$V_{div} = V_{in}(\frac{R2}{R1+R2}) \tag{1}$$

The first important part of developing our circuit is by creating a voltage divider in which this equation is purposed. A voltage will be passed in, V_{in}, and re-scaled by a pair of parallel resistors R_1 and R_2. This output will be called the divided voltage, V_{div}. Ideally, we use this voltage divider to limit the size of the input to get a cleaner signal output. The op-amp will be amplifying our input and can sufficiently provide a large output with a smaller input.

$$\Delta\phi = \Delta t * 360 * \nu \tag{2}$$

$\Delta\phi$, is the measurable phase shift that is found by measuring Δt between two wave-forms. The statistic is found by comparing peak to peak amplitudes because we want to measure how much the waveform has shifted when processed through the op amp. We multiply by the frequency, ν, and 360.

$$A = \frac{V_{out}}{V_{in}} \tag{3}$$

Next, we want to determine the standard gain of the circuit, A, we can get this statistic by comparing the output, V_{out}, and the input, V_{in}. The voltage input is divided, so when calculating the gain it also needs to be multiplied by the parallel resistor factor that is found in EQ(1).

$$A_{OL} = \frac{A_{max}}{\sqrt{1+\frac{V}{V_o}}} \tag{4}$$

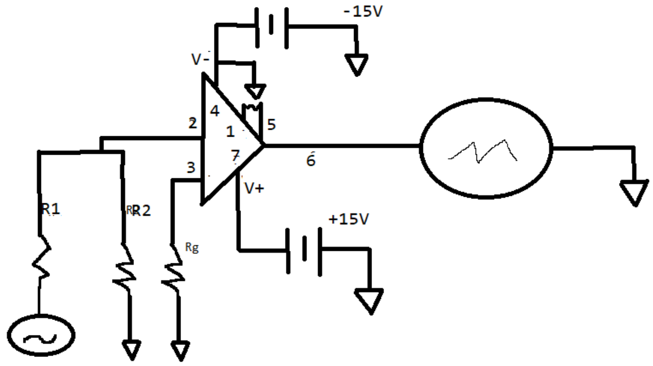

FIG. 2. Open Loop Circuit Diagram.

Then we are able to calculate the gain of the open loop circuit, A_{OL}, by using the parameters A_{max}, the highest ordinary gain measured,ν, the frequency being passed into our parameters, and ν_o, the cut-off frequency which will be determined by fitting our data to this equation using our parameters to estimate the cut-off frequency through curve fitting using python's SciPy functions.

TABLE I. Data table for the open-loop circuit diagram.

ν	V_{in}	V_{out}	$\Delta\phi$	A_{OL}
102.6 KHZ	2.00 V	4.20 mV	273.33°	31097.87
63.69 KHZ	2.04 V	19.2 mV	261.35°	34750.79
44.68 KHZ	2.00 V	26.4 mV	266.95°	37076.48
20.348 KHZ	600 mV	816 mV	234.4°	40870.81
10.356 KHZ	600 mV	184 mV	261.58°	42805.49
8.283 KHZ	600 mV	88 mV	262.46°	43242.42
6.405 KHZ	600 mV	496 mV	268.748°	43650.02
4.11 KHZ	600 mV	324 mV	236.74°	44164.13
2.52 KHZ	600 mV	240 mV	257.76°	44531.17
1.03 KHZ	660 mV	1.92V	242.658°	44883.55
855.0 HZ	260 mV	27.8 V	91.45°	44925.49
740.0 HZ	200 mV	23.6 V	91.15°	44953.11
611.0 HZ	174 mV	25.4 V	92.19°	44984.16
435.0 HZ	616 mV	28.8 V	90.85°	45026.62
331.1 HZ	404 mV	24.6 V	91.05°	45051.744
239.9 HZ	304 mV	27.4 V	90.68°	45073.83
142.3 HZ	180.0 mV	26.8 V	93.23°	45097.50
75.3 HZ	90.0 mV	24.4 V	86.75°	45113.78
42.08 HZ	1.02V	23.2 V	88.0092°	45121.85
22.66 HZ	536 mV	22.8 V	82.1402°	45126.57

III. METHODS, RESULTS, AND ANALYSIS: OPEN LOOP

For the setup of the open loop circuit we divided the voltage using our parallel resistors to make a voltage divider. The values for R_2 stayed constant at 10 ohms but R_1 was changed for the varying ranges of frequencies. We took our data from a range of 20 HZ to 100K HZ. R_1 was exchanged to 10.6K ohms, 9.96k ohms, 1K ohms, 570 ohms, and 100 ohms. The 1k and 570 ohm resistors were most frequently used in our process.

