# Opamp Characteristics and Amplifier Design

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In the oscilloscope screenshots, $v_{in}$ vs. $t$ is in yellow, and $v_{out}$ vs. $t$ is in green unless otherwise specified.

## 1 Opamp Performance

### 1.1 Saturation

$v_+$ is connected to $v_{in}$ and $v_-$ is connected to ground. Due to the high open-loop gain, $v_{out}$ saturates positively when $v_{in} > 0$ and negatively when $v_{in} < 0$.

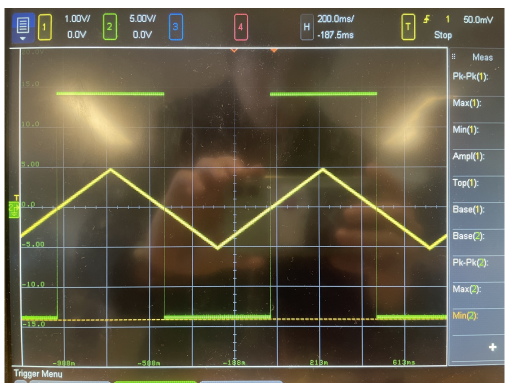


Figure 1: Scope screenshot

### 1.2 Output Voltage Swing

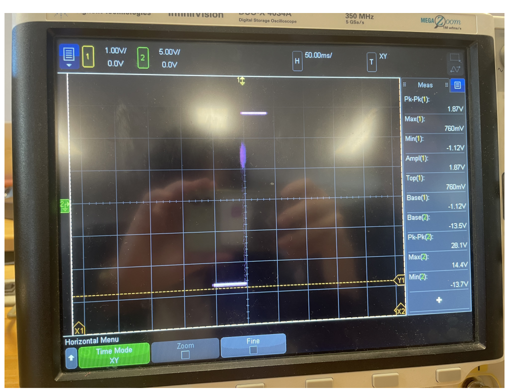


Figure 2: Screenshot for XY output swing

With a $2\,\mathrm{k\Omega}$ resistor as load, the maximum output is $14.4\,\mathrm{V}$, and the minimum is $-13.7\,\mathrm{V}$. This is consistent with the data sheet's typical voltage swing of $\pm 13\,\mathrm{V}$.

## 1.3 Large Signal Voltage Gain

Due to the high opamp gain, we need a small input voltage to accurately measure the gain.
We input a $V_p = 1\,\mathrm{mV}$ triangular wave at $1\,\mathrm{Hz}$. However, at this small input voltage, significant noise is present. We estimated the gain by extrapolating the slope.


Figure 3: Screenshot for a small input

The slope of the triangular wave is $\frac{1\,\mathrm{mV}-(-1\,\mathrm{mV})}{0.5\,\mathrm{s}} = 4\,\mathrm{mV/s}$
The output voltage switches from $-13.7\,\mathrm{V}$ to $14.4\,\mathrm{V}$ in $52\,\mathrm{ms}$. In this $52\,\mathrm{ms}$ period, $\Delta v_{in} = 4\,\mathrm{mV/s}\cdot 52\,\mathrm{ms}$

$$\begin{aligned} A &= \frac{\Delta v_{out}}{\Delta v_{in}} \\ &= \frac{14.4\,\mathrm{V} - (-13.7\,\mathrm{V})}{4\,\mathrm{mV/s}\cdot 52\,\mathrm{ms}} \\ &\approx 135\,\mathrm{V/mV} \end{aligned}$$

Our temperature is close to $25\,^\circ\mathrm{C}$. $20\,\mathrm{V/mV} < 135\,\mathrm{V/mV} < 200\,\mathrm{V/mV}$. Our large-signal voltage gain is below the typical value, but above the minimal value, so it's acceptable.

## 1.4 Short Circuit Current

Finally, the function generator is replaced by a fixed DC source of $10\,\mathrm{V}$, and the output is shorted to ground through an ammeter.
The short circuit current is $27.2\,\mathrm{mA}$, which is around the typical value of $25\,\mathrm{mA}$.


Figure 4: $i_{sc}$ measurement

## 2 Unity Gain Buffer

### 2.1 DC Input

I would expect $v_{out}$ to be the same as $v_{in}$. When $v_{in} = 0$, $v_{out} = 0$ as well. This is verified by our output measurement: $v_{out} = 0\,\text{V}$.

