PHY405 Lab 4: Operational Amplifier Fundamentals

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(Dated: February 21, 2025)

OPEN LOOP CHARACTERISTICS

An operational amplifier (op-amp) is an integrated circuit that amplifies the difference in voltage between two inputs, V_a (the inverting input) and V_b (the non-inverting input). The specific op-amp we use in this lab is the LF356 op-amp.

An open-loop op amp is an op-amp without any feedback, which means its gain cannot be regulated. In an open-loop op-amp, the output voltage is given by $V_{out} = A_{open}(V_b - V_a)$, where A_{open} is the open-loop gain (typically on the order of 10^5), so even the smallest difference in V_a and V_- will cause V_b to saturate the power supply.

R1: Open-Loop Op-Amp Circuit Bode Plot

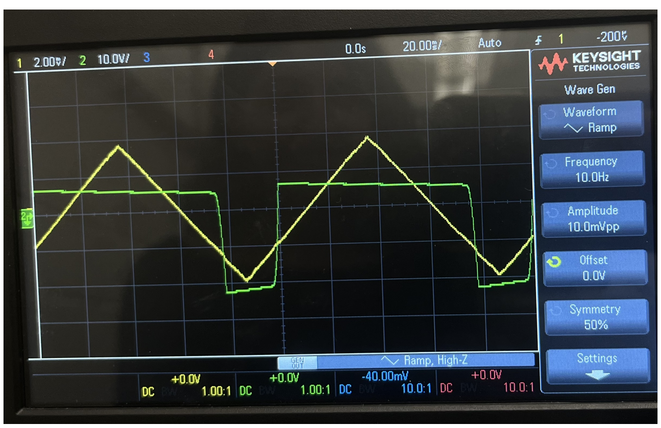


FIG. 1: Oscilloscope capture showing the input (yellow) and output (green) waveforms for the open-loop op-amp circuit with a 10 Hz, 10 mV ramp input. The output is severely clipped due to saturation.

R-2: Explanation of Observed Output

Given the large gain ($A_{\text{open}} \approx 10^5$) of the open-loop configuration, the output did not follow the input signal linearly; instead, it acted as a comparator, abruptly switching between two voltage extremes, which were capped by the limits of the power supply ($\pm 25V$ for the E36311A 80W Triple Output Power Supply) [2].

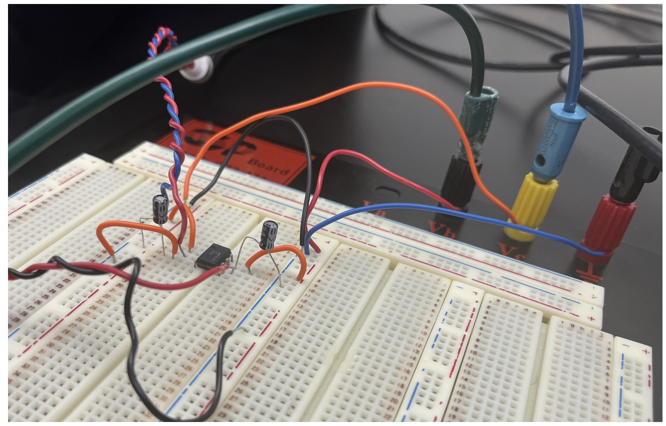


FIG. 2: Open-loop Op-Amp Circuit.

In other words, the op-amp continually compared the voltages at the inverting and non-inverting inputs, such that:

- As soon as $V_b > V_a = 0$ (i.e., slightly positive) the output saturated to +25V.
- Similarly, as soon as $V_{\text{in}} < V_-$, the output saturated to −25V.

The sharp transitions in the output waveform indicate the switching point, which is slightly offset from 0V due to input offset voltage (typically 3mV [?]) in the op-amp.

It is also observed that the output voltage does not immediately switch between −25V and +25V. This effect arises due to the finite slew rate of the LF356 op-amp 12 V/μs [?], which prevents the output from instantaneously reaching the power supply rails.

Additionally, the output voltage does not remain perfectly flat at the saturation limits but instead exhibits minor variations. This effect can be attributed to factors such as internal feedback dynamics within the op-amp.

Overall, we see that in open-loop mode, the op-amp does not function as an amplifier but as a threshold detector or comparator.

NON-INVERTING AMPLIFIER

R-3: What resistance values and tolerances did you choose for R_1 and R_2?

