Laboratory 5 : Introduction to Operational Amplifiers

Concept

The properties of ideal operational amplifiers (op amps) are introduced and compared to the properties of the common 741 opamp. The ideal inverting and non-inverting configurations are explored.

Helpful hints and warnings

Operational amplifiers are integrated circuits (consisting of many internal transistor, diodes, resistors and capacitors) which require a bipolar power source. It is imperative that symmetric positive and negative potentials be applied to the + and - power pins, such as ±12.0 V or ±14.7 V. The power supply should provide ±15 V or less. Check the specification sheet for the absolute maximum power supply potential. Unlike the passive devices encountered in previous laboratory experiments, opamps can be destroyed by the application of excessive potential differences. Remember to connect the power supply ground to the oscilloscope ground. Besides the limitation on the power pins, the two signal inputs also have a limitation on the maximum applied potential. Check the specification sheet. The output of an op amp can be sensitive to changes in the potentials provided by the power supply, $\pm V_{cc}$. It is generally wise to include 100 nF capacitors between each power supply line and the system ground to dampen any such variations.

Experimental Instructions

The TL071 and LM741 Op Amps

Listen to the presentation of the instructor concerning the physical connections and operational parameters of these general purpose op amps.

1. Read the *Introduction to Operational Amplifiers* notes.
2. Physical structure.
   (a) Plastic package vs. ceramic packages, and insertion into the breadboard.
   (b) Pin out.
3. Functionality.
   (a) Op amp concept: differential gain that is large and independent of frequency and amplitude of the input signal.
   (b) Ideal op amp behavior: infinite input resistance, infinite gain at all frequencies, zero output resistance, zero output offset, zero bias current.
   (c) Specification sheet: slew rate, maximum output current, input offset potential, input bias current, gain bandwidth product, input resistance, open-loop gain, CMRR, PSRR.

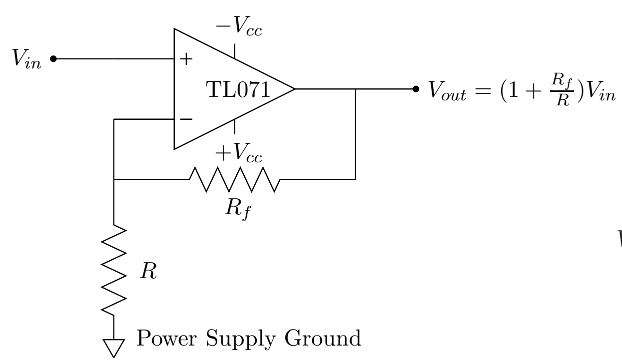
Non-Inverting Amplifier Using the TL071 or AD711

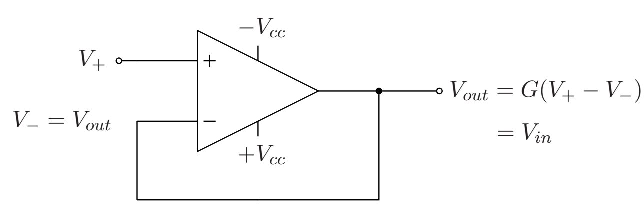
The TL071 is an op amp with JFET inputs, a structure which leads to virtually no input bias currents and a huge input resistance, both unmeasurable with your instruments.

The gain of the ideal non-inverting configuration is easy to derive. Begin with $V_{out} = G(V_+ - V_-) = G(V_{in} - FV_{out})$, where F is the feedback fraction $R_2/(R_1 + R_2)$. Then,

$$V_{out}(1 + GF) = GV_{in} \rightarrow V_{out} = \frac{G}{1+GF}V_{in} \simeq \frac{V_{in}}{F} = (1 + \frac{R_1}{R_2})V_{in} = AV_{in} \ .$$

For the ideal case, this gain A is independent of frequency. Notice that if $R = \infty$ and $R_f = 0$ then the gain is 1.





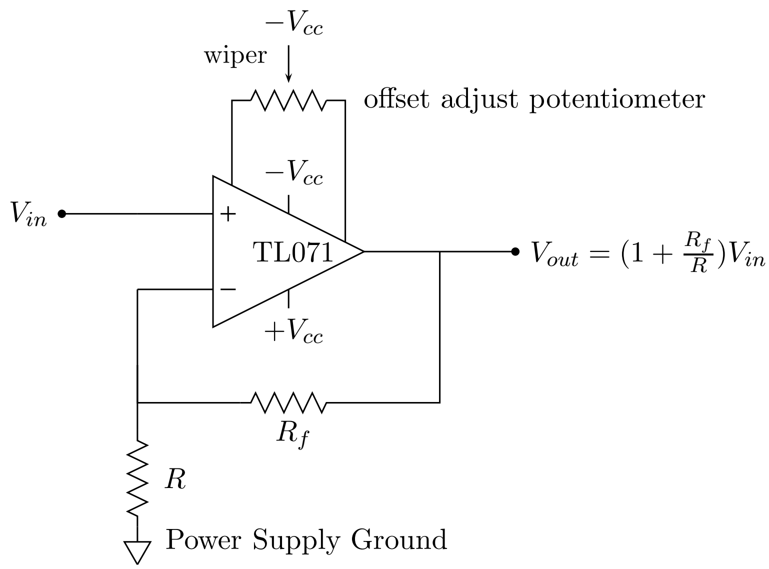
$F = 1$

1. Before investigating $A(\omega)$, we must correct for a subtle but sometimes important nonideality. The constant offset potential V_o will produce a constant background,

