Laboratory 3: Op-Amp Imperfections

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***Abstract*—This investigation provides a comprehensive study of the limitations and drawbacks associated with operational amplifiers (op-amps). The labrotory covers several topics related to op-amp imperfections, including offset voltage, input bias and offset currents, offset compensation, effects of finite gain and bandwidth on closed-loop operation, nonlinear behavior such as slew-rate limiting and output saturation, and the effects of output saturation.**

***Index Terms*—Operational amplifiers, DC imperfections, AC imperfections, Offset voltage, Input bias, Offset currents, Nonlinear behavior, Slew-rate limiting, Output saturation, Experimental values**

I. Introduction

Throughout the ECSE 311 course thus far, we have been working with operational amplifiers under the assumption that they operate ideally. However, in practical applications, op amps can exhibit both DC and AC imperfections. In this laboratory session, we investigated these imperfections by utilizing the NI Elvis II+ test instrument with various circuit configurations with the LM741 op-amp. The first part of the investigation discusses offset voltage and the different techniques used to minimize its impact on the performance of op-amps. The second part deals with input bias and offset currents, including their causes and effects on op-amp operation. Offset compensation techniques are also presented in this section. The third part of the lab covers the effects of finite gain and bandwidth on closed-loop operation. It provides a detailed discussion of the frequency response of op-amps and how it affects their performance in different arrangements of circuits. The fourth part of the lab deals with nonlinear behavior such as slew-rate limiting and output saturation. It presents the causes of these phenomena and how they affect op-amp performance in different circuits. Finally, the lab provides a discussion of output saturation effects and how they can be minimized. Slew-rate limiting is also discussed in detail in this section. By comparing theoretical and experimental values, we gained a clearer understanding of these imperfections.

II. Methodology and Analysis

A. *Offset Voltage*

In this section of part 1 we constructed the inverting amplifier circuit according to the circuit schematic in figure 1. Here, R1=100 Ω and R2= 100k Ω . To understand the mathematical relationship between the output and offset voltage, we assume that there is a voltage source connected to the non-inverting terminal of the opamp. We know from theory that the input and output voltage relationship of a non-inverting amplifier is as seen in figure 2. Here, offset voltage can be considered the input voltage. We already know R2 and R1, thus we obtained the relationships found in figure 3.

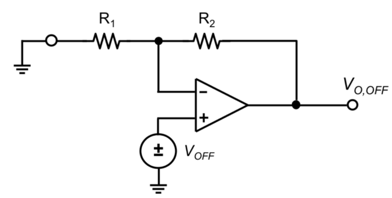

Fig. 1. Circuit Schematic for observing the effect of Offset voltage on an inverting amplifier configuration.

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

Fig. 2. Non-Inverting Gain

$$V_{out} = V_{OFF}(1 + 1000)$$
$$V_{OFF} = \frac{V_{out}}{1001}$$

Fig. 3. VOFF Calculation

Then, we measured Vout using the digital multi-meter and obtained the result seen in figure 4. Thus our measured Vout is –7.8985 V. When we plug this value into the equation seen above in figure 3 we obtain a value for Voff of -7.89 mV. However, since the input is connected to the inverting pin, we are concerned with the magnitude. The magnitude of the input offset voltage of the LM741 op amp is indicated as 6 mV within Texas Instrument's data sheet [1]. Thus, we can conclude that our measurement of offset voltage is valid with minor deviation from the value indicated in the manufacturer's data sheet. This deviation may be due to circuit noise created by the flow of electrons.

B. *Input Bias and Offset Currents*

In this section, we investigated input bias and offset currents within the op amp using the two circuit configurations seen in figures 5 and 6. The circuit in figure 5 is used to identify the current IB,1 that is drawn by the non-inverting terminal of

Fig. 4. Vout Multimeter Reading

the op-amp and the circuit of figure 6 is used to identify the current IB,2 drawn by the inverting terminal of the op-amp.