- $R_1 = 15 \pm 1\Omega$, with a tolerance of $\pm 5\%$

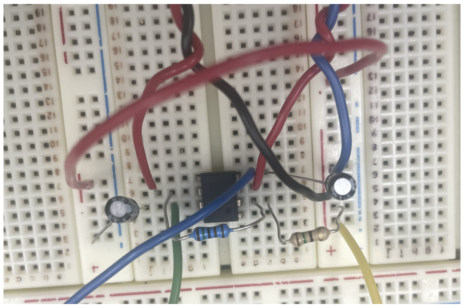


FIG. 3: Non-inverting amplifier circuit

- $R_2 = (1.500 \pm 0.001)$ kΩ, with a tolerance of $\pm 1\%$

R-4: Measuring the amplifier's transfer function $H(f)$

The transfer function of the amplifier, defined as:

$$H(f) = \frac{V_{\text{out}}(f)}{V_{\text{in}}(f)} \tag{1}$$

was measured for sine wave signals ranging from 50 Hz to 5 MHz. The measured gain response was analyzed using the oscilloscope's frequency response analysis (FRA) feature (Figure 4).

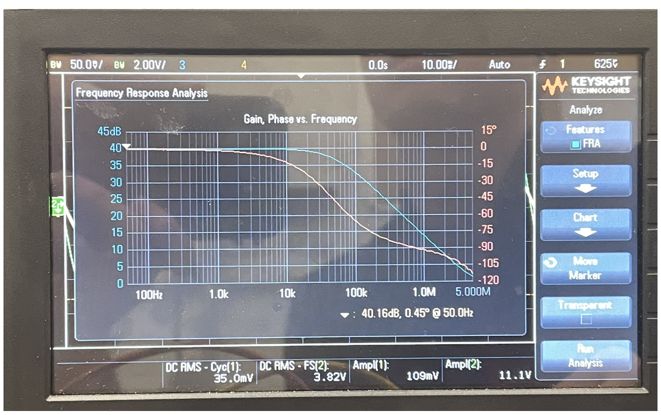


FIG. 4: Bode plot for sine wave signals between 50 Hz and 5 MHz

The gain-bandwidth product (GBW) of the LF356 operational amplifier is specified in the datasheet as approximately 5 MHz [1]. The bandwidth of the amplifier can be estimated by identifying the frequency at which the gain drops by 3 dB from its maximum value.

From the experimentally obtained Bode plot (Figure 4), the measured gain is approximately 40 dB at low frequencies. The -3 dB point occurs at approximately 50 kHz, which defines the bandwidth of the amplifier.

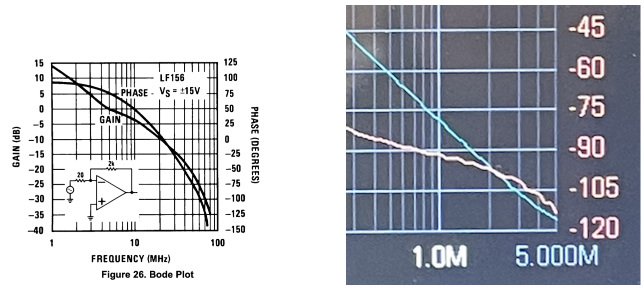
Using the gain-bandwidth relationship:

$$\text{GBW} = A_v \times f_c \tag{2}$$

where A_v is the gain and f_c is the -3 dB bandwidth, we calculate:

$$100 \times 50 \text{ kHz} = 5 \text{ MHz} \tag{3}$$

This is in agreement with the expected GBW value of 5 MHz from the LF356 datasheet. Thus, our observed results align well with theoretical expectations.



(a) Bode Plot for LF356 Op-Amp from Data Sheet [2].

(b) Our Bode plot, zoomed in to focus on high-frequency behavior.

FIG. 5: Comparison between the Bode plot of the LF356 Op-Amp from the datasheet (left) and our experimentally obtained Bode plot (right). The high-frequency behavior in our experiment closely resembles the roll-off trend seen in the datasheet.

However, while the Bode plot provides a frequency-dependent perspective on gain behavior, it is also useful to verify the amplifier's performance at a specific test frequency by directly measuring the input and output voltage amplitudes using the oscilloscope. These measurements allow us to confirm the gain at a given frequency and quantify uncertainties in the voltage readings.

The uncertainties for our oscilloscope measurements were determined based on the Keysight InfiniiVision 1000 X-Series data sheet [3].

