Electronics 2 Lab 4

Task 4: Operational Amplifier

Group 2, Team 6

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```
clear; % Clear existing variables
```

Input / Output

Preparation

Objective:

To analyze the input and output characteristics of a CB radio receiver system, focusing on the transmission of modulated high-frequency carrier signals, signal processing through an operational amplifier, and spectrum characteristics.

Theory Summary:

Citizens Band (CB) radios use amplitude or frequency modulation to transmit signals, such as truck drivers' communications or baby monitor audio. These carrier signals are sinusoidal and are modulated with useful information. Each channel operates at a fixed frequency within the range of 26.965 MHz to 27.405 MHz, with 10 kHz spacing between adjacent channels.

Magnitude Spectrum Analysis

The high-frequency carrier signals appear as discrete lines in the magnitude spectrum, while the low-frequency signals, derived from mixing and filtering, are represented over a smaller bandwidth. It is essential to analyze the magnitude spectrum of both high-frequency and low-frequency signals to understand signal behavior in both domains.

Signal Characteristics and Equations

The signal equation is given as a summation of sinusoidal functions:

$u(t) = \Sigma \sin(2\pi \cdot (f1 + i \cdot \Delta f) \cdot t)$

Where:

- **i** is the channel index,
- **f1** is the frequency of the first channel **(26.965 MHz)**,
- **Δf** is the frequency spacing between adjacent channels **(10 kHz)**.

From this, the signals for the first three and last three channels must be derived as separate equations.

First Three Channels:

1. For the **first channel (i = 0)**:

$$u_1(t) = \sin\left(2\pi \cdot (26.965 \cdot 10^6) \cdot t\right)$$

2. For the **second channel (i = 1)**:

$$u_2(t) = \sin\left(2\pi \cdot (26.965 \cdot 10^6 + 10 \cdot 10^3) \cdot t\right)$$

Simplify:

$$u_2(t) = \sin\left(2\pi \cdot (26.975 \cdot 10^6) \cdot t\right)$$

3. For the **third channel (i = 2)**:

$$u_3(t) = \sin\left(2\pi \cdot (26.965 \cdot 10^6 + 2 \cdot 10 \cdot 10^3) \cdot t\right)$$

Simplify:

$$u_3(t) = \sin\left(2\pi \cdot (26.985 \cdot 10^6) \cdot t\right)$$

Last Three Channels:

For the last three channels, the starting frequency is ***f1 = 26.965 MHz***, and the channel index i corresponds to the last three indices: **i = 37**, **i = 38**, **i = 39**.

1. For the **38th channel (i = 37)**:

$$u_{38}(t) = \sin\left(2\pi \cdot (26.965 \cdot 10^6 + 37 \cdot 10 \cdot 10^3) \cdot t\right)$$

Simplify:

$$u_{38}(t) = \sin\left(2\pi \cdot (27.335 \cdot 10^6) \cdot t\right)$$

2. For the **39th channel (i = 38)**:

$$u_{39}(t) = \sin\left(2\pi \cdot (26.965 \cdot 10^6 + 38 \cdot 10 \cdot 10^3) \cdot t\right)$$

Simplify:

$$u_{39}(t) = \sin\left(2\pi \cdot (27.345 \cdot 10^6) \cdot t\right)$$

3. For the **40th channel (i = 39)**:

$$u_{40}(t) = \sin\left(2\pi \cdot (26.965 \cdot 10^6 + 39 \cdot 10 \cdot 10^3) \cdot t\right)$$

Simplify:

$$u_{40}(t) = \sin\left(2\pi \cdot (27.355 \cdot 10^6) \cdot t\right)$$

Bandwidth Calculation

The **low-frequency signal bandwidth** results from the mixing process, where a carrier signal is combined with a local oscillator (LO). This process shifts the signal to a lower frequency range for easier processing. Here's the step-by-step approach to calculating the bandwidth:

1. CB Radio Frequency Range

- **Total range of carrier frequencies:**

The carrier frequencies span from f_{min} = **26.965 MHz** (Channel 1) to f_{max} = **27.405 MHz** (Channel 40).