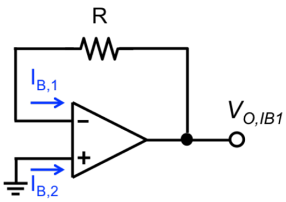

Fig. 5. Circuit Configuration for IB1 measurement

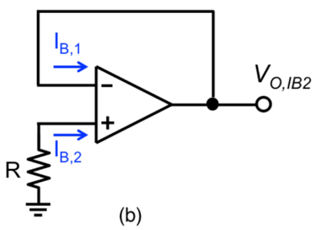

Fig. 6. Circuit Configuration for IB2 measurement

In both configurations we used $R = 1M\Omega$. In order to calculate IB1, we know the following relationship: $Vout = IB1 * R$. And so, When we plug in the value of R we obtain: $IB1 = Vout/(1M\Omega)$ by Ohm's Law. With the configuration of figure 5, we measured a reading of 45.213 mV; while the configuration of figure 6 gives us a reading of -47.573 mV.

Thus, $IB1 = (45.213mV)/(1M\Omega) = 45.213nA$. And the relationship between Vout and IB2 is: $Vout = -IB2 * R$. Thus, $IB2 = -Vout/R$ and, $IB2 = (-47.573mV)/(1M\Omega) = -47.573nA$.

Through this, we have now obtained every value necessary to find the offset current IOS. Offset current can be found with relationship: $Ios = |IB1 - IB2|$. Plugging in our values we find the offset current to have a value of $Ios = 92.786nA$. The data sheet of LM741 indicates that input offset current is typically 85 nA, close to our findings throughout the lab.

C. Offset Compensation

We modified the circuit in figure 1 in order to reduce DC imperfections, more specifically, in terms of compensating the offset that occurs. The modified circuit is seen in figure 7.

This modification involves Rc in a parallel connection with R1 and R2, which are again, 100Ω and $100k\Omega$, respectively. Using the digital multimeter we obtained a value for Vo of

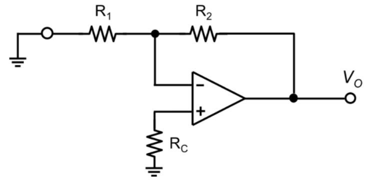

Fig. 7. Modified version of the circuit in Figure 1 in order reduce the effect of offset voltage

-2.5 V. And by using the equation in figure 3, we can arrive at an offset voltage of -2.5mV, which is lower than the value obtained in part A, -7.89 mV. Thus, we can conclude that this modification has successfully achieved its goal, of reducing the DC offset voltage.

D. Effects of Finite Gain and Bandwidth on Closed-Loop Operation

For part 2 we are asked to investigate effects of finite gain and bandwidth on the closed-loop operation. To do this, we constructed the circuit in figure 8 by applying a 100 Hz sine wave with peak to peak voltage of 100 mV as an input.

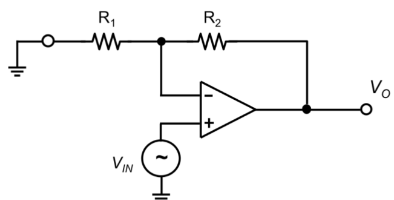

Fig. 8. : Noninverting amplifier schematic in order to investigate the effects of finite gain and bandwidth on closed loop operation

We performed analysis on this configuration with varying combinations of resistors. The first trial, we constructed the circuit with $R1 = 10k\Omega$ and $R2 = 50k\Omega$. For the second trial we kept the same value for R1, but set $R2 = 100k\Omega$. And for the third, $R2 = 220k\Omega$ while R1 is the same.

For each of these combinations, we ran an instance of the bode plot analyzer in order find the gain at the -3 db drop. We then converted the db reading to V/V, to then compare with the theoretical value of the gain of a noninverting amplifier $Gain(V/V) = (1 + R2/R1)$. We then used the equation in figure 9 to realize the percent error obtained from our setup. The results of these trials are summarized in the table in figure 10. From this table we can observe that the percent error increases and deviates heavily more as R2 increases.

$$Percentage\ Error = \frac{|Theoretical\ value - Measured\ value|}{Theoretical\ value} \cdot 100$$

Fig. 9. Percentage Error Equation

E. Output Saturation Effects

If we pass a sine wave through a linear system, the output will also be a sine wave. In other words, it will retain its

