WASHINGTON STATE UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

EE 352, ELECTRICAL ENGINEERING LABORATORY

LAB #4

Non-ideal operational amplifier behavior

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Lab Overview

The purpose of this lab was to explore the various real-world applications of op amps, specifically the OP27 op amp, and to gain an understanding of real-world limitations of the non-ideal characteristics of the amplifier. This lab specifically exposed us to the effects of open-loop gain bandwidth, slew rate distortion, offset measurements, and the common-mode rejection ratio (CMRR).

1 Effects of open-loop gain bandwidth product

1.1 Purpose

The purpose of this experiment was to investigate the effects of the open-loop gain bandwidth the output voltage of the amplifier.

1.2 Theoretical background

The open-loop gain of a non-ideal opamp is dependent on the frequency as a first-order system with dc gain A_0 and cutoff frequency f_b. Generally, this gain is expressed as

$$A(jf) = \frac{A_0}{1 + jf/f_b} \tag{1}$$

This can be approximated as the cutoff frequency f_b is less than $10\,\mathrm{Hz}$. As such, we can now express the gain as

$$A(jf) \approx \frac{A_0 f_b}{jf} = \frac{f_t}{jf} \tag{2}$$

If the gain-bandwidth product f_t is known, we can estimate the cutoff frequency for the non-inverting amplifier, shown in Figure 1 as

$$f_0 = \frac{f_t}{1 + R_2/R_1} \tag{3}$$

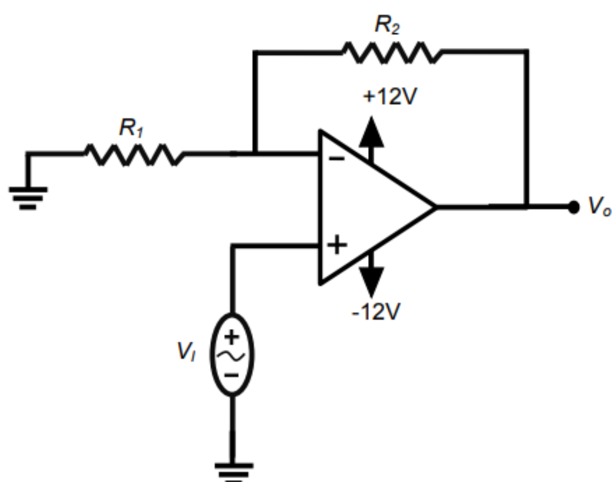

Figure 1: Circuit diagram of the non-inverting amplifier used in experiment 1.

From the OP27 datasheet, the minimum and typical gain-bandwidth product is $5.0\,\mathrm{MHz}$ and $8.0\,\mathrm{MHz}$. If R_1 is fixed as $1\,\mathrm{k\Omega}$, then we can adjust R_2 to find the expected cutoff frequencies as shown in Table 1 below.

Table 1: Expected gains and cutoff frequencies of various R_2 configurations.

Gain (V/V)	R_2	Cutoff Frequency f_0 Minimum	Typical
11	$10\,\mathrm{k\Omega}$	$454\,\mathrm{kHz}$	$727\,\mathrm{kHz}$
48	$47\,\mathrm{k\Omega}$	$104\,\mathrm{kHz}$	$167\,\mathrm{kHz}$
101	$100\,\mathrm{k\Omega}$	$50\,\mathrm{kHz}$	$74\,\mathrm{kHz}$

The first amplifier with $11\,\mathrm{V/V}$ gain was simulated using OrCAD PSPICE, resulting in the response shown in Figure 2.