The ammeter, shorted from $v_+$ to ground, does not read any current to its precision of 1 µA. It is unable to read the input bias current on the order of 80 to 500 nA, as specified by the data sheet.


Figure 5: DC $i_+$ measurement

### 2.2 AC Input

Now the $v_+$ is driven by a sine wave $v_{out} = v_{in}$.
The ammeter, now set to measure AC current, again cannot measure anything to its precision. According to the data sheet, the input offset current is on the order of 20 to 200 nA, so our ammeter cannot read anything.


Figure 6: AC $i_+$ measurement

$v_{out}$ follows $v_{in}$, as shown by the overlapping traces below:

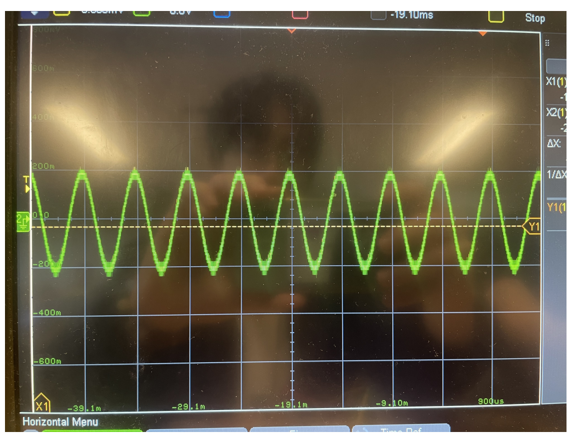


Figure 7: Screenshot of $v_{in}$ (yellow) and $v_{out}$ (green). The traces overlap.

(a) The bias current is within specification, within the limits of our measurement precision.

(b) The assumption that "opamp draws no current at its input terminals" is valid.

(c) The virtual short assumption is also valuid, as $v_{out} = v_N = v_P$. Both input terminals are virtually shorted with proper negative feedback.

# 3 Unity Gain Buffer vs. Voltage Divider

When a $5\,\mathrm{k}\Omega$ resistor is added to the opamp input, the output remains the same.

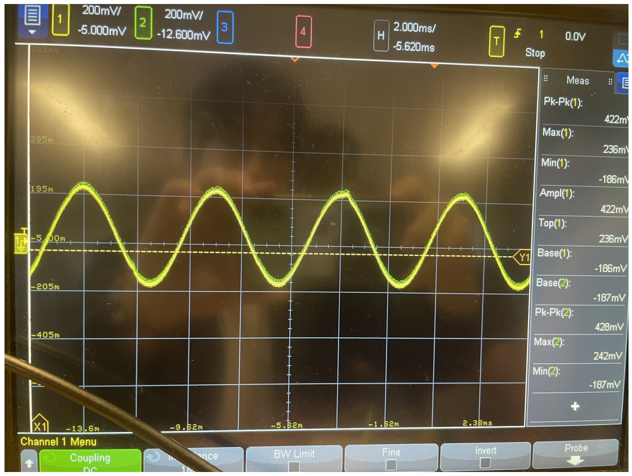


Figure 8: Screenshot with opamp. The input/output traces overlap.

Then the opamp is removed, and the $5\,\mathrm{k}\Omega$ resistor is connected directly to the $2\,\mathrm{k}\Omega$.

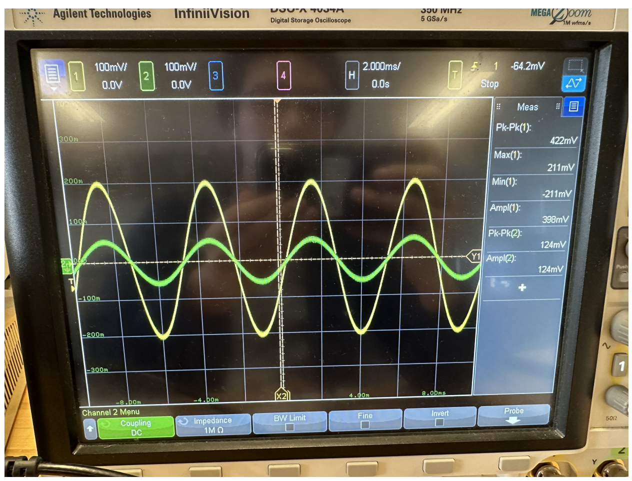


Figure 9: Screenshot without the opamp.