R2 Value (Ω)	Gain (dB)	Gain (V/V)	Theoretical Gain (V/V)	Percent Error (%)
50k	13.91	4.96	6	17.3
100k	14.57	5.35	11	51.4
200k	14.77	5.48	23	76.2

Fig. 10. Gain and Error Table for Noninverting Amplifier

shape. However, we will observe distortions in its shape when a system exhibits nonlinear behavior. This phenomenon can be quantified in a piece-wise manner as seen in figure 11, where A is the gain and Vmax and Vmin are the amplifier's saturation limits.

$$v_o(t) = \begin{cases} V_{MAX} & \text{if } v_o(t) > V_{MAX} \\ A \cdot v_{IN}(t) & \text{if } V_{MIN} \leq v_o(t) \leq V_{MAX} \\ V_{MIN} & \text{if } v_o(t) < V_{MIN} \end{cases}$$

Fig. 11. Piece-Wise Quantification of Distortion Through a Non-Linear System

We applied a 1kHz sine wave as an input to the circuit in figure 8 with $R1 = R2 = 10k\Omega$. We first applied a 1V peak to peak and obtained the oscilloscope plot found in figure 12. As we can observe, we do not see any saturation when peak to peak voltage is 1V. The op-amp behaves in a linear manner. However, we began to observe saturation when we applied a 10V peak to peak sine wave as seen in figure 13. It can be observed that Vmin = -7.89 V and Vmax = 9.26 V. This matches with the op-amp data sheet as it shows ±10V saturation limit.

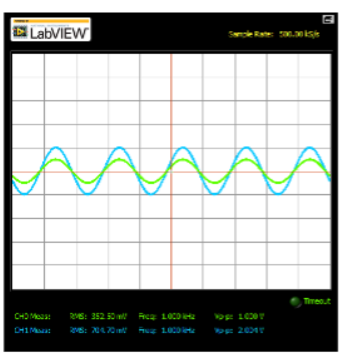

Fig. 12. Oscilloscope Plot with a 1V Peak-To-Peak

F. Slew Rate Limiting

If the maximum rate of change of the output signal exceeds the slew rate limit, it will stop resembling the shape of the input signal, exhibiting non-linear behavior. In this section, we investigate this by first applying a 100 Hz square wave with equal positive and negative voltage levels of 100 mV

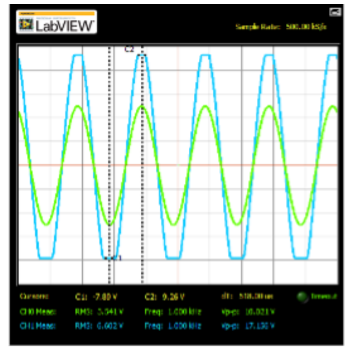

Fig. 13. Oscilloscope Plot with a 10V Peak-To-Peak

through the circuit in figure 8 with $R1 = R2 = 10k\Omega$. The oscilloscope plot of this setup can be found in figure 14. We can observe from the figure that the circuit exhibits a gain of 2, in a linear manner. We then increased the amplitude of the square wave input until the output shape no longer resembled a square wave. We first started to observe this when we applied 5.5V peak to peak voltage square wave, seen in figure 15.

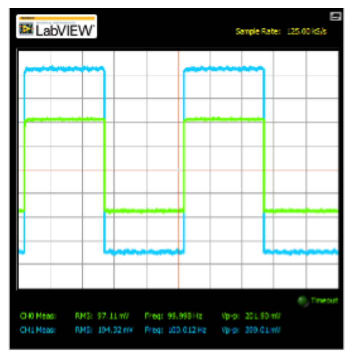

Fig. 14. Oscilloscope of input and output of noninverting amplifier circuit with 100 Hz square wave with 100 mV amplitude

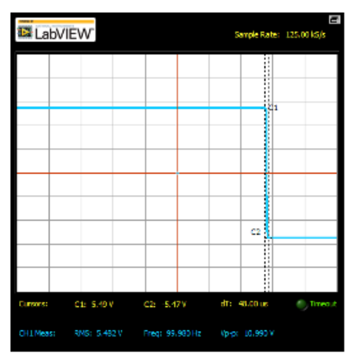

Fig. 15. Oscilloscope capture for slew rate calculation with 100 Hz, 5.5 Vpp square wave input

