Operational Amplifier

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Operational Amplifiers are used to amplify voltage signals of both alternating and direct current. This experiment covers the amplification of a frequency input via open and closed loop systems where the gain for a closed loop system is much more stable at the lower frequencies and has a maximum gain of 110, and a stable gain of 92, where the cutoff frequency is 3.67 $*10^5$ Hz and the frequency at which the gain begins to decreases is 1.1 $*10^4$ Hz. On the other hand, our open loop gain is slightly less stable since no feedback is provided, essentially creating a linear path for the voltage. The achieved maximum gain is 1.0 $*10^5$ where the stable gain is around 1 $*10^5$ and a decrease in gain is observed at 10 Hz, where the cut-off frequency of the open-loop circuit is at 3.4 $*10^5$ Hz. The phase shift of the open loop has a cut-off frequency at 3.8 $*10^5$ Hz. finally, if a direct current is applied to the closed-loop circuit, we observe a max saturation voltage of +14.21 V and a min of -14.07 V.

I. BACKGROUND AND USES

Amplifiers as the name imply; amplify weak signals. An example would be a radio or speaker, where a weak radio signal is received and amplified to be heard. Here we are looking at Operational amplifiers, which amplify voltages in circuits found in almost all electronic devices. The Operational Amplifier was first created in 1963 by Robert Widlar [2]. Though the design was not ideal at the time, it was the first of its kind to amplify voltage signals at an extreme cost. Later on, R. Widlar would go on to design other operational amplifiers that create a similar result at a reasonable price.

Op Amplifiers require two different voltage inputs to achieve the amplification, where the power supply runs in positive and negative voltages. We do this because we want the op amplifier to operate in both polarities of the incoming signal, essentially it's a requirement for the amplification to work. With all this in mind let's build a circuit to observe the amplification of a frequency.

II. CIRCUITS AND METHODOLOGY

We can build two main circuits here, a circuit with feedback and one without known as open-loop and closed-loop circuits. This feedback is meant to keep a certain output regardless of input. We are inputting a very small frequency and very large frequency values, we will need resistors to observe the higher values and lower values. Our voltage input will stay constant unless the resistors change, our voltage input is manipulated by our resistors. Without these resistors, we cannot observe much of the entire spectrum of the amplification. Mainly we want to compare the open-loop circuit to a closed-loop circuit, to do this we want to compare our gain. Gain is essentially the quotient between our voltage input and voltage output observed. We will be using an oscilloscope to observe the Vin peak-peak before manipulating the circuit which was 18.8 Volts for the majority of our data, and we will observe a Vout peak-peak and take the quotient. For now here are the main circuits that will be used in this experiment:

A. Open-loop and Closed-loop Circuits

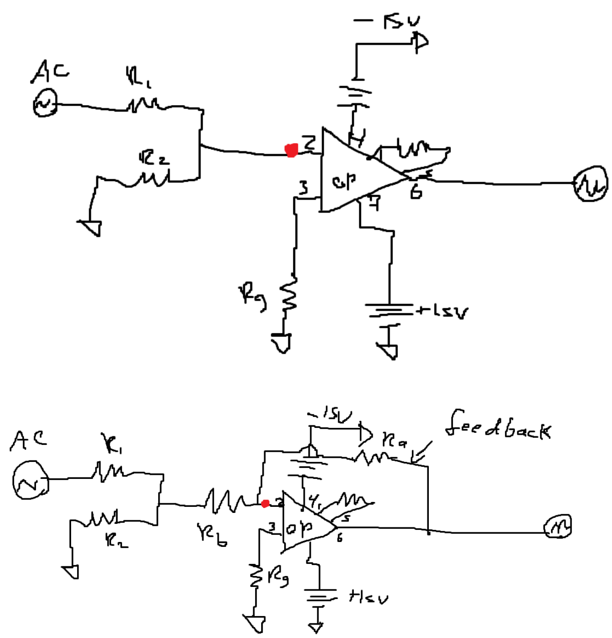

FIG. 1 : Notice the addition of 2 resistors from open-loop to closed-loop

The R's in the circuits represent our resistors, where all constants except for our R_1, between our 1 and 5 circuits have a potentiometer. This POT is an adjustable resistor, it helps with regulating the resistors around the circuit. One instance where it is very useful is when the graph output is not resembling a sin function anymore. Adjusting the screw on top of the POT will realign our resistors and give us the ideal output we desire.