$v_{out}$ is significantly smaller than $v_{in}$. There is a significant voltage drop, because the output resistance of the previous stage divides the output voltage. In fact, $\frac{V_{out,pp}}{V_{in,pp}} = \frac{124\,\mathrm{mV}}{422\,\mathrm{mV}} \approx \frac{2}{7} = \frac{2\,\mathrm{k}\Omega}{5\,\mathrm{k}\Omega + 2\,\mathrm{k}\Omega}$.

A unity gain buffer "buffers" out any output resistance of the previous stage because the opamp essentially has infinite input impedance, blocking any input current and, therefore blocking voltage drop.

# 4 Inverting Amplifier

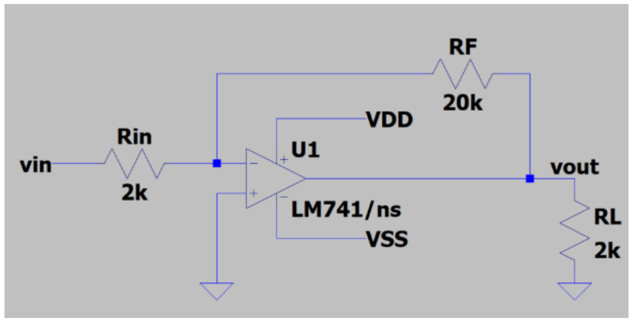


Figure 10: Circuit schematic of the inverting amplifier

$$A_v = -\frac{R_f}{R_{in}} = -\frac{20\,\mathrm{k}\Omega}{2\,\mathrm{k}\Omega} = -10$$

Result under a $2\,\mathrm{k}\Omega$ load:

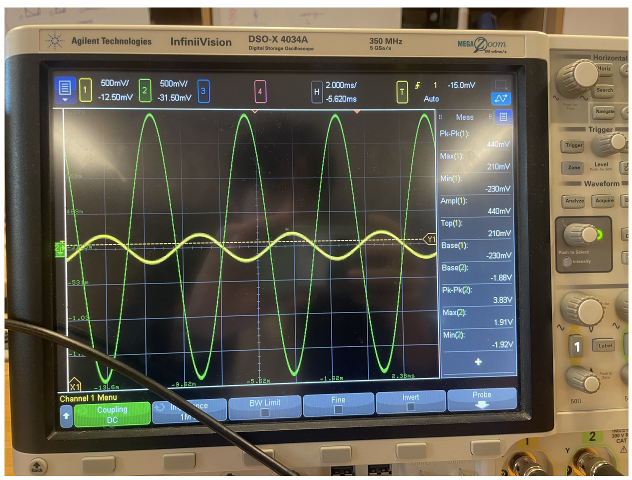


Figure 11: Screenshot for result

# 5 Variable-gain Inverting Amplifier

We used a potentiometer to vary the $R_f$ and vary the gain.

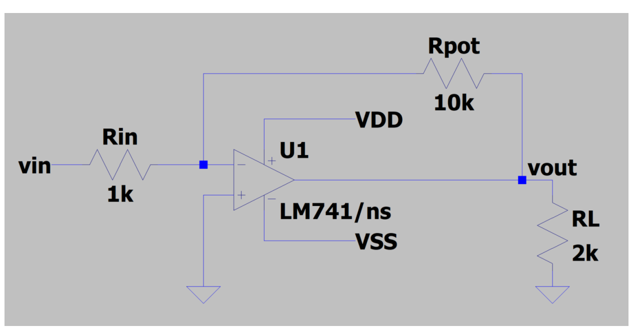


Figure 12: Circuit schematic of the inverting amplifier with variable gain

- When $R_{pot} = 0$, $A_v = -\frac{R_2}{R_{in}} - \frac{0}{1\,\mathrm{k}\Omega} = 0$.
- When $R_{pot} = 5\,\mathrm{k}\Omega$, $A_v = -\frac{R_2}{R_{in}} = -5$
- When $R_{pot} = 10\,\mathrm{k}\Omega$, $A_v = -\frac{R_2}{R_{in}} = -10$.

## 5.1 Result

Results under a $2\,\mathrm{k}\Omega$ load. The vertical scales differ for $v_{in}$ and $v_{out}$.