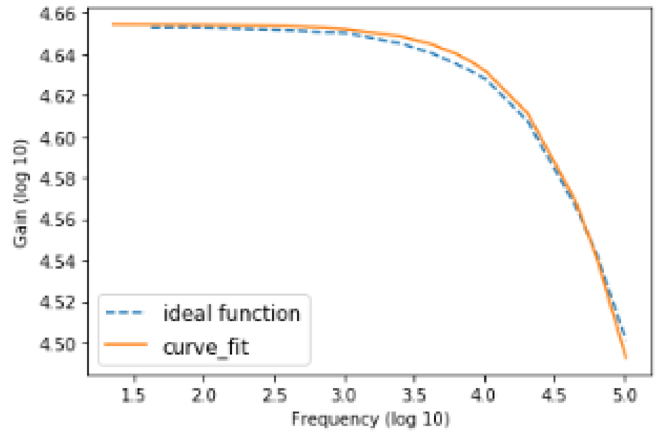

FIG. 3. Using A_{max} and ν_o as parameters to do a fitted curve to find the cutoff frequency and determine A_{OL}. Log scale for x and y.

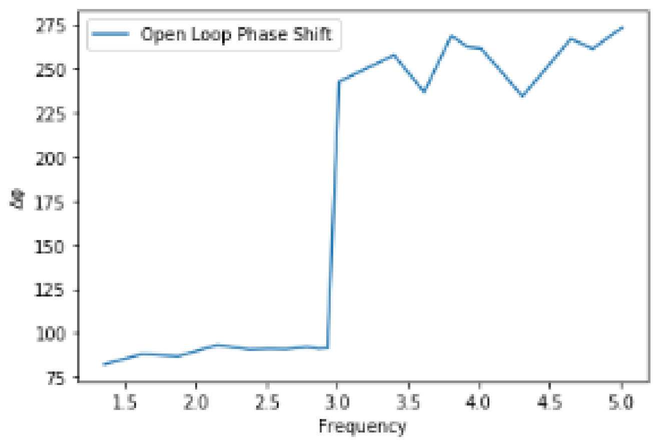

FIG. 4. Phase Shift diagram plotted log in the x-axis and normal in the y-axis.

We observed our output on 2 channels on an oscilloscope, the first channel to observe the wave provided by the AC input supply, and the second channel to observe the output. We measured our voltages based on the peak to peak values for the second channel of the oscilloscope. Then to determine the cut-off frequency to measure the open loop gain I used curve fit to find that value and re-evaluate EQ(4) using the cutoff frequency found to be around nearly 93,000 HZ.

By collecting ν and Δt we were able to plot the phase shift that was expected to have a very large step-like function in the graphical analysis. Using EQ(2) we were able to determine the phase shift for all respective frequencies. In our graph was plotted on a semi-log scale, where the frequency was plotted logarithmically. It was found that our data was in the region of which the large step could be seen in the 10^3 frequency region.

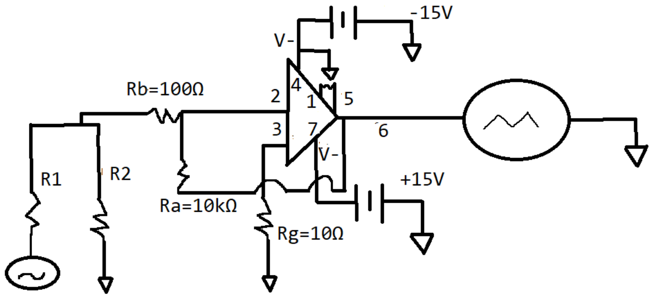

FIG. 5. Closed Loop Circuit Diagram.