Notice in FIG 1 the red dots, those represent the Vin Value we will use to find the gain, and the formula to

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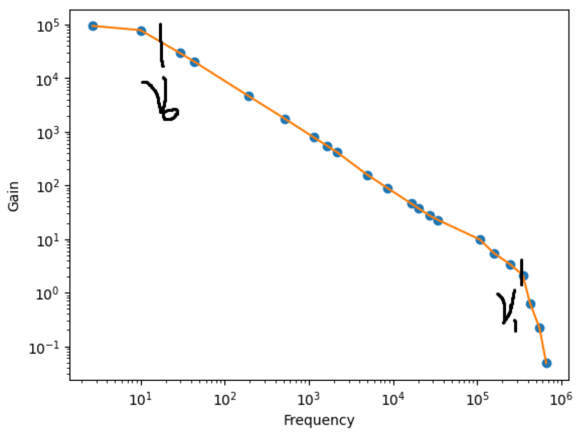
find this is:

$$Vin = (R_2/(R_1 + R_2)) * V_o \quad (1)$$

Where our Red dot represents Vin and V_0 is our initial voltage input, aka our constant which is 18.8 volts for the majority of the experiment. Once we have this Vin we can take the quotient with our read value for Vout after the amplification, and we achieve our gain. We plot this in logarithmic scale and achieve our graph:

B. Open-loop and closed-loop Frequency vs Gain



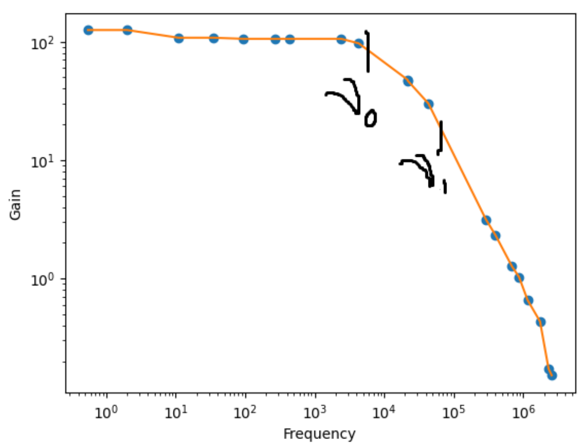


FIG. 2 : First graph represents the open-loop circuit where ν_0 represents the beginning of the gain decreases, and ν_1 is the cut-off frequency. The second graph is the closed-loop circuit. Notice how cut-off frequencies are very similar in position.

ν_1 is the value of cut-off frequency, where we no longer get a stable gain, in other words, the maximum input the amplifier can handle. Our ν_0 value represents where the gain is no longer constant. In our second graph from FIG 2, we notice that there is a negative slope, this is the gain decreasing as the frequency increases, we see it as well in our closed-loop graph; however; it's a much smaller window. we want to find the stable gain of each graph essentially the plateau at the very top, we want to find our frequency where gain begins to decrease, and we want to find our cut-off frequency when the gain is no longer stable.

Next, we need to look at phase-shift for the open loop to find/confirm our voltage cut-off, and we need to find the voltage saturation of the min and max voltages of our closed-loop circuit to find/confirm our stable gain. We find the change in the time between the input of our graph and the output. This will give us a change in the time between initial input and input after amplification. This is caused by the shunt capacitor, which is the capacitance between the input terminals of an op-amp. we achieve a ϕ value using the following formula:

$$\phi = 360\nu\Delta t \quad (2)$$

If we graph the found value of ϕ vs the frequency, we achieve the following graph:

C. Phase shift of open-loop circuit

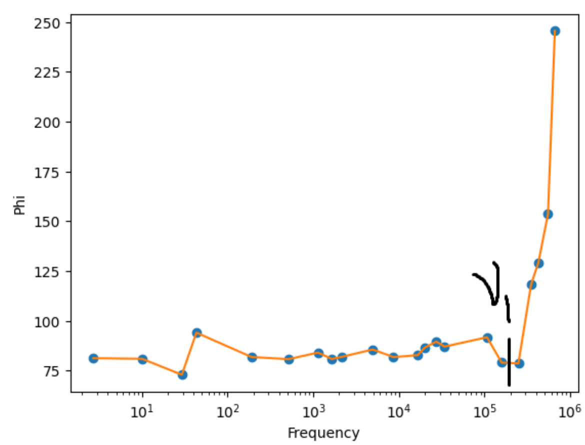


FIG. 3 : Notice how the ν_1 is at the same frequency as open-loop and closed-loop cut-off frequency

We can use this to confirm the cut-off frequency, and asses our data further. We notice that it is around 80-100 degrees which means that its oscillation is consistent, it should oscillate at only 90 degrees, and if we average it out we achieve the value of 88 degrees. pretty good estimate of our data. Finally, we want to look at our direct current voltage cut-off of the closed-loop circuit. This will tell us the gain via a slope, and the max and min saturated voltage accepted by our circuit. To do this we essentially have a voltmeter reading the output and input, we applied a direct current to the system via jumper cables. Graphing this for Vin vs Vout we achieve:

D. Voltage Min and Max of Closed-loop Circuit

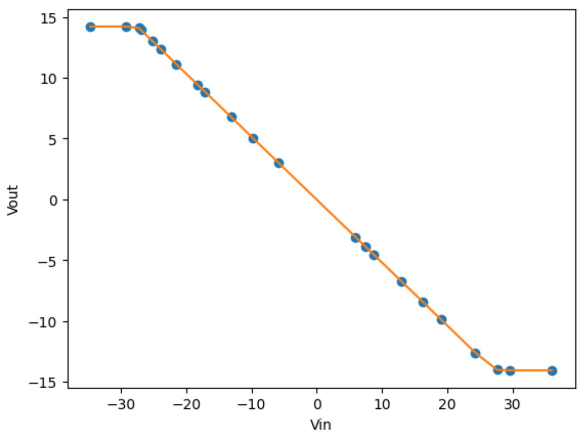


FIG. 4 : Voltage input vs voltage output of DC closed-loop circuit

The slope here can tell us what the gain is of the closed loop circuit, essentially this is to confirm values and to find the min and max voltage of the circuit.