Figure 13: $A_v = 0$

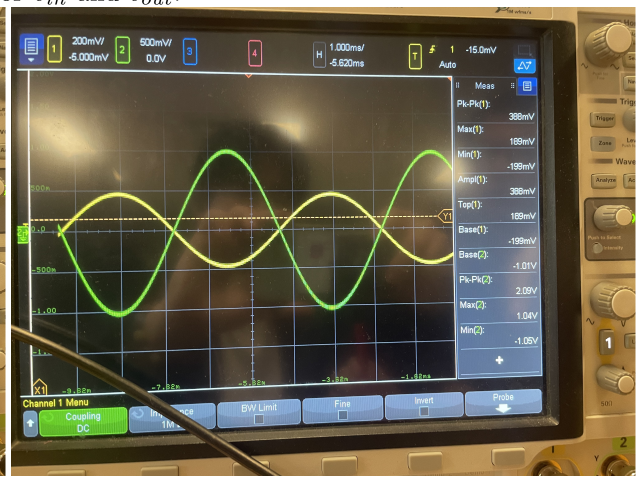


Figure 14: $A_v = -5$

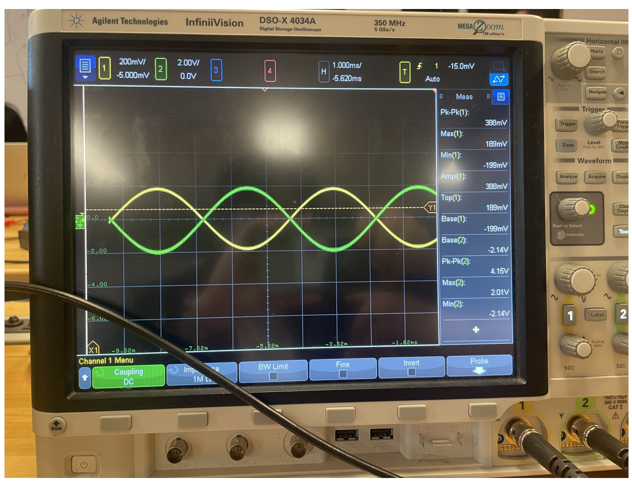


Figure 15: $A_v = -10$

# 6 Non-inverting Amplifier

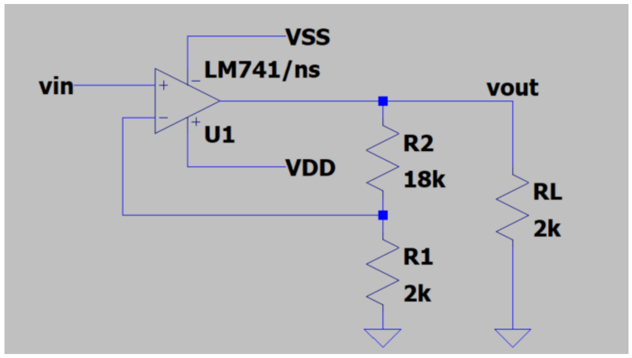


Figure 16: Circuit schematic for the noninverting amplifier with a gain of 10

$$A_v = 1 + \frac{R_2}{R_1} = 1 + \frac{18\,\text{k}\Omega}{2\,\text{k}\Omega} = 10$$

Result under a $2\,\text{k}\Omega$ load:

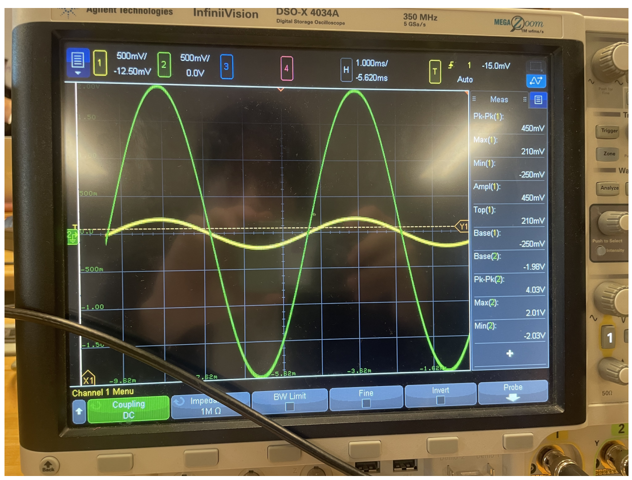


Figure 17: Screenshot of the result. $A_v = 10$.