$$V_{out} = G(V_+ - V_-) = G(V_{in} + V_o - V_-) = G(V_{in} + V_o - FV_{out})$$

$$V_{out} = \frac{G}{1+GF}(V_{in} + V_o) \simeq \frac{1}{F}(V_{in} + V_o) = \left(1 + \frac{R_f}{R}\right)(V_{in} + V_o) \ .$$

Find the value of V_o from the specification sheet for the op amp. An offset null circuit can be added to eliminate the offset error. The nulling circuit varies from op amp to op amp, but the circuit appropriate for the Tl071 is pictured below.



(a) From the specification sheet, find the specific value of potentiometer needed and then build this circuit with a gain of 1000. Adjust the pot to minimize V_{out} with $V_{in} = 0$.

(b) Does this modification actually work? What is the minimum effective value of V_o that you can achieve?

(c) Now that the offset error is minimized, it is easier to measure noise on the output line. Is there any noise, and if so, is there a dominant frequency?

2. Having eliminated the effect of V_o, the frequency dependence of the gain can now be investigated. Use $R = 1$ kΩ and $R_f = 1$, 9, 99 and 999 kΩ so that the gains are expected to be 2, 10, 100 and 1000. Also, use the unity gain configuration.

   (a) For each gain, use scan_2.py to record $A(\omega)$ over the decadic range [1.0, 7.5] with at least 100 data points. Save the graphs of $|A|$ in dB versus $\log\nu$ and of $\arg(A)$. Also, save the data as csv files.

   (b) The decrease in gain as the frequency increase arises from the inherent frequency dependence of G. Plot $|A(\omega)|$ in dB for all five gains on the same graph using response_plot.py. Do the same for the phase measurements. From these plots determine the parameters $G_\circ$ and $\omega_\circ$ in the model

   $$G(\omega) = \frac{G_\circ}{1 + i\omega/\omega_\circ} \ ,$$

   a function reminiscent of the response function of the RC low pass filter,

   $$A(\omega) = \frac{1}{1 + i\omega RC} \ .$$

   Use simulate.py to simulate your data at each gain, including open-loop. Plot the simulations with your data using response_plot.py or your favorite graphing package. Compare your value of $G_\circ$ to that given in the specifications document.

3. When the gain is 1, an interesting peak occurs in $A(\omega)$ around $\nu = 2$ MHz. Use scan_2.py over the decadic range [4.0, 7.0] to observe more detail. Record this apparent "resonance" frequency $\nu_\circ$. Now apply a square wave at about 10 kHz and look for behavior that might be associated with $\nu_\circ$. This behavior is eliminated in *compensated* op amps by reducing the gain-bandwidth product.

4. The measurement of $A(\omega)$ is based on the assumption of linearity, that is, $V_{out}(\omega) = A(\omega)V_{in}(\omega)$, not $V_{out}(\omega) = A(\omega)V_{in}(\omega) + B(\omega)V_{in}^2(\omega) + \cdots$. This assumption can be tested in two ways.

   (a) Choose a gain between 10 and 100, and configure the function generator to produce a bipolar ramp at a frequency well below the breakpoint or characteristic frequency for that particular gain. Capture the input and output waveforms with scope.py and plot the data in xy mode. Also, save the data so that you can fit the xy plot to a linear function. Is the response linear to within experimental error?

   (b) Switch to a sine wave and observe the FFT of both the input and output signals. When harmonics of the fundamental frequency are observed, the *Total Harmonic Distortion* (THD) is defined as the sum of the powers in all the harmonics as a fraction of the total power. Measure the THD in dB for the input signal and the output signal for several values of V_{pp}. As $|V_{out}|$ approaches $|V_{cc}|$, THD will be substantial. Record data and graphs using the fft option in scope.py.