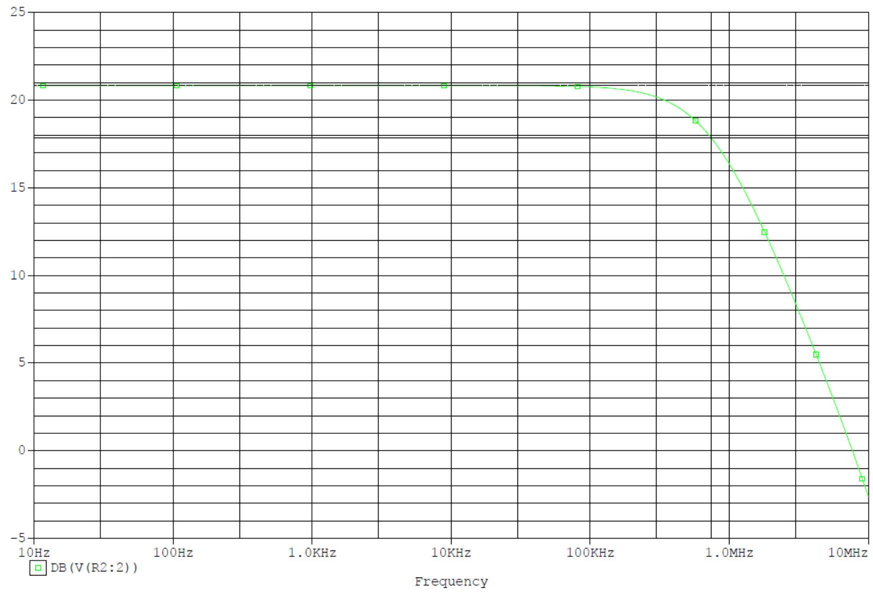

Figure 2: Simulation of the 11 V/V amplifier

1.3 Procedure

The follow steps were carried out, as instructed by the lab assignment.

1. The OP27 opamp was connected as a non-inverting amplifier using $R_2 = 10\,\mathrm{k\Omega}$ (nominal) in the circuit shown in Figure 1.
2. The function generator was attached to the input of the circuit and teed to CH1 of the oscilloscope. The output of the circuit was attached to CH2 of the oscilloscope.
3. An input $20\,\mathrm{mV}$ (peak-to-peak) sine wave was generated at $100\,\mathrm{Hz}$ using the function generator.
4. The input and output voltages were measured using the oscilloscope and the gain was recorded in Excel. As the frequency was low, this was assumed to be the dc gain.
5. The frequency was increased slowly until it reached $\frac{G_{DC}}{\sqrt{2}} \approx 0.707 G_{DC}$. This was assumed to be the corner frequency. The gain-bandwidth product was calculated and recorded in the lab notebook.
6. This data was plotted using Excel.
7. Steps 2 through 5 were repeated for the $47\,\mathrm{k\Omega}$ and $100\,\mathrm{k\Omega}$ resistors.

1.4 Results and analysis

Measured component values

The resistors were measured using the DMM and listed in Table 2.

Table 2: Experimental and nominal component values.

Component		Nominal	Experimental	% Error (Tolerance)
R_1		$1\,\text{k}\Omega$	$0.9728\,\text{k}\Omega$	2.7% (5%)
R_2	(11 V/V)	$10\,\text{k}\Omega$	$9.743\,\text{k}\Omega$	2.6% (5%)
R_2	(48 V/V)	$47\,\text{k}\Omega$	$46.42\,\text{k}\Omega$	1.2% (5%)
R_2	(101 V/V)	$100\,\text{k}\Omega$	$99.48\,\text{k}\Omega$	0.5% (5%)

Gain bandwidth values

For each resistor, the gain bandwidth product was calculated and noted in Table 3 below. The average gain bandwidth product was $5.65\,\text{MHz}$, between the minimum and typical value expected in the datasheet. As this was in range, there is no error to be calculated in this experiment.

Table 3: Gain bandwidth products of each resistor value.