# 7 Non-inverting Amplifier with Variable Gain

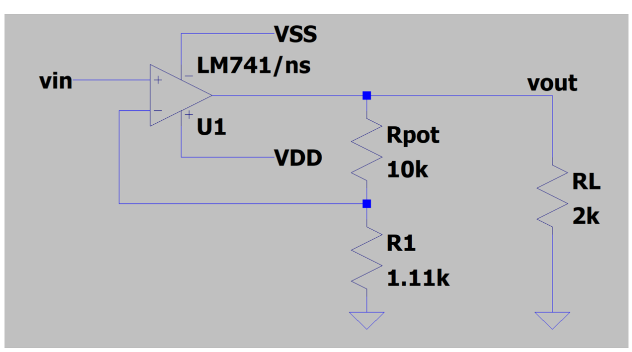


Figure 18: Circuit schematic for the variable noninverting amplifier.

- When $R_{pot} = 0$, $A_v = 1 + \frac{R_2}{R_{in}} = 1$.
- When $R_{pot} \approx 4.44\,\mathrm{k}\Omega$, $A_v = 1 + \frac{R_2}{R_1} = 5$
- When $R_{pot} = 10\,\mathrm{k}\Omega$, $A_v = 1 + \frac{R_2}{R_1} = 10$.

Results under a $2\,\mathrm{k}\Omega$ load:

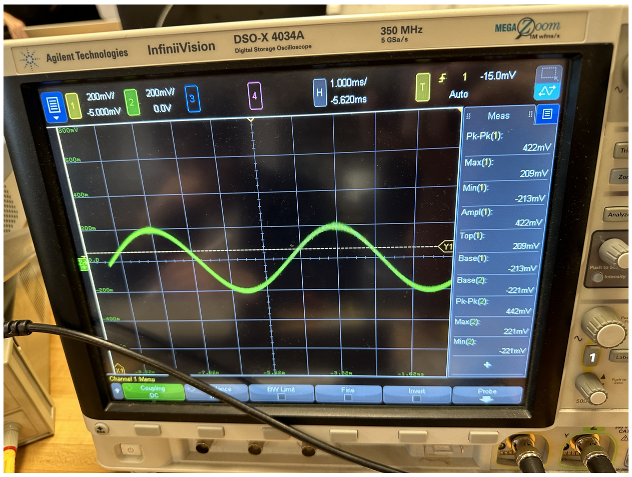


Figure 19: $A_v = 1$

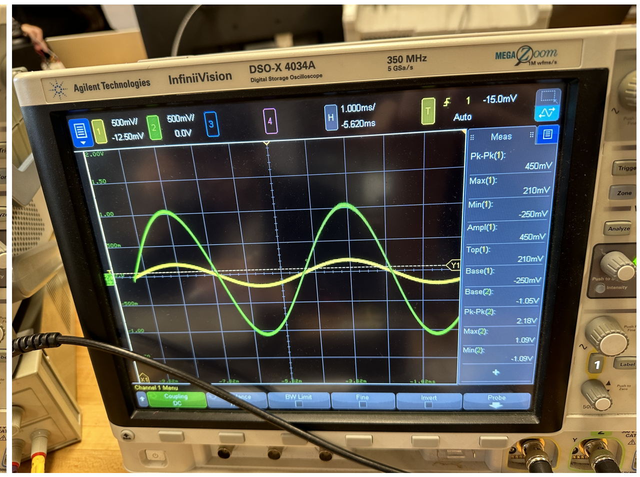


Figure 20: $A_v = 5$

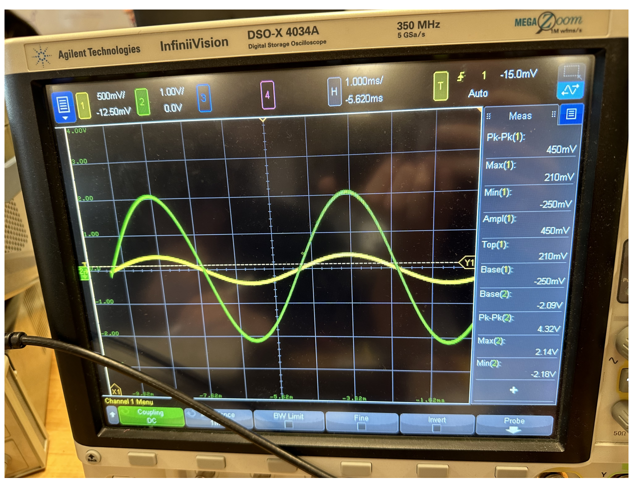


Figure 21: $A_v = 10$. The output scale is twice the input scale.

