Operational Amplifiers: Part II

Spring 2015

Objectives

- Measurement of non-ideal op amp characteristics such as DC open-loop gain, slew rate, full- power bandwidth, and input offset voltage.

Parts and Equipment Required

Components and Materials Needed:

- 741 Operational amplifier (1).
- 100Ω resistor (1).
- 10kΩ resistor (2).
- 100kΩ resistor (1).
- Data sheet for the uA741 Operational amplifier.

Equipment to be Used:

- Banana cable sets (5).
- Oscilloscope probes (2).
- Potentiometer adjustment tool (1).
- BNC-to-BNC cable (1)
- BNC-to-alligator cable (1)

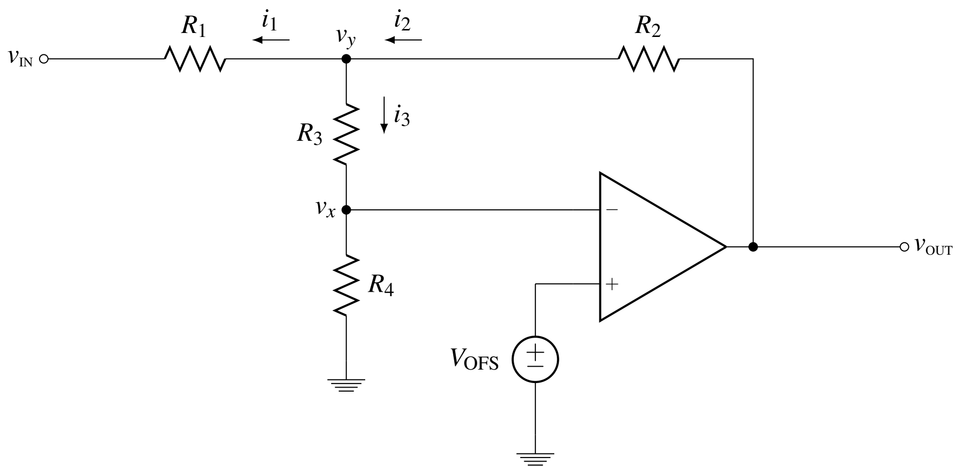

Figure 1: Circuit used for measuring the op amp's open-loop gain with resistor values $R_1 = 10\text{k}\Omega$, $R_2 = 10\text{k}\Omega$, $R_3 = 100\text{k}\Omega$, and $R_4 = 100\Omega$.

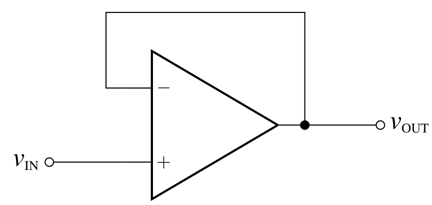

Figure 2: A unity-gain voltage follower configuration.

1 Pre-Lab Exercises

In this lab, you will measure several non-ideal characteristics of the 741 op amp. In practice, these characteristics are very challenging to measure. The exercises below introduce some practical measurement techniques that can be used in our laboratory.

Exercise 1. The circuit shown in Fig. 1 is configured to allow measuring the op amp's offset voltage and open-loop gain. In this exercise, you will analyze the circuit's response to the offset voltage when $v_{\text{IN}} = 0$. Assume that the op amp has infinite open-loop gain and zero input bias current. Then there should be a perfect virtual short so that $V_X \approx V_{\text{OFS}}$ (note that we are using the all-capital notation to indicate a DC offset). Examine the circuit and verify that the following equations are correct:

$$I_2 = I_1 + I_3$$
$$I_1 = \frac{V_Y}{R_1}$$
$$I_2 = \frac{V_{\text{OUT}} - V_Y}{R_2}$$
$$I_3 = \frac{V_{\text{OFS}}}{r_4}$$

From these equations, solve for V_{OUT} and show that it is equal to

$$V_{\text{OUT}} = V_{\text{OFS}} \left(\left(1 + \frac{R_3}{R_4}\right) \left(1 + \frac{R_2}{R_1}\right) + \frac{R_2}{R_4} \right). \tag{1}$$

Using the resistor values stated in Fig. 1, evaluate the expression in parenthesis and state the numerical value for the offset gain $G_o = V_{\text{OUT}}/V_{\text{OFS}}$.