Nominal R_2 (Measured)	Gain	Cutoff frequency	Gain bandwidth product
$10\,\text{k}\Omega$ ($9.743\,\text{k}\Omega$)	$10.8\,\text{V/V}$	$825\,\text{kHz}$	$6.3\,\text{MHz}$
$47\,\text{k}\Omega$ ($46.42\,\text{k}\Omega$)	$48.4\,\text{V/V}$	$162\,\text{kHz}$	$5.54\,\text{MHz}$
$100\,\text{k}\Omega$ ($99.48\,\text{k}\Omega$)	$102\,\text{V/V}$	$71\,\text{kHz}$	$5.12\,\text{MHz}$

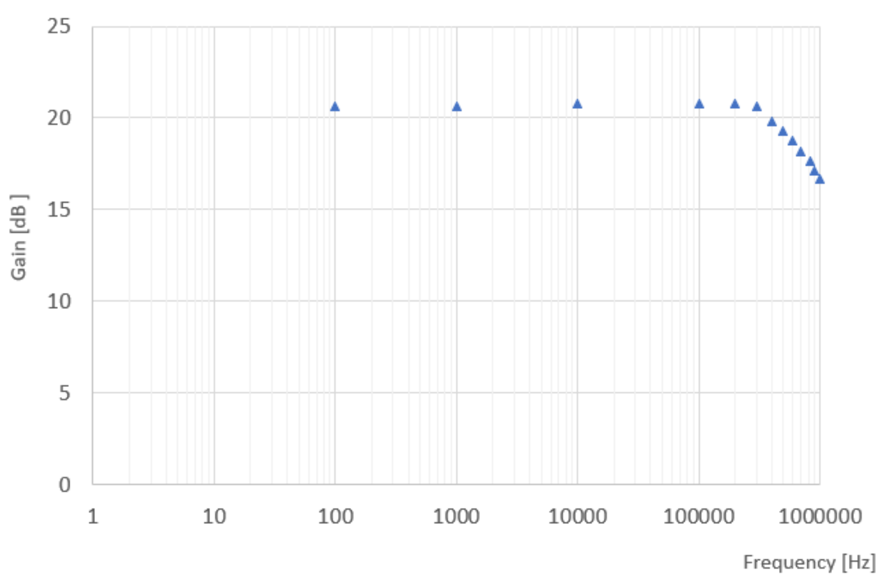

Figure 3: Plot of the measured gain of the 11 V/V amplifier.

1.5 Conclusion

The non-ideal characteristics were visible during this experiment as the bandwidth of the op amp was dependent on the frequency of the input signal attenuated the output gain. This was especially apparent at higher frequencies, acting as a low-pass filter before $800\,\mathrm{kHz}$.

2 Slew rate distortion

2.1 Purpose

Unlike ideal opamps, real-world opamps have limits on the output current and have an effective capacitance on the output of the amplifier. This provides some limitations on the apparent transfer characteristics of the amplifier.

2.2 Procedure

The follow steps were carried out, as instructed by the lab assignment.

1. Using the OP27 opamp, a unity gain amplifier was constructed.
2. The function generator was teed to CH1 of the oscilloscope and the input of the circuit.
3. A $0.1\,\mathrm{V/V}$ rectangular wave was applied using the function generator. The time/div was adjusted until the slew rate was clear and resulted in a ramping function to the steady-state voltage. Then, the slew rate was estimated.
4. The estimated SR was compared to the expected datasheet SR value. The oscilloscope plot was saved to the flash drive.
5. From the experimental SR value, f_{max} was estimated for a sine wave with a $1\,\mathrm{V}$ (peak-to-peak) value.
6. A $1\,\mathrm{V}$ peak-to-peak sine wave was applied using the function generator. The frequency was increased until a distortion became evident on the output of the amplifier. The frequency was recorded.

2.3 Results and analysis

Using the square wave response, the time/div was adjusted until the slew became evident, as shown by Figure **??** below. The change in voltage and time was measured and used in the slope calculation, giving us the slew rate,

$$\begin{aligned} \Delta V &= 19.2\,\mathrm{mV} \\ \Delta t &= 0.0104\,\mu\mathrm{s} \\ SR &= 1.8461\,\mathrm{V}/\mu\mathrm{s} \end{aligned} \tag{4}$$

Relative to the datasheet value, this was found to be in range of the expected 1.2 to $2.8\,\mathrm{V}/\mu\mathrm{s}$. Next, a sine wave was applied and the frequency was adjusted until distortion became evident. Distortion was seen initially at $600\,\mathrm{kHz}$ and was very clear as it progressed up to $700\,\mathrm{kHz}$. At $600\,\mathrm{kHz}$, it was somewhat over the estimated and theoretical value of $680\,\mathrm{kHz}$, but still in range of our expectations.