# 8 Summing Amplifier

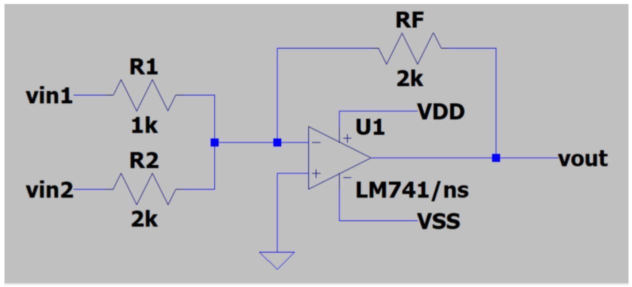


Figure 22: Circuit schematic for the summing amplifier

$$v_{out} = -\frac{R_F}{R_1}v_{in1} - \frac{R_F}{R_2}v_{in2} = -\frac{2\,\mathrm{k\Omega}}{1\,\mathrm{k\Omega}}v_1(t) - \frac{2\,\mathrm{k\Omega}}{2\,\mathrm{k\Omega}}v_2(t) = -(2v_1(t) + v_2(t))$$

$v_1(t)$ is driven with a sinusoid, and $v_2(t)$ is driven with a square wave of the same peak amplitude and frequency.

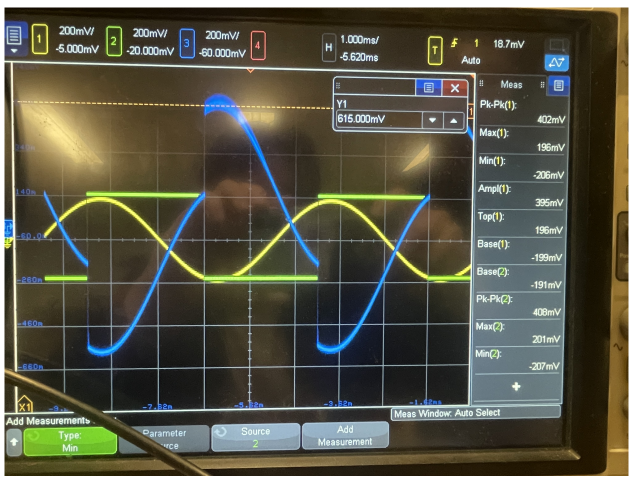


Figure 23: Screenshot with $v_1(t)$ in yellow, $v_2(t)$ is green, and output in blue

# 9 Difference Amplifier

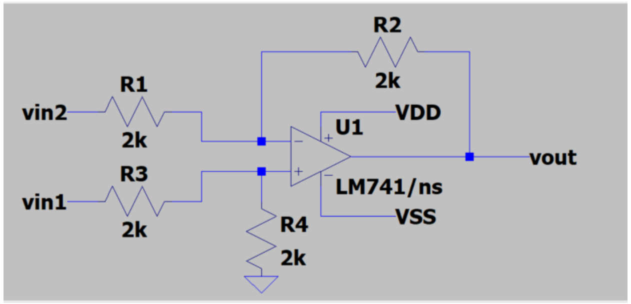


Figure 24: Circuit schematic for the difference amplifier

By setting $\frac{R_3}{R_4} = \frac{R_1}{R_2}$,

$$v_{out} = \frac{R_2}{R_1}(v_{in1} - v_{in2}) = \frac{2\,\text{k}\Omega}{2\,\text{k}\Omega}(v_1(t) - v_2(t))$$

$v_1(t)$ is driven with a sinusoid, and $v_2(t)$ is driven with a square wave of the same peak amplitude and frequency.

Figure 25: Screenshot with $v_1(t)$ in yellow, $v_2(t)$ is green, and output in blue