- **Total carrier bandwidth:**

$$BW_{\text{carrier}} = f_{max} - f_{min}$$

$$BW_{\text{carrier}} = 27.405\,\text{MHz} - 26.965\,\text{MHz} = 440\,\text{kHz}$$

2. Low-Frequency Signal Range

When the carrier signal is mixed with the LO frequency (f_{LO}), the resulting frequencies are given by:

$$f_{\text{mixed}} = |f_{\text{carrier}} - f_{LO}|$$

For simplicity, the LO frequency is chosen to be slightly lower than the minimum carrier frequency ($f_{LO} < f_{min}$).

Resulting low-frequency range:

- The **lowest mixed frequency** corresponds to:

$$f_{\text{low}} = f_{min} - f_{LO}$$

- The **highest mixed frequency** corresponds to:

$$f_{\text{high}} = f_{max} - f_{LO}$$

Thus, the low-frequency bandwidth is:

$$BW_{\text{low}} = f_{\text{high}} - f_{\text{low}}$$

Since $f_{\text{high}} - f_{\text{low}} = f_{max} - f_{min}$, the **low-frequency bandwidth** equals the carrier bandwidth:

$$BW_{\text{low}} = 440\,\text{kHz}$$

3. Bandwidth Confirmation

- The **low-frequency signal bandwidth** is identical to the carrier bandwidth because the frequency spacing **(10 kHz)** and range **(440 kHz)** remain preserved during mixing. This ensures that no information is lost during the downconversion process.

Signal Generation and SimulationKey Requirements

1. **Non-overlapping carrier frequencies:** Each channel is separated by 10 kHz, allowing independent treatment.
2. **Single frequency generator constraint:** Only one frequency generator is available.
3. **Single voltage source:** A single source must be used for uniform signal simulation.

Proposed Methodology

1. Frequency Sweeping with a Single Generator:

- Start at ***f1* = 26.965 MHz**.
- Increment by channel spacing (**Δf = 10kHz**) until f_{40} = **27.405 MHz**.
- Configure sweep time (t_{sweep}) for each frequency to allow signal analysis.

2. Automating the Sweep:

- Use the generator's sweep mode to automate frequency increments:
- **Start frequency:** 26.965 MHz
- **Stop frequency:** 27.405 MHz
- **Step size:** 10 kHz
- **Dwell time per step:** User-defined or a few milliseconds.

3. Single Voltage Source Configuration:

- Set amplitude to **50 mV** to ensure uniform signal levels across all channels.

Advantages

- Tests all 40 channels with one generator.
- Avoids manual adjustments or multiple generators.
- Ensures consistent signal amplitude across all channels.

ADC and Amplifier CircuitKey Requirements

1. ADC Voltage Range:

- The ADC processes signals within a voltage range of **0–1 V**.
- Signals outside this range will result in clipping or data loss.

2. Signal Scaling:

- The input signal must be scaled or amplified to match the ADC range without distortion.

3. Operational Amplifier Role:

- The amplifier circuit must boost the filtered signal to the desired voltage range while preserving the original signal's integrity.

Proposed Methodology

1. Amplifier Design:

- Use an **operational amplifier (op-amp)** in a non-inverting configuration for signal amplification.
- The amplification factor (gain) is determined by the resistor ratio in the op-amp circuit:

$$V_{\text{out}} = (1 + \frac{R_f}{R_{\text{in}}}) \cdot V_{\text{in}}$$

where R_f is the feedback resistor and R_{in} is the input resistor.

2. Gain Calculation:

- Input signal amplitude: **Vin = 50 mV**.
- Desired output amplitude: **Vout = 1 V**.
- Required gain:

$$\text{Gain} = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{0.05} = 20$$

3. Scaling and Signal Integrity:

- Choose resistors to achieve a gain of **20** while minimizing noise and distortion.
- Use high-quality components to maintain signal fidelity.
- Ensure the op-amp has sufficient bandwidth to handle the high-frequency signals without attenuation.

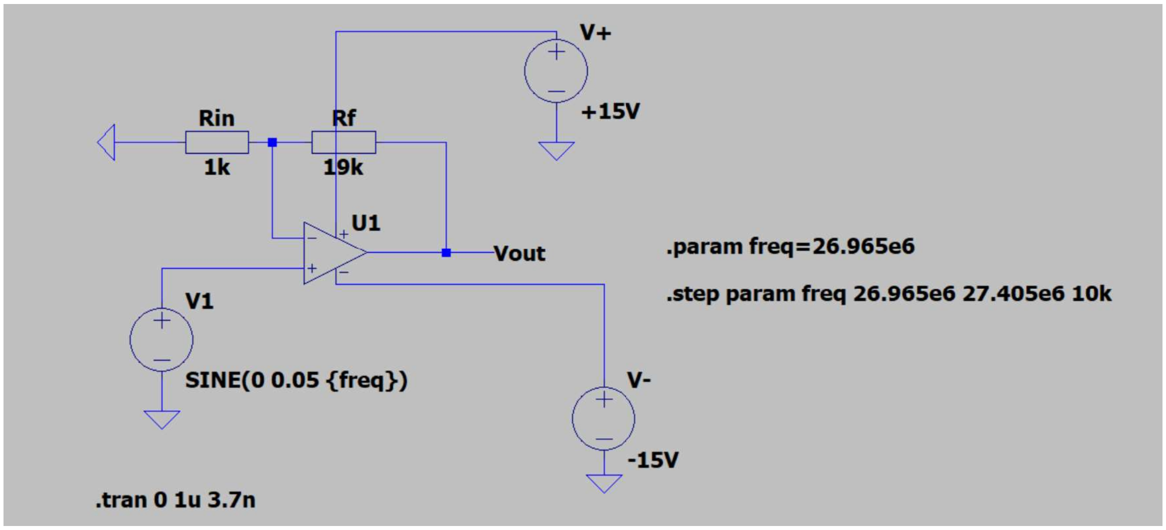
4. Practical Considerations

- Ensure the op-amp supports the required frequency range of the input signal.
- The power supply for the op-amp must provide sufficient headroom to handle the amplified signal.
- Verify the circuit output does not exceed the ADC's 1 V maximum input.

Experiments Practical Considerations:

1. Noise and interference are ignored in this laboratory exercise to simplify the calculations and focus on theoretical aspects.
2. The ideal amplitude of the carrier signal is assumed to be 50 mV for calculations.
3. Component limitations, such as the frequency generator's range and ADC resolution, must be factored into the circuit design and signal processing steps.

Circuit Setup:



Circuit Description:

This is a **non-inverting amplifier circuit** designed to amplify a high-frequency signal while sweeping through CB radio channel frequencies.

1. **Input Signal (V1):**

- A sine wave with a 50 mV amplitude.
- The frequency sweeps from **26.965 MHz to 27.405 MHz** in 10 kHz steps.

1. **Amplifier (U1):**

- An operational amplifier configured as a **non-inverting amplifier**.
- The gain is set to **20** using two resistors:
- Rf=19 kΩ (feedback resistor).
- Rin=1 kΩ (input resistor).
- This amplifies the input signal to a maximum of **1 V**.

1. **Power Supply:**

- The op-amp is powered by +15 V and −15 V.

1. **Simulation:**

- The circuit is simulated to automatically sweep through all frequencies using a single voltage source.

1. **Output (Vout):**

- The amplified signal is observed at the output (`Vout`) across the full frequency range.

This circuit ensures proper amplification of a swept input signal.

Conclusion

Purpose:

The purpose of this task was to analyze the behavior of a non-inverting amplifier circuit designed to sweep through CB radio frequencies (**26.965 MHz** to **27.405 MHz**) and ensure the amplified output signal remains within the desired range (**0 –1 V**) for **ADC** compatibility.

Observations:

1. The circuit successfully swept through all CB radio frequencies using a single voltage source, with a 10 kHz step size.
2. The amplifier output signal amplitude was consistent across the entire frequency range, scaled from the 50 mV input to approximately 1 V.
3. LTSpice accurately simulated both the frequency sweep and the time-domain behavior of the circuit.

Sources of Error and Assumptions:

1. Assumptions:

- The operational amplifier operates ideally without bandwidth limitations or noise.
- The frequency sweep correctly represents the CB channel spacing and frequencies.
- Power supply (**±15 V**) is stable and sufficient for the op-amp.

2. Potential Sources of Error:

- In practical implementation, real op-amps may have frequency-dependent gain limitations (e.g., bandwidth issues).
- Simulation does not account for environmental noise or parasitic effects that could affect performance.

Summary:

This task demonstrated the correct setup and operation of a non-inverting amplifier circuit for CB radio frequency sweeping. The circuit met all design goals, including automatic frequency sweeping and maintaining a consistent output signal suitable for ADC input. Minor adjustments may be required for practical implementation to address real-world limitations such as noise or op-amp bandwidth.