For $V_{\text{in}} = 109$ mV (Channel 1, 50 mV/div setting), the full-scale voltage is:

$$50 \text{ mV/div} \times 8 \text{ div} = 400 \text{ mV} \tag{4}$$

The DC vertical gain accuracy for < 10 mV/div is $\pm 4\%$ of full scale:

$$4\% \times 400 \text{ mV} = 16 \approx 2 \text{ mV} \tag{5}$$

For $V_{\text{out}} = 11.0$ V (Channel 2, 2.00 V/div setting), the full-scale voltage is:

$$2.00 \text{ V/div} \times 8 \text{ div} = 16.00 \text{ V} \tag{6}$$

The DC vertical gain accuracy for ≥ 10 mV/div is $\pm 3\%$ of full scale:

$$3\% \times 16.00 \text{ V} = 0.48 \approx 0.5 \text{ V} \tag{7}$$

Therefore, the final results with uncertainties are:

$$V_{\text{in}} = 109 \pm 16 \text{ mV}, \quad V_{\text{out}} = 11.0 \pm 0.48 \text{ V} \tag{8}$$

Thus, the gain in linear terms is:

$$H(f) = \frac{11.0V}{0.109V} \approx 101 \pm 5 \tag{9}$$

And in decibels (dB), using:

$$G_{\text{dB}} = 20 \log_{10}\left(\frac{V_{\text{out}}}{V_{\text{in}}}\right) = 20 \log_{10}(101) \approx 40 \text{ dB} \tag{10}$$

This aligns well with the expected gain of approximately 40 dB.

R-5: Maximum Gain and Bandwidth

The observed maximum gain is approximately:

$$A_v = 40 \text{ dB} \Rightarrow 10^{40/20} = 100. \tag{11}$$

This aligns well with the theoretical gain of 101 calculated from the resistor values:

$$A_v = 1 + \frac{1500}{15} = 1 + 100 = 101 \tag{12}$$

From the bode plot (Figure 4), we see that the point at which the output amplitude is reduced by no more than 3 db occurs at approximately 50kHz. Thus, using the measured gain of 100 and estimated bandwidth from the plot, we find:

$$\text{GBP} = A_v \times BW = 100 \times 50\text{kHz} \approx 5 \text{ MHz}, \tag{13}$$

which is precisely the value stated by the op-amp's data sheet [**?**].

Overall, the results confirm the expected behavior, with minor discrepancies potentially due to component tolerances and measurement limitations.

INVERTING AMPLIFIER

R-6: Verification of the Inverting Amplifier

To confirm that the circuit functions as an inverting amplifier, we measured its output response using an oscilloscope. The theoretical gain for an inverting amplifier is given by:

$$A_v = -\frac{R_4}{R_3} \tag{14}$$

where R_3 and R_4 were selected to achieve a gain of approximately -100.

To verify the inversion of the input signal, a sinusoidal input signal at 50 Hz with an amplitude of 100 mV_{pp} was applied to the circuit. The resulting output waveform was observed on an oscilloscope, as shown in Figure 6.

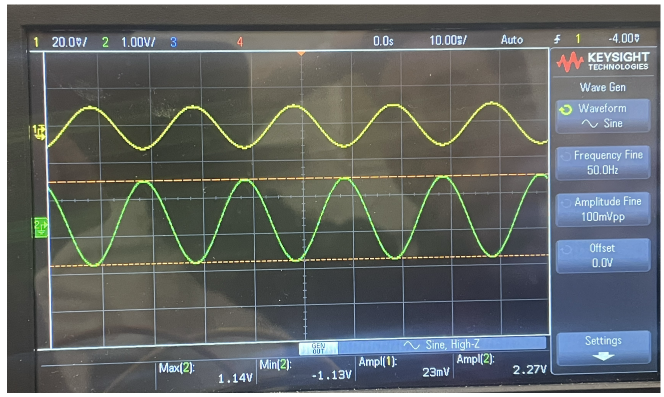


FIG. 6: Oscilloscope capture showing the input (yellow) and output (green) waveforms for the inverting amplifier. The 180° phase shift confirms signal inversion.

The output waveform (green) is clearly inverted with respect to the input waveform (yellow) as evidenced by the 180° phase difference, indicating that the amplifier is functioning as expected. The measured gain from the oscilloscope confirms the expected amplification factor.

Additionally, a breadboard implementation of the inverting amplifier is shown in Figure 7.