Now, using the equation for the slew rate found in figure 16, we can calculate our slew rate to be about 0.23 V/us. The op amp data sheet, mentions a slew rate of 0.5 V/us. Hence, our measured slew rate is close to the value on the data sheet.

$$Slew\ Rate = \frac{(5.49 + 5.47)V}{48\ \mu s} = 0.23\ \frac{V}{\mu s}$$

Fig. 16. Slew Rate Equation

We then changed the input to our circuit to a 100 Hz sine wave with 1V amplitude. We used this configuration as our first trial to this part of the investigation. Using the oscilloscope, we observed at what frequency does the signal begin to become distorted. We repeated this step for an input of a sine wave of 1.5V, 2V, 3V and 4V amplitudes, and collected the fm which we found the respective signal to be distorted. Figure 17 summarizes our findings along side the product of the amplitude and the cutoff frequency.

Amplitude (V)	Frequency (Hz)	Amplitude * Frequency
1	900.024	900.02
1.5	599.593	899.39
2	450.01	900.02
3	300.068	900.20
4	225.006	900.02

Fig. 17. Amplitude of the sine wave and frequency when distortion appears and their products

Finally we plotted the amplitude of the input sine signals against the frequencies at which they were distorted. This plot can be seen in figure 18. It is noted from this plot that as the amplitude of the input signal increases, the frequency at which distortion occurs decreases.This allows us to believe that these devices are less accurate/ or more susceptible to error when working with higher magnitudes of overall power.

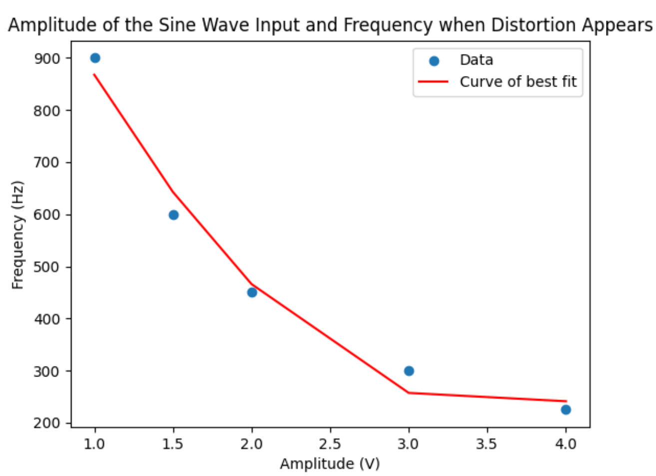

Fig. 18. Amplitude of the sine wave and frequency when distortion appears

III. Conclusion

Throughout the ECSE 311 course, we have learned about the ideal operation of operational amplifiers, which is fundamental to circuit design and analysis. However, in practical applications, op amps can exhibit DC and AC imperfections that can affect their performance. In this laboratory session, we used the LM741 op-amp and the NI Elvis II+ test instrument to investigate these imperfections through various circuit configurations.

Our investigation focused on offset voltage and the different techniques to minimize its impact on op-amp performance, as well as input bias and offset currents and their effects on op-amp operation. We also explored offset compensation techniques to reduce these effects. The lab session also covered the impact of finite gain and bandwidth on closed-loop operation and how it affects op-amp performance in different circuits. Moreover, we discussed nonlinear behavior, including slew-rate limiting and output saturation, and how they can affect op-amp performance. We also discussed output saturation effects and techniques to minimize them.

By comparing theoretical and experimental values, we gained a deeper understanding of these imperfections, their causes, and effects on op-amp performance. This understanding is crucial for designing and analyzing circuits in practical applications.

Overall, the laboratory session enhanced our knowledge of op-amp operation and the importance of considering imperfections in practical applications. We now have a better understanding of how to minimize the impact of these imperfections and how to design circuits that operate optimally in real-world scenarios.

IV. References

[1] Texas Instruments. (2019). LM741 Operational Amplifier Datasheet. [Online]. Available: https://www.ti.com/lit/ds/symlink/lm741.pdf. [Accessed: Feb. 24, 2023].

[2] A. S. Sedra and K. C. Smith, Microelectronic Circuits, 8th ed. Oxford University Press, 2019.