III. CALCULATIONS

Let's first find our maximum gain of each circuit, to do this we just take the largest value at the very top of the graphs shown in FIG 2. Fairly straightforward, the found value for the open loop was 1.0 $*10^5$ and for the closed loop, the found max gain was 110. Next, we want to find our frequency where we no longer get consistent gain, we do this with the following formula:

$$A_{OL} = A_{max}/(1+(\nu/\nu_0)^2)^{1/2} \quad (3)$$

Where A_{OL} is our gain. Plugging this data into a calculator gives us a curve fit to plot this. We need to plot between each interval to accurately determine where the true location of that interval. There are many ways to do this, the method I used was to take the parameters of the function using the curve fit. Once this was done, I ended with a value of 10.5 Hz for the open-loop circuit. The same thing can be done with the closed-loop circuit and the value at which the gain starts to decrease is 1.1 $*10^4$ Hz. Now that we have these values, we want to find where the cut-off frequency is, theoretically and logically it should be at the same frequency since that is observed in our initial graphs. We will do this with the following formula:

$$A_{OL} = A_{max}/((1+(\nu/\nu_0)^2)^{1/2}(1+(\nu/\nu_1)^{2^{1/2}})) \quad (4)$$

Where ν_1 is our cut-off frequency value. Using parameters once again we can find this value towards the higher frequencies as described by FIG 2, and using the values we found earlier for our ν_0, we can now find the cut-off frequencies of both open and closed loop circuits using the formula above, which comes out to be 3.4 $*10^5$ Hz for open-loop and 3.67 $*10^5$ Hz for closed-loop, which makes sense considering their location on the graph. Now that we have all our values for the open and closed loop circuits let's look at the phase shift of the open loop. As stated earlier the cut-off frequency should stay consistent and to find this cut-off frequency we use the following formula:

$$\phi = tan^{-}1(\nu/\nu_1) \quad (5)$$

We curve-fit it once again to this will all our data, and achieve a value of ν_1 Aka the cut-off frequency for the open-loop. This value came out to be 3.8 $*10^5$ Hz which is in very good agreement with where it is generally with all our data. Next, we want to find the gain in stability. For open-loop that is the very top of the graph and the slope. At the top, it is around 1.0 $*10^5$ gain, and as we increase in frequency, we decrease in gain, and we decrease by 9.3 $*10^4$ every magnitude of power in Hz. For closed-loop, since the gain is much more consistent all the way until the KHz, we can find our gain by taking the average of all those values, which comes out to be 102. To confirm this value we can then find the slope of the Vin vs Vout graph from FIG 4, finding this slope gives us our gain for closed-loop which comes out to be 92. This works because we are applying a direct current to our circuit, In doing so we just observe a constant amplification from Vin to Vout, taking the quotient as stated earlier gives us our gain. Finally, we want to look at the saturated voltage min and max of the circuit that is observed on the graph, no math had to be done and we got +14.21 V and -14.07 V.

All the values thus far have been in very good agreement with one another, meaning all data thus far is valid. Before I move on to the conclusion I want to mention the resistors used in the experiment, first resistors R_2 and R_g in the open-loop circuit must be the same resistor power, in this experiment 10 ohms was used. R_1 changes depending on the frequency input, at lower frequencies it is necessary to use extremely high resistors. For example; the resistor I used at 2.7 Hz was 333 KOhms, as long the resistor is at an appropriate value, there should be no problem with any replicated work. For the closed-loop circuit, we have to make some smaller changes, every resistor other than R_1 will stay the same, and the same goes for the open-loop circuit. Now for R_2 10 Ohms was used again, however; R_g the resistor became 100 ohms and that is because of the feedback we get from our Vout. We must match this resistor with R_b. and finally, we used 10 KOhms for our R_a resistor.

IV. CONCLUSION

Operational Amplifiers have many uses, they are in essentially all modern electronics such as phones, tablets, cameras, computers, etc. They are useful because they are voltage buffers, creators of analog filters, and threshold detectors. They are much stabler at lower frequencies when a closed-loop circuit is occurring. A closed-loop circuit is one with feedback that essentially sends back the signal and stabilizes it with a current gain. At higher frequencies past the value of 1.1 $*10^(4)$ Hz the differences between the closed-loop and the open-loop circuit are minimal. We observe the gain max in the open loop at lower frequencies, this is useful in real items such as speakers, microphones, etc. We can also observe a phase shift inside the open-loop circuit where it is moderately even at 90 degrees until the cut-off frequency is hit which tells us that the feedback goes from positive to negative, essentially the gain is negative. Finally, we looked at the saturation voltage of the closed-loop circuit where we find our min and max voltage. What this tells us is that the circuit will not go over 15 V even if we give it more, The maximum achieved voltages were 1 less than 15 V.

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