2.4 Conclusion

This op amp had a clear slew rate, which was especially visible during the step response. The slew rate resulted in a slow ramp up to the unity signal. This was additionally visible in the sine response, albeit much less so: the distortion did not become evident until roughly 600 to $650\,\mathrm{kHz}$. At higher frequencies, the signal became much more distorted, completely changing waveforms by $700\,\mathrm{kHz}$, and becoming nearly triangular waves.

3 DC Offset Voltage, DC Offset Current, DC Bias Current

3.1 Purpose

The purpose of this experiment was to find the offset voltage, current, and bias currents that are internal to the op amp. These values are a non-ideal characteristic contained with the operational amplifier that specifically are reflected in the inverting and non-inverting terminals.

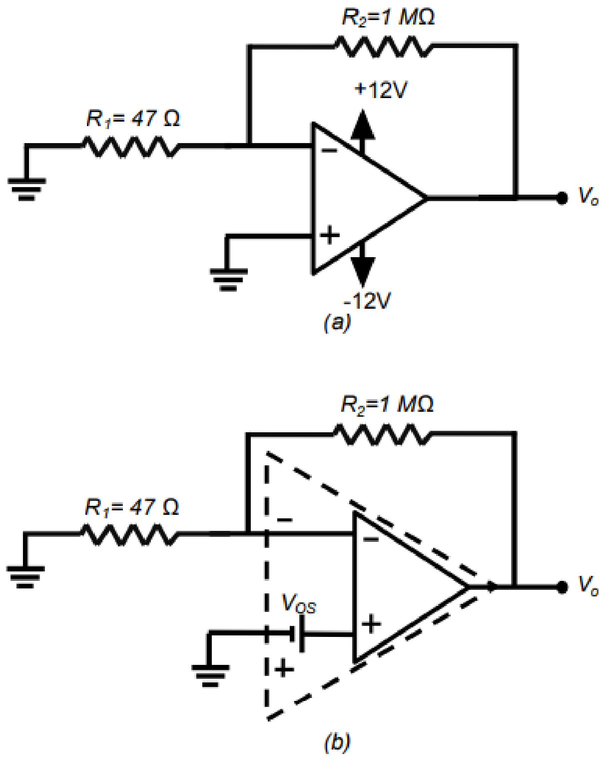

Figure 4: Circuits used in calculating the dc offset voltages.

3.2 Procedure

The follow steps were carried out, as instructed by the lab assignment.

1. Estimate the input offset voltage
   (a) The circuit shown in Figure 4(a) was constructed and the two resistor values were recorded. The output voltage was recorded using the DMM.
   (b) From this, the offset voltage was estimated and compared to the typical and maximum offset voltage from the datasheet.
2. Estimate the input bias currents and input offset currents.
   (a) The circuit shown in Figure 5(a) was constructed. The resistor value was recorded and the output voltage was measured using the DMM.
   (b) The inverting current was estimated using this value using the offset voltage from Step 1.
   (c) Then, Figure 5(b) was constructed and the output voltage was measured again.
   (d) The non-inverting current was estimated similarly.
   (e) From these values, the input bias and offset currents were estimated, then compared to the datasheet values.
3. DC offset compensation circuit.
   (a) The circuit shown in Figure 6 was constructed and the resistor values were recorded. The output voltage was measured using the DMM.
   (b) Resistor R_x was added to compensate for the offset measurement and the output voltage was measured again.
   (c) The new output voltage was compared to the original uncompensated voltage.