5. Measure the *Power Supply Rejection Ratio* (PSRR) by measuring V_{out} for $V_{cc} = 16$ and 8 V and calculating the ratio in dB. This is a difficult measurement that requires the highest achievable resolution and signal to noise ratio. Therefore, this should be a DC or zero frequency measurement made with the DMM, not the oscilloscope. Chose a gain between 10 and 100, and use the function generator as the source of V_{in} and set V_{in} such that $V_{out} \approxeq V_{cc} - 2$ V. The amplification of the input offset potential V_{off} is a complication. Use offset triming to minimize its effect. As the definition of PSRR use
$$\text{PSRR} = -\log\left|\frac{V_{out}(V_{cc}=16) - V_{out}(V_{cc}=8)}{V_{out}(V_{cc}=8)}\right| .$$
   How does your value compare to that in the datasheet?

6. Measure the *Common Mode Rejection Ratio* (CMRR) as $20\log|G/G'|$ for the open-circuit expression $V_{out} = G(V_+ - V_-) + G'(V_+ + V_-)$. Use the open-loop configuration with $\nu = 10$ Hz, and at such a low frequency you will have to use DC coupling on the oscilloscope. Tie the two inputs to the same source so that $V_+(\nu) = V_-(\nu)$ and $V_{out} = G'(V_+ + V_-)$. As for G, use either your zero frequency value $G_\circ$ or the value in the datasheet. There will be a DC background signal of $G_\circ V_o$ due to the input offset potential $V_\circ$. If you cannot trim the input offset potential so that the ouput of your amplifier is not saturated (ie, $V_{out} < V_{cc} - 1$), then this experiment will not work.

7. When the output changes are large, that is, swinging back and forth between $\pm V_{cc}$, the waveform can be limited or distorted by the *slew rate* of the op amp. This is typically given in the specification sheet in units of Volts/μsec. Measure the slew rate of your op amp by applying an input square wave and observing the rising and falling slopes of the output waveform. Compare your slew rate to that given in the datasheet.

8. The op amp has a maximum output current, which means when a load resistor R_L is connected to the output, V_{out} will be smaller than anticipated if R_L is too small. Find the value of R_L at which V_{out} is measurably smaller than that observed when $R_L = \infty$. Calculate the maximum deliverable output current, and compare that to the value on the datasheet for the op amp.

Non-Inverting Amplifier Using the LM741

The LM741 is an op amp with BJT inputs, a structure which leads to significant bias currents and only a large input resistance. It is pin-compatible with the TL071, so the same noninverting circuit can be used. There will be a difference in the offset correction circuit, so reading the datasheet is imperative.

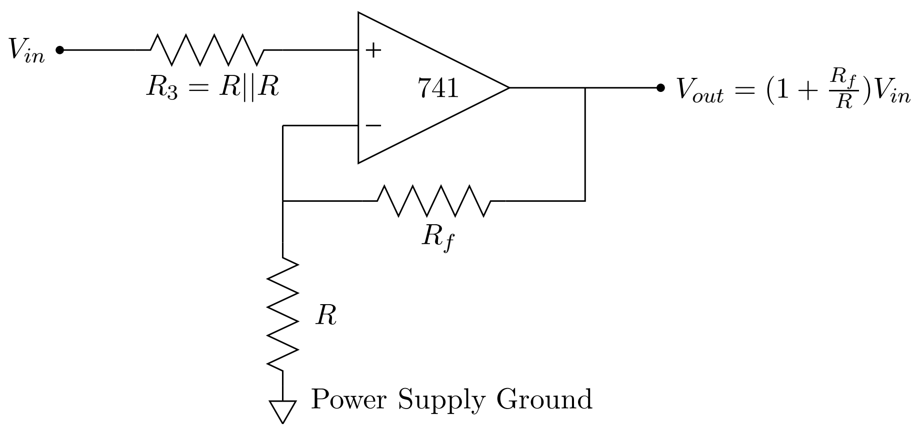
1. The 741 is far from ideal, and a more accurate expression for the output is

$$V_{out} = (1 + \frac{R_f}{R})V_{in} + (1 + \frac{R_f}{R})V_{off} + I_B R_f \ .$$

   I_B is the *input bias current*, and V_{off} is the *input offset potential*.

   (a) With $R_f = 1$ kΩ and $R = 100$ kΩ , measure V_{out} for $\nu = 0$ and $V_{in} = 0$. Be sure to measure the values of R_f and R as precisely as possible.
   (b) Measure V_{out} with $R_f = 1$ MΩ , $R = 10$ kΩ and $V_{in} = 0$.
   (c) Calculate V_{off} and I_B using these two measurements.

2. The input bias current error can be corrected by adding a resistor $R_3 = R_f||R$ to the input noninverting input of the op amp. To investigate the effect of this resistor, build an amplifier with $R_f = 100$ kΩ , $R = 1$ kΩ and $R_3 = R_f||R$.