IV. THEORETICAL BACKGROUND

A. Math and Equations: Closed Loop

$$G = \frac{R_a}{R_b} \tag{5}$$

G, is similar to A in the open loop setup, it is the closed loop's constant gain that is found by dividing the newly added resistors R_a and R_b.

$$||A_{CL}|| = \frac{G}{\sqrt{1 + \frac{(1-G)^2}{A_{OL}^2}}} \tag{6}$$

The closed loop gain, A_{CL}, is found by making use of EQ(4) in the open loop setup. We want to fit our data to this function by providing G and the open loop circuit gain, A_{OL}. The brackets surrounding A_{CL} are to show that A_{CL} should be a positive value.

TABLE II. Data Table for the closed loop circuit diagram setup. The output gain for the closed loop was a constant value G, of 100, because of resistors R_a and R_b in Fig 2. The output closed loop gain was fitted using A_{CL} and the respective frequencies for the open loop setup.

ν	V_{in}	V_{out}	A_{CL}
1.388 MHZ	1.38 V	16.0 mV	43047.21
763.3 KHZ	1.38 V	16.0 mV	40281.09
523.5 KHZ	1.42 V	14.8 mV	33581.57
309.8 KHZ	7.40 V	7.08 mV	30327.39
216.9 KHZ	7.40 V	62.0 mV	28530.16
107.7 KHZ	7.32 V	45.2 mV	25713.36
17.76 KHZ	2.72 V	16.8 mV	23561.97
6.276 KHZ	4.40 V	14.4 mV	19933.65

V. METHODS, RESULTS, AND ANALYSIS: CLOSED LOOP

Setting up the closed loop circuit was fairly simple as we added two resistors R_a and R_b that were connected to the input and output. The purpose of these was to reduce feedback for the output. The resistor values chosen for R_a and R_b were respectively 10K ohms and 100 ohms. Then by using python functions I was able to use the frequencies of the open loop circuit and the open loop gain to determine values for A_{CL} and then fit the data for the closed loop circuit to observe the curve of the closed loop.

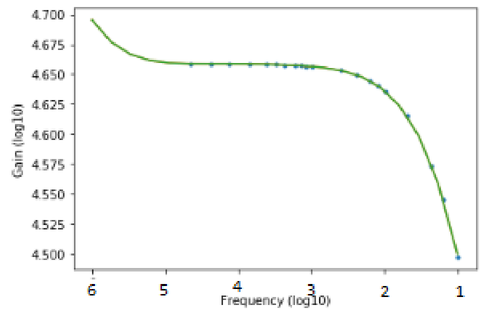

FIG. 6. Closed Loop Fit x-y log scale polyfit to determine the gain to fit collected data to using the passed back function.

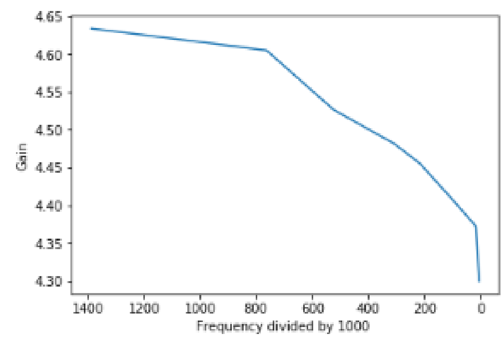

FIG. 7. Closed Loop AC input data fitted to the function $-1973x^2 + 975x + 3.446e4$ provided by FIG. 5. Frequencies were scaled down by a division of 1000 and the Gain was scaled log base 10.

TABLE III. Data Values taken by switching from an AC power supply input to a DC power supply and measuring the input and output voltage for the closed loop circuit.

Vin	Vout
-5.14 V	509.0 mV
-4.09 V	405.0 mV
-3.023 V	299.5 mV
-2.086 V	206.0 mV
-1.035 V	102.1 mV
1.034 V	1.5 mV
2.044 V	1.8 mV
3.072 V	-34.0 mV
4.09 V	-135.2 mV
5.0 V	-226.2 mV

VI. CLOSED LOOP: DC INPUT

In this part of this experiment the alternating current (AC) power supply input was exchanged with a DC input power supply. Originally, we planned to use the original resistors that were used in the closed loop setup with AC input using R1 of 10K Ω and R2 staying at 10 Ω but discussing with others in the lab lead us to try to use a 1KΩ resistor for R1.