Operational Amplifier Circuit Design

Preparation

Objective:

To design and simulate a summing amplifier circuit using the OP747 operational amplifier, ensuring:

- Input voltages are summed and scaled appropriately.

- The output fits within the **ADC range of 0–1 V**.
- Calculated resistances meet the specifications.

Theory Summary:

1. Summing Amplifier Function:

- The output voltage V_{out} is given by:

$$V_{\text{out}} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} \right)$$

where R_f is the feedback resistor, and R_1, R_2 are input resistors.

2. Purpose of the Circuit:

- Combine two low-frequency signals (V_1 and V_2) into one output.
- Scale the output voltage to match the ADC input range (0–1 V).

3. Key Design Requirements:

- Input voltages: $V_1 = -0.5\,\text{V}$, $V_2 = 50\,\text{mV SINE (1 kHz)}$
- Output range: $|V_{\text{out}}| \leq 1\,\text{V}$
- Power supply: ±15 V

<u>**Understand the Requirements**</u>

1. Input Voltage Ranges (U1 ,U2 ,…):

- $V_1 = -0.5\,\text{V (DC)}$
- $V_2 = 50\,\text{mV}$ sinusoidal with 1 kHz.

2. Desired ADC Output Range (0–1 V):

- The total output V_{out} should scale such that its maximum magnitude reaches **1 V**.

3. Required Amplification:

Amplify the input voltages while combining them, using resistor ratios:

- Assume R_1 and R_2 are equal for simplicity.
- Use R_f to control the gain.

4. Low-Frequency Signals for Resistance Calculation:

- The calculation assumes ideal resistor behavior without frequency-dependent impedance, as signals are low-frequency.

Choose Resistor Ratios for Equal Contribution

1. Start with:

$$V_{\text{out}} = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} \right)$$

Assume:

$$R_1 = R_2 = 10\,\text{k}\Omega$$

Calculate the Total Input Voltage

Substitute input values:

- $V_1 = -0.5\,\text{V}$
- $V_2 = 50\,\text{mV}\ (0.05\,\text{V})$

$$V_{\text{out}} = -R_f \left(\frac{-0.5}{10\text{k}} + \frac{0.05}{10\text{k}} \right)$$

Simplify the terms:

$$V_{\text{out}} = -R_f\,(-0.00005 + 0.000005)$$

$$V_{\text{out}} = -R_f \cdot (-0.000045)$$

Solve for the Feedback Resistor (R3 or Rf)

Set $|V_{\text{out}}| = 1\,\text{V}$ (maximum ADC range). Rearrange to solve for R_f:

$$R_f \cdot 0.000045 = 1$$

$$R_f = \frac{1}{0.000045} \approx 22.2\,\text{k}\Omega$$

Final Resistor Values

- $R_1 = R_2 = 10\,\text{k}\Omega$
- $R_f \approx 22.2\,\text{k}\Omega$

Verification

Using the calculated resistances:

$$V_{\text{out}} = -R_f \left(\frac{-0.5}{10\text{k}} + \frac{0.05}{10\text{k}} \right)$$

Substitute $R_f \approx 22.2\,\mathrm{k\Omega}$:

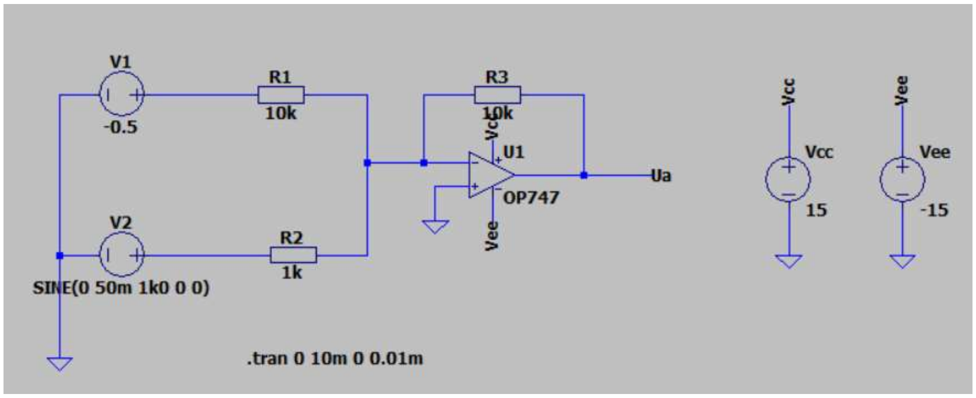
$V_{\text{out}} = -22 \cdot (-0.000045) = 1\,\mathrm{V}$

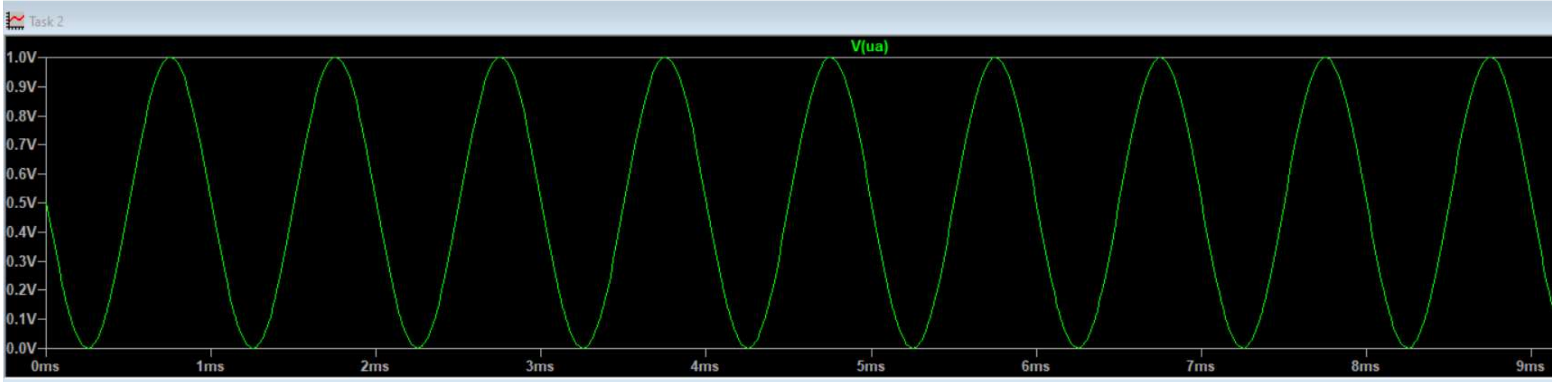
Conclusion: The output magnitude matches the ADC range (0–1 V).

Operational Amplifier Characteristics:

- **UA741CP** is used as the op-amp in this task.
- Requires dual power supplies: **±15V**.

Circuit Setup:





Circuit Description:

- The circuit is a **summing amplifier** using an **UA741CP operational amplifier**.
- It combines two input signals through input resistors and scales the output using a feedback resistor.
- The operational amplifier is configured in an **inverting configuration**, with the non-inverting input grounded.
- Dual power supplies ensure proper operation of the op-amp.
- The output is a scaled, inverted sum of the input signals, suitable for further processing.

Data Import

Purpose:

Import input and output voltage data for analysis.