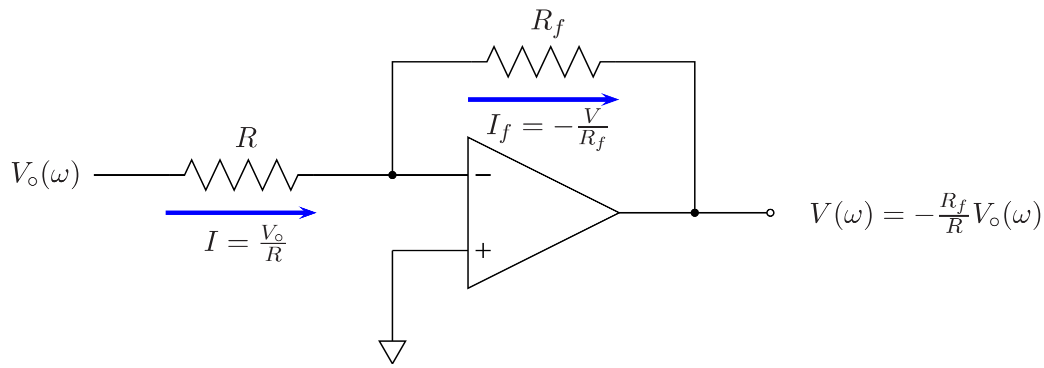


   (a) Measure $V_{out}(\nu = 0)$ with $V_{in}(\nu = 0)$.
   (b) Change R_f to 1 MΩ and R to 10 kΩ and measure $Vout(\nu = 0)$ again.
   (c) Use your measurements to calculate I_B. How effective is this simple modification in reducing the input bias current error?

3. Measure the input resistance.

Inverting Amplifier Using the LM741

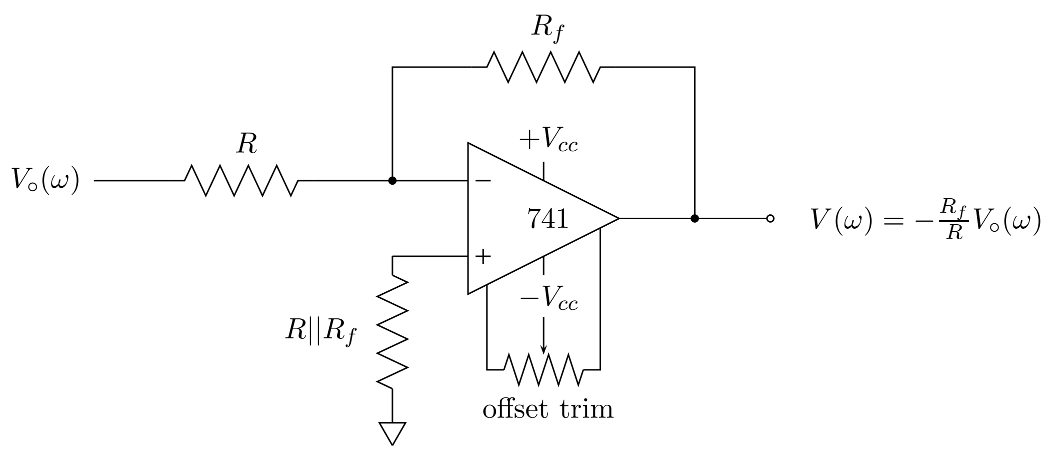
1. The gain of the ideal inverting configuration is easy to derive also. Remembering that $V_- = V_+$ for an ideal op amp,
$$I = \frac{V_\circ - V_-}{R} = \frac{V_\circ}{R} \text{ and } I_f = \frac{V_\circ - V_{out}}{R_f} = -\frac{V_\circ}{R_f} \ .$$
Since no current flows into an ideal op amp, $I = I_f$ and
$$V_{out} = -\frac{R_f}{R} V_\circ \ .$$



   (a) Verify for the case $R_f = 2$ kΩ and $R = 1$ kΩ that the DC gain is indeed -2, making measurements as accurately as possible.

   (b) Measure the input resistance of this circuit. Why should it be simply R? Explain any deviation from this value.

2. The frequency dependence of the gain should be the same as for the noninverting configuration. Verify this assumption using $R = 1$ kΩ and $R_f = 1$, 2, 10, 100 and 1000 kΩ so that the gains are expected to be 1, 2, 10, 100 and 1000. The offset should be trimmed by adjusting the trimpot (use the trimpot value specified in the datasheet for the opamp) with the input $V_\circ$ grounded.



   (a) For each gain, use scan_2.py to record $A(\omega)$ over the decadic range [1.0, 7.5] with at least 100 data points. Save the graphs of $|A|$ in dB versus $\log \nu$ and of $\arg(A)$. Also, save the data as csv files.

   (b) The decrease in gain as the frequency increase arises from the inherent frequency dependence of G. Plot $|A(\omega)|$ in dB for all five gains on the same graph using response_plot.py. Do the same for the phase measurements. Other than an overall phase shift of π, are there any differences between the inverting and noninverting graphs?