For data collection we had set on keeping the voltage low at a range of -0.5V to 0.5V in order to be preventive of anything happening to the op-amp as we had heard from other groups that they had used a low voltage input on their DC power supply. A problem we ran into when attempting data collection was that our output voltage seemed too small in comparison to the results of others and our expectations. We then decided to increase the voltage of our setup and changed our range from -5.0V to 5.0V.

There is a variety of possibilities that could have caused us to get the wrong output. First, I think it is possible that we overwhelmed the amplifier when changing resistors around or switching around connections any connections to our reading meters. I did try to see if disconnecting the power supply would have an significant impact while inputting an very low voltage to avoid risking actually breaking the op-amp. When the power supply turned off then the voltage reading of the output matched the input that the external dc power supply was providing. For now I think it ruled the possibility of the op-amp being broken.

Other alternative methods I would possibly consider adding another voltage divider to the external DC power supply to be certain of small inputs being put into the op amp. The thing that seemed quite interesting when trying to make adjustments was the potentiometer. The potentiometer had a different offset and it is possible that it was offset so much that it prevented us from reading a properly amplified input but I'm not too certain regarding that. The op-amp is somewhat of a voltage divider and can control how much is going through the op-amp so it is possible that if we had adjusted pot enough that we would've read larger output signals.

VII. INTERPRETATION AND CONCLUSIONS

In the open loop circuit the gain appears to be inversely proportional to the frequency. For larger frequencies the gain is smaller and for the smaller frequencies the gain is larger. For the closed loop circuit the gain value G, remains constant, but the gain for the closed loop is directly proportional to the frequency. At approximately 10^5 frequencies the V_{in} and V_{out} reach a point where they're no longer changing in values because they've reached the cutoff as seen in Table II. The DC input into the closed loop circuit had a lot of issues and I think that there could be a lot of opportunity to be more cautious about applying too much voltage and or making sure all wires and leads are properly connected so that each input is known and expected to do what is said it's supposed to do.

In this experiment there was a lot of opportunity to make errors primarily with creating the circuit on the breadboard. Human error can take into account a large portion of mishaps that occur and or poor data collection. The biggest concern that I had with this experiment is making sure that all inputs were connected to the op-amp properly and that all wire leads were completely connected as sometimes it is difficult to tell on the breadboard. There was a substantial amount of noise in the open-loop circuit which lead to us frequently using the oscilloscope's acquire function that allowed us to take averages of the function outputs. At lower end frequencies for the open loop the voltage railed very rapidly and the potentiometer had to be adjusted quite often.

TABLE IV. Data Table listing the Frequencies and Gains of the open and closed circuit.

v_{OL}	A	A_{OL}	v_{CL}	A_{CL}	G
102.6 KHZ	2.093	31097.87	1.388 MHZ	43047.21	100
63.69 KHZ	9.38	34750.79	763.3 KHZ	40281.09	100
44.68 KHZ	13.16	37076.48	523.5 KHZ	33581.57	100
20.348 KHZ	137.36	40870.81	309.8 KHZ	30327.39	100
10.356 KHZ	30.97	42805.49	216.9 KHZ	28530.16	100
8.283 KHZ	14.81	43242.42	107.7 KHZ	25713.36	100
6.405 KHZ	83.49	43650.02	17.76 KHZ	23561.97	100
4.11 KHZ	54.54	44164.13	6.276 KHZ	19933.65	100
2.52 KHZ	40.40	44531.17			
1.03 KHZ	293.82	44883.55			
855.0 HZ	1176.15	44925.49			
740.0 HZ	1298.0	44953.11			
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22.66 HZ	45132.09	45126.57			

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[1] J. K. Roberge, *Operational Amplifiers: Theory and Practice* (John Wiley Sons, 1975).
[2] A. C. Melissinos, *Experiments in Modern Physics* (Academic Press, 2003).