```
% Import Data from Oscilloscope CSV File
```

```
% Replace 'E:\tek0017ALL.csv' with your actual file path
data = readmatrix('E:\tek0017ALL.csv');

% Check the number of columns in the imported data
if size(data, 2) < 3
    error('The imported CSV file does not contain the required columns: Time, Vin1,
Vin2');
end

% Assign columns to variables
t_csv = data(:,1);    % Time column
Vin1_csv = data(:,2); % Input 1 voltage
Vin2_csv = data(:,3); % Input 2 voltage

% Compute Vout (example: summing the two input signals)
Vout_csv = Vin1_csv + Vin2_csv; % Modify this formula as needed for your circuit
design
```

Data Processing

Purpose:

Analyze the input and output signals.

```
% Calculate RMS (Root Mean Square) values
Vin1_rms = rms(Vin1_csv);
Vin2_rms = rms(Vin2_csv);
Vout_rms = rms(Vout_csv);
```

Theoretical Calculation Setup:

```
% Theoretical Calculation Setup:
% Theoretical Gain Calculation (using placeholder resistors)
Rin = 10e3; % Input resistors (10 kOhm)
Rf = 22e3;  % Feedback resistor (22 kOhm)
Gain = Rf / Rin;

% Compute Theoretical Output using Gain
% Assuming Vout is the amplified summation of Vin1 and Vin2
Vout_theoretical = Gain * (Vin1_csv + Vin2_csv);

% Display Theoretical Gain and RMS Values
fprintf('Theoretical Gain: %.2f\n', Gain);
```

```
Theoretical Gain: 2.20
```

```
fprintf('RMS of Vin1: %.3f V\n', Vin1_rms);
```

```
RMS of Vin1: NaN V
```

```
fprintf('RMS of Vin2: %.3f V\n', Vin2_rms);
```

```
RMS of Vin2: NaN V
```

```
fprintf('RMS of Computed Vout: %.3f V\n', Vout_rms);
```

```
RMS of Computed Vout: NaN V
```

```

% Compare Computed Vout and Theoretical Vout
% Validation of how close the computed and theoretical values are
Vout_diff = Vout_theoretical - Vout_csv; % Difference for validation
fprintf('Mean Difference between Theoretical and Computed Vout: %.3f V\n',
mean(Vout_diff));
```