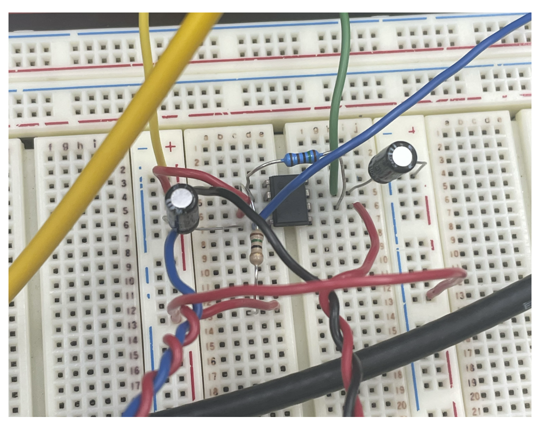


FIG. 7: Breadboard implementation of the inverting amplifier.

INPUT IMPEDANCE

R-7: Input Impedances of Falstad Circuits

- **(A) Ideal Non-Inverting Amplifier:**

$$V_{in} = -417mV, \quad I_{in} = 0$$
$$Z_{in} = \infty$$

- **(B) Real Non-Inverting Amplifier:**

$$A_{open} = 10^5$$
$$\beta = \frac{1k}{10k + 1k} = \frac{1}{11}$$
$$Z_{opamp} = 2M\Omega \ [\mathbf{?}\ ]$$
$$Z_{in} = (1 + \beta A_{open}) Z_{opamp}$$
$$= 1.81 \times 10^{10}\Omega$$

- **(C) Ideal Inverting Amplifier:**

$$Z_{in} = R_{in} = 1k\Omega$$

- **(D) Real Inverting Amplifier:**

$$Z_{in} = 1k\Omega$$

R-8: Doubling Impedance

- **(A) Real Inverting Amplifier:**
To double the input impedance while keeping the gain the same, both resistors R_1 and R_f should be doubled:

$$R_1' = 2R_1, \quad R_f' = 2R_f$$

This ensures that Z_{in} doubles while maintaining the same gain:

$$A_v' = -\frac{2R_f}{2R_1} = -\frac{R_f}{R_1} = A_v$$

- **(B) Real Non-Inverting Amplifier:**
Say we double R_f and R_1. This would mean the feedback factor β is doubled, and the gain remains:

$$A_v = 1 + \frac{R_f}{R_1}$$

This keeps the gain unchanged. However, for the input impedance:

$$Z_{in,\text{initial}} = (1 + A_v\beta) Z_{opamp}$$
$$Z_{in,\text{new}} = (1 + 2A_v\beta) Z_{opamp}$$
$$= Z_{in,\text{initial}} + A_v\beta Z_{opamp}$$

This result is not exactly double the initial impedance, as it is missing an additional Z_{opamp} term.

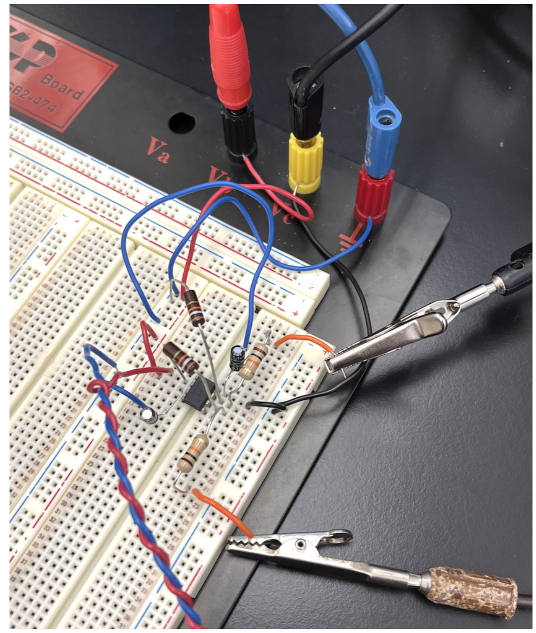


FIG. 8: Breadboard implementation of differential amplifier circuit

R9: DIFFERENTIAL AMPLIFIER

For the final design task, we implemented a differential amplifier using the LF356 op amp. The resistor values were measured precisely, yielding:

$$R_1 = (9.83 \pm 0.001)\,\text{k}\Omega, \quad R_3 = (9.81 \pm 0.001)\,\text{k}\Omega,$$

$$R_2 = (18.58 \pm 0.001)\,\text{k}\Omega, \quad R_4 = (18.52 \pm 0.001)\,\text{k}\Omega.$$