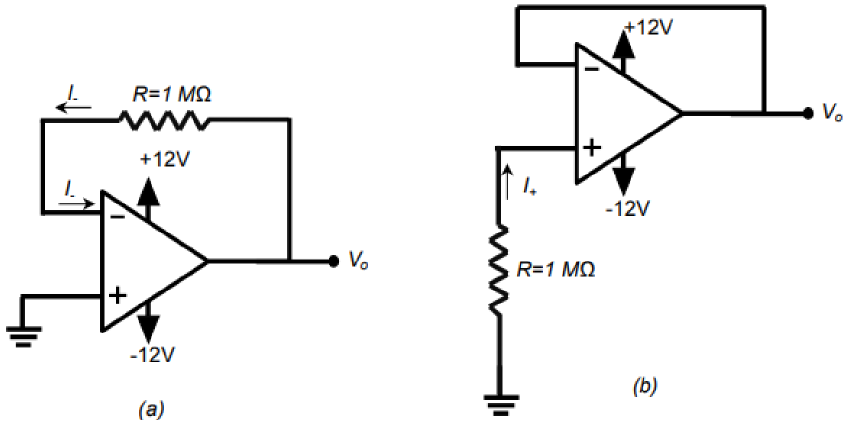

Figure 5: Circuit used in measuring the dc offset current.

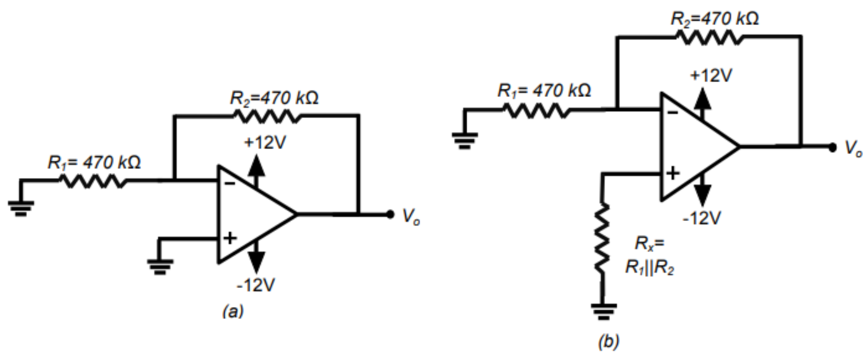

Figure 6: Circuit used in measuring the bias currents.

3.3 Results and analysis

Measured component values

Table 4: Experimental and nominal component values.

Component	Nominal	Experimental	% Error (Tolerance)
R_1	$47\,\Omega$	$46.64\,\Omega$	
R_2	$1\,\mathrm{M}\Omega$	$1.0149\,\mathrm{M}\Omega$	
R	$1\,\mathrm{M}\Omega$	$1.0149\,\mathrm{M}\Omega$	
R_1			
R_2			
R_x			

The dc offset voltage was found to be $38.25\,\mu\mathrm{V}$, in range of the data sheet. The currents I_- and I_+ were found to be $-0.386\,\mathrm{nA}$ and $0.362\,\mathrm{nA}$. From this, the bias current I_B and offset current was found as $73\,\mathrm{nA}$. Both of these exceed the specification from the datasheet, indicating this op amp has a particularly low bias current internally.

3.4 Conclusion

The offset values of the OP27 amplifier were verified and our values were within the specifications listed in the datasheet. The input currents were fairly minimal, in the nano-ampere range, indicating a nearly-ideal behavior and minimal draw from the input. This is a desirable behavior and outperforms the typical range as listed in the datasheet.

4 Common Mode Rejection Ratio (CMRR)

4.1 Purpose

In this experiment, the common mode rejection ratio was introduced, a number representing the ratio of the differential-to-common mode gain. Ideally, this number is infinite, indicating an ideal op amp.