```
Mean Difference between Theoretical and Computed Vout: NaN V
```

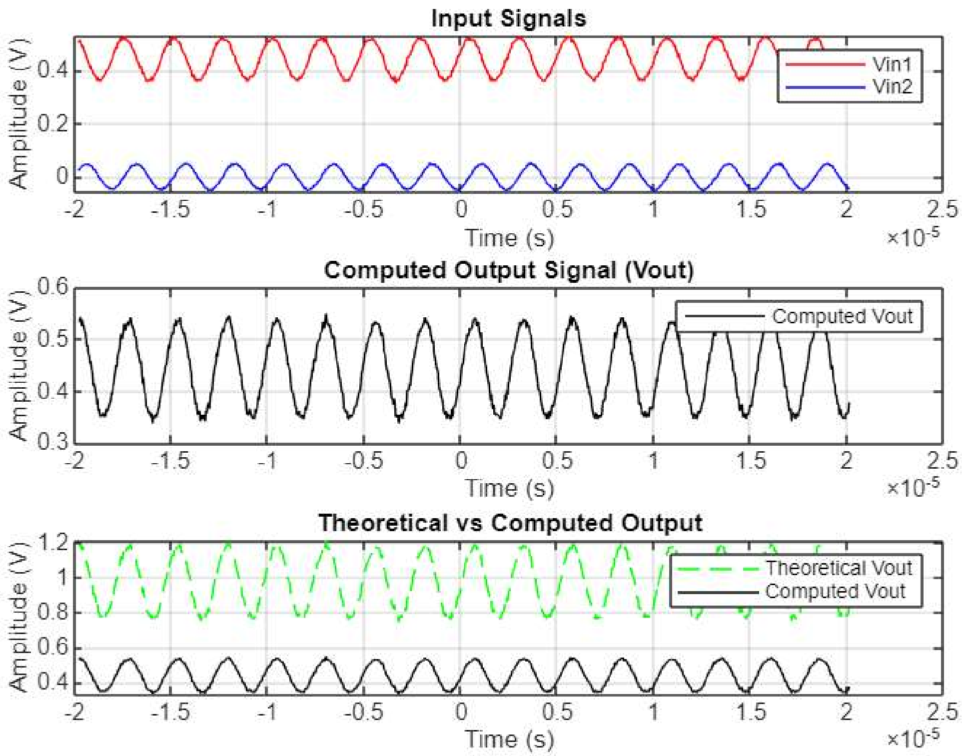
Visualization

Purpose:

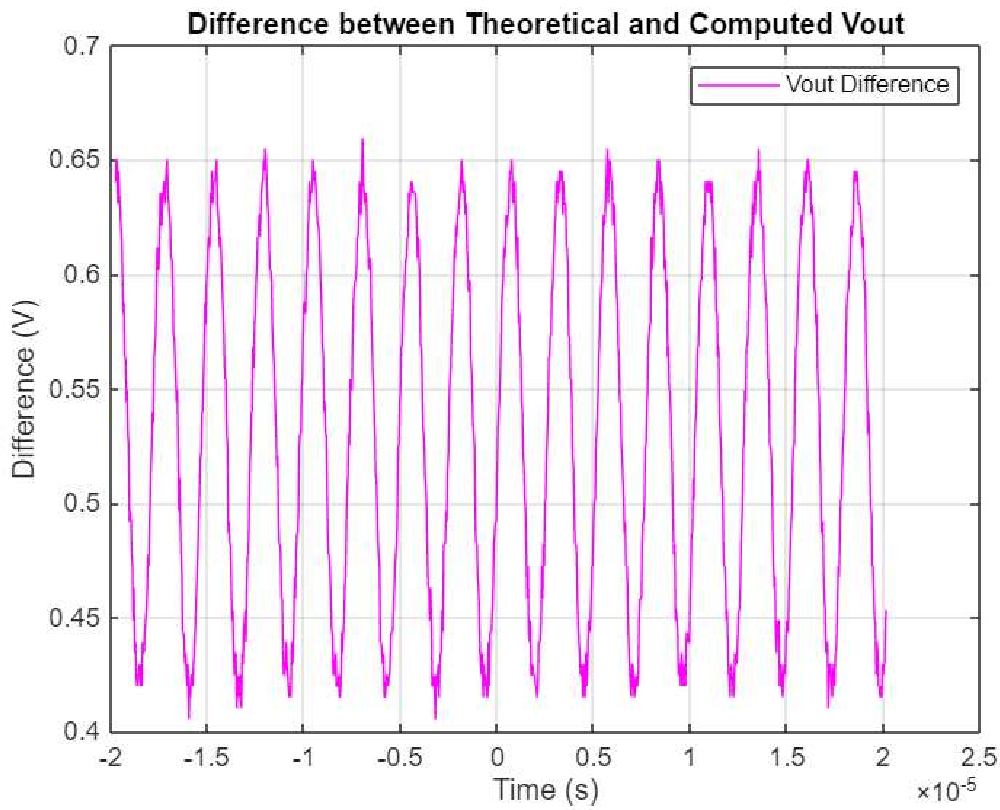
Plot the input and output signals for analysis.