Nominally, these were taken as $R_1 = R_3 = 10\,\text{k}\Omega$ and $R_2 = R_4 = 18\,\text{k}\Omega$, which gives a theoretical gain of

$$\frac{R_2}{R_1} \approx \frac{18\,\text{k}\Omega}{10\,\text{k}\Omega} = 1.8.$$

Using the precise measured values, the gain becomes:

$$\frac{R_2}{R_1} \approx \frac{18.58\,\text{k}\Omega}{9.83\,\text{k}\Omega} \approx 1.89.$$

The op amp was powered using dual supply rails at $\pm 12\,\text{V}$. To ensure stable operation and reduce noise, we placed two $0.1\,\mu\text{F}$ decoupling capacitors as close as possible to the op amp's power pins:

- One capacitor was connected between the positive supply (V^+) and ground.
- The other capacitor was connected between the negative supply (V^-) and ground.

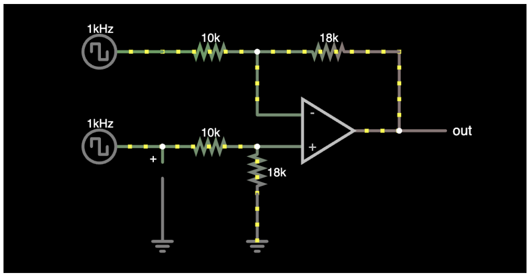


FIG. 9: Falstad simulation of differential amplifier

FIG. 10: Scope output for differential amplifier, paused when the two waveforms were in-phase

Signal Inputs and Theoretical Output

- **Non-inverting input**: WaveGen set to a $\sim 1\,\mathrm{kHz}$ square wave, $1.6\,\mathrm{Vpp}$.
- **Inverting input**: Demo Probe Comp signal ($\sim 1\,\mathrm{kHz}, \sim 2.5\,\mathrm{Vpp}$).

The differential amplifier output is given by:

$$V_{\mathrm{out}}(t) = 1.8\,\big(V_{+}(t) - V_{-}(t)\big).$$

Over a full cycle, the maximum possible difference between the voltages is ($2.5\,\mathrm{V}$ minus $1.6\,\mathrm{V}$) is $0.9\,\mathrm{V}$, which multiplied by 1.8 is $\sim 1.62\,\mathrm{Vpp}$.

Observed Output and Phase Drift

On the oscilloscope, we measured an output of approximately $\sim 1.63\,\mathrm{Vpp}$, in good agreement with the theoretical estimate of $\sim 1.62\,\mathrm{Vpp}$. Although the two inputs (Demo Probe Comp and WaveGen) were each near $1\,\mathrm{kHz}$, they were not phase-locked. Consequently:

- The output exhibited a stable peak-to-peak amplitude (around $1.6\,\mathrm{Vpp}$) because each input waveform maintained a constant amplitude, and the differential amplifier applied a fixed gain of 1.8.
- The phase relationship between the two input waves drifted slowly over time. When triggering the scope on the amplifier output, the other signal (WaveGen) appeared to "slide" relative to the output signal, reflecting their slight frequency mismatch.

Despite this phase drift, the *peak-to-peak* measurement of the output remained consistent, as each cycle reached the same upper and lower voltages determined by the instantaneous difference of the two square waves.

Overall, the differential amplifier worked as intended, producing a time-varying output whose amplitude is set by the difference in the two input square waves. The measured $\sim 1.63\,\mathrm{Vpp}$ closely matches the theoretical calculation of $\sim 1.62\,\mathrm{Vpp}$. The slow phase drift observed on the scope is a normal consequence of having two independent signals of slightly different frequencies. Nonetheless, the *amplitude* of the output remains stable, confirming that the circuit behaves as a proper difference amplifier.

[1] Texas Instruments, "LF356 Operational Amplifier Datasheet," `https://www.ti.com/lit/ds/symlink/lf356.pdf`.

[2] Keysight Technologies, "E36311A 80W Triple Output Power Supply," `https://www.keysight.com/ca/en/product/E36311A/80w-triple-output-power-supply-6v-5a-25v-1a.html`.

[3] Keysight Technologies, "InfiniiVision 1000 X-Series Oscilloscopes Data Sheet," `https://www.keysight.com/ca/en/assets/7018-06411/data-sheets/5992-3484.pdf`, 2019. [Accessed: Feb. 16, 2025].