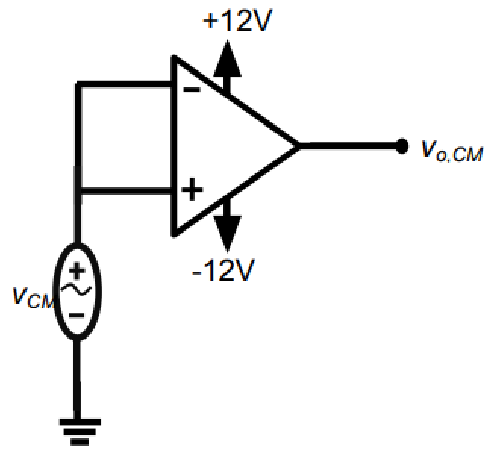

Figure 7: Circuit used to measure the common mode gain.

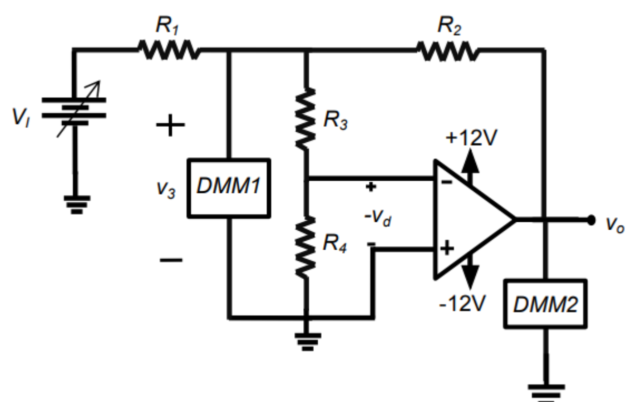

Figure 8: Circuit used in the second part of the CMRR experiment, allowing the differential gain to be calculated.

4.2 Procedure

The follow steps were carried out, as instructed by the lab assignment.

1. Measuring common mode gain A_{cm}

(a) Using the OP27 op amp, the circuit shown in Figure 7 was connected and a $10\,\mathrm{V_{pp}}$ sine wave was attached to both input terminals of the op amp.

(b) With the oscilloscope, the input and output terminals were measured and saved on the thumb drive.

(c) The common mode gain was calculated.

2. Measuring the differential gain

(a) Using the OP27 opamp, the circuit was connected as shown in Figure 8. The resistor values were measured using the DMM and recorded in the lab notebook. The input was set using the function generator at a low magnitude and the DC offset was varied.

(b) The DC offset was varied and the output voltage was measured using the DMM. The offset was adjusted until it reached $9\,\mathrm{V_{pp}}$.

(c) The last step was repeated but the offset voltage was varied until it reached $-9\,\mathrm{V_{pp}}$.

(d) The differential gain was calculated.

4.3 Results and analysis

Measured component values

Table 5: Experimental and nominal component values.

Component	Nominal	Experimental	% Error (Tolerance)
R_1	$1\,\mathrm{k\Omega}$	$0.9828\,\mathrm{k\Omega}$	
R_2	$4.7\,\mathrm{k\Omega}$	$4.547\,\mathrm{k\Omega}$	
R_3	$47\,\mathrm{k\Omega}$	$46.66\,\mathrm{k\Omega}$	
R_4	$47\,\Omega$	$46.24\,\Omega$	

The function generator was set to $2\,\mathrm{mV}$ (pp) as it was unable to reach the desired $1\,\mathrm{mV}$ (pp). The DMM read $9.002\,\mathrm{V}$ (dc) and the alternate DMM read $8.95\,\mathrm{mV}$. Using this, the offset voltage was found to be $-8.861\,\mathrm{mV}$. Next, the opposite voltage was found as $14.95\,\mathrm{mV}$, resulting in an offset voltage of $-1.480 \times 10^{-5}\,\mathrm{V}$. The differential gain was found to be

$$A_d = 3\,030\,813.3\,\mathrm{V/V} = 124.6\,\mathrm{dB}$$

The CMRR was then found as

$$CMRR = 1\,377\,642\,273 = 182\,\mathrm{dB}$$

4.4 Conclusion

The CMRR found far exceeding the specification, of a minimum and typical value of 100 and 120 dB. This is notable as an ideal op amp would have an infinite CMRR.