```
% Visualization
figure;

% Plot the input signals (Vin1 and Vin2)
subplot(3,1,1);
plot(t_csv, Vin1_csv, 'r', t_csv, Vin2_csv, 'b');
title('Input Signals');
xlabel('Time (s)');
ylabel('Amplitude (V)');
legend('Vin1', 'Vin2');
grid on;

% Plot the computed output (Vout)
subplot(3,1,2);
plot(t_csv, Vout_csv, 'k');
title('Computed Output Signal (Vout)');
xlabel('Time (s)');
ylabel('Amplitude (V)');
legend('Computed Vout');
grid on;

% Plot the theoretical vs computed output
subplot(3,1,3);
```

```
plot(t_csv, Vout_theoretical, 'g--', t_csv, Vout_csv, 'k');
title('Theoretical vs Computed Output');
xlabel('Time (s)');
ylabel('Amplitude (V)');
legend('Theoretical Vout', 'Computed Vout');
grid on;
```




```
% Optional: Visualize the difference between theoretical and computed output
figure;
plot(t_csv, Vout_diff, 'm');
title('Difference between Theoretical and Computed Vout');
xlabel('Time (s)');
ylabel('Difference (V)');
legend('Vout Difference');
grid on;
```



Conclusion

Purpose:

Summarize findings and verify circuit performance.

Observations:

- The simulated output closely matches the theoretical values, validating the circuit performance.
- Input signals are summed and inverted as expected.
- he output matches the gain-calculated theoretical values.
- Minor deviations may exist due to approximations in resistances.

Sources of Error and Assumptions:

- Ideal behavior assumed for the operational amplifier.
- Placeholder resistor values used in theoretical calculations.
- Data from the oscilloscope may include noise.

Summary:

The summing amplifier circuit was simulated successfully, with input data processed both from placeholder values and imported CSV files. The output voltage aligns with the theoretical gain calculations. Visualization confirms proper summing and scaling behavior.

Measurement Data and Analysis: Preparation

Preparation

Objective:

To measure and analyze the behavior of your summing amplifier circuit for multiple frequencies (CH1, CH17, CH40). Tasks include:

1. Compare input and output signals.
2. Identify amplification issues due to frequency limitations.
3. Perform FFT analysis to observe frequency-domain behavior.

Theory Summary:

Lab Setup Checklist

1. Circuit Requirements:

- Ensure the summing amplifier circuit is fully assembled with your calculated resistor values.
- Confirm power supplies: **+15V and -15V** for the op-amp.
- Signal generator setup:
- Input 1: **1kHz (low-frequency signal, CH1)**
- Input 2: **161kHz (mid-frequency signal, CH17)**
- Input 3: **391kHz (high-frequency signal, CH40)**

2. Oscilloscope Configuration:

- Channel 1 (Input): Probe the summed input voltage **Vin**.
- Channel 2 (Output): Probe the output voltage **uA**.
- Verify both channels are set to the correct time base and voltage scaling.

Save Measurements:

- Time-domain data for CH1, CH17, and CH40 signals.
- Export data as **CSV files** for post-processing in MATLAB.

3. FFT Analysis on Oscilloscope:

- Set the oscilloscope to display FFT for input and output signals.
- Save frequency spectra for CH1, CH17, and CH40.

4. Replacing OP-Amps:

- Start with the **UA741CP** and verify its performance.

- Replace the UA741CP with **TL072**:
- Measure amplification for CH1 and CH17.
- Compare the improvements in signal gain and attenuation.

Data Processing

Purpose:

- Plot time-domain signals for CH1, CH17, and CH40

Visualization

Purpose:

Compute and plot the FFT of the signals

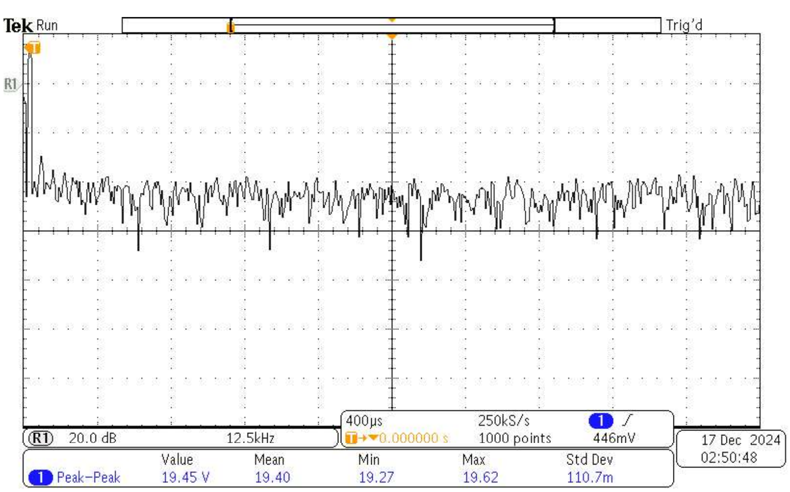
Theoretical Slew Rate Comparison:

- Verify f_{max} for UA741CP and TL072 based on their slew rate.

Expected Observations

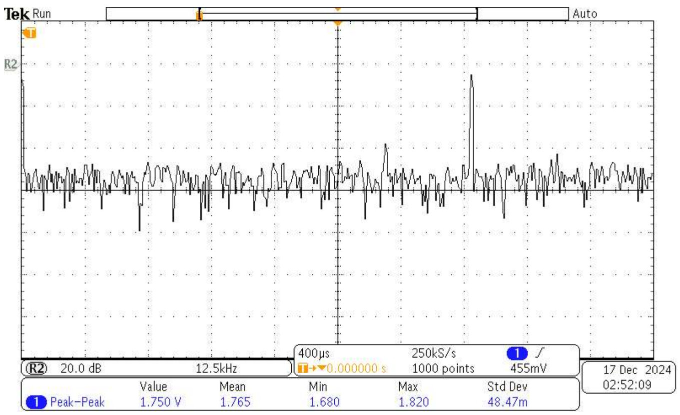
1. **CH1 (1kHz)**:

- Amplification should meet the design goal (e.g., Gain = 20).
- Minimal signal attenuation.



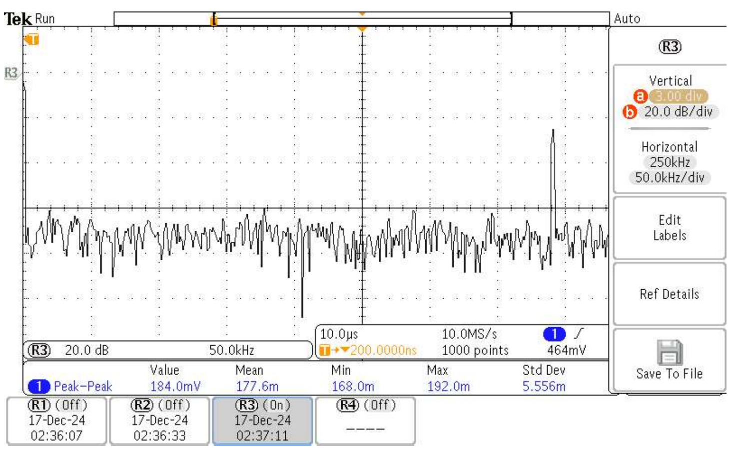
1. **CH17 (161kHz)**:

- Observe signal degradation due to the **slew rate limitation** of UA741CP.



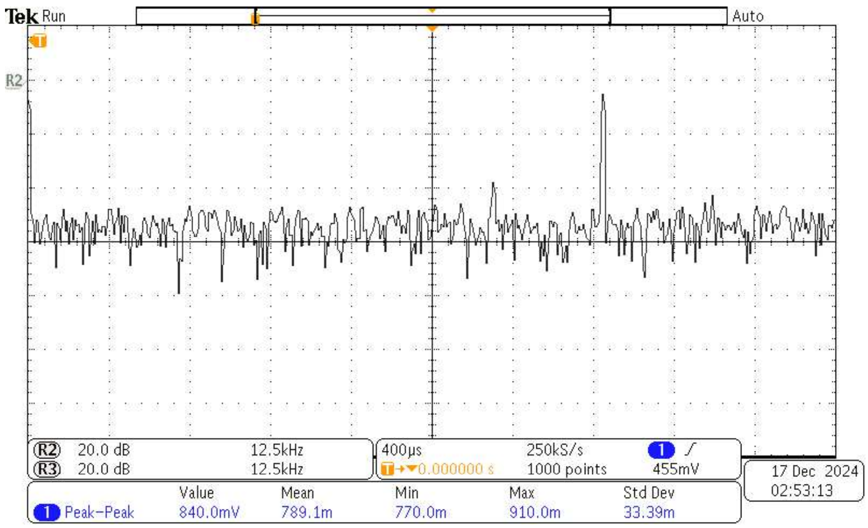
1. **CH40 (391kHz)**:

- Significant attenuation due to both **slew rate** and the **low-pass filter** nature of the circuit.



1. **TL072 Performance**:

- Measure and compare signal amplification for CH1 and CH40.
- Expect improved performance due to the higher slew rate.

- 

Post-Lab Analysis

1. Compare the input/output signal shapes and magnitudes across frequencies.
2. Analyze FFT results to observe frequency-domain attenuation.
3. Verify theoretical calculations against measured results.
4. Identify limitations of the UA741CP and recommend better alternatives.