Exercise 2. The circuit shown in Fig. 1 can also be used to estimate the op amp's open-loop gain A. To do this, we apply a sinusoidal input at v_{in} and measure the gain as the *ratio of amplitudes* $v_{\text{out}}/v_{\text{in}}$ (here we are using the all-lowercase notation to indicate AC signal amplitudes). To analyze the AC behavior, we assume finite open-loop gain but we still assume zero input bias current (this assumption is acceptable for the uA741 since I_{bias} is extremely small, around 10 nA).

By analyzing the currents in this circuit, it can be shown that

$$v_y \approx v_{\text{in}} \left(\frac{R_2 (R_3 + R_4)}{(R_1 + R_2)(R_3 + R_4) + R_1 R_2 + A R_1 R_4} \right) \tag{2}$$

$$\approx v_{\text{in}} \left(\frac{R_2 (R_3 + R_4)}{A R_1 R_4} \right), \tag{3}$$

where the approximation is made because the op amp's open-loop gain A is expected to be very large. (You are encouraged, but not required, to try and derive this result as an exercise). By using this approximation, the op amp's open-loop gain can be estimated:

$$A \approx \left(\frac{v_{\text{in}}}{v_y} \right) \left(\frac{R_2 (R_3 + R_4)}{R_1 R_4} \right) \tag{4}$$

To abbreviate this result, we define a constant

$$G_a = \left(\frac{R_2 (R_3 + R_4)}{R_1 R_4} \right),$$

so that the open-loop gain can be quickly computed as

$$A \approx \frac{v_{\text{in}}}{v_y} G_a.$$

Suppose that $v_{\text{in}} = 1\,\text{V}$ and v_y is measured to be $0.01\,\text{V}$. Based on Equation 4, calculate the op amp's open-loop gain A. Once you have obtained an estimate for A, substitute it into both (2) and (3), and compare the differences in these results. Based on your comparison, how accurate is the approximation used to obtain Equation 3?

Exercise 3. Suppose the op amp has a *slew rate* $\text{SR} = 0.5\,\text{V/µs}$ and the rail voltages are $\pm 15\,\text{V}$. Calculate the *Full Power Bandwidth* (FPBW):

$$\text{FPBW} = \frac{\text{SR}}{2\pi |V_R|}. \tag{5}$$

Now suppose the op amp is configured as a voltage follower as shown in Fig. 2, and the input is a sinusoid with zero offset:

$$v_{\text{IN}} = (2\,\text{V}) \sin(2\pi f t). \tag{6}$$

What is the maximum operating frequency f_{rmmax} for which slewing is avoided?

2 Physical Experiments

In your hardware session, you will attempt to measure the op amp's input offset voltage, open-loop gain and slew rate. When you complete each of your measurements, **write your result in a table on the white board** so that you can compare your measurements with those obtained by other students. This will give us a picture of how much variation occurs in these parameters.

Procedure 1. Connect your op amp in the configuration shown in Fig. 1. Use the DMM to precisely measure all resistor values in your circuit. Using the measured values, evaluate the expressions in Equation 1 and 4.

Procedure 2. Connect the input v_{IN} to ground. Measure V_{OUT} and infer the value of V_{OFS} based on Equation 1.

Procedure 3. Now measure the DC open-loop gain of the op amp. To do this, use the function generator to supply an input signal at v_{in} with a frequency below 1 Hz. To observe such low frequencies on the oscilloscope, you will need to adjust the time setting to about `SEC/DIV` and use the `RUN/STOP` button to capture a snapshot of the waveforms. Adjust the amplitude and offset of v_{in} to ensure that v_{out} is not saturated or distorted, and is large enough to obtain a precise amplitude measurement. Use the oscilloscope to measure the peak-to-peak amplitudes at v_{in} and v_y, then estimate A using Equation 4.

Procedure 4. Wire your op amp in a unity-gain voltage follower configuration. Using the function generator, provide an input signal v_{in} with a peak-to-peak amplitude of about 4 V and a frequency of 50 kHz. On the oscilloscope, observe the waveform at v_{out} and estimate the slew rate by using the cursors to obtain Δv_{out} and Δt in the linear segments. AC coupling is recommended for this measurement.

Procedure 5. Reduce the signal frequency to about 40 kHz and observe the waveform at v_{out}. Can you perceive any distortion in the output waveform? Switch the oscilloscope to the FFT display. Can you see evidence of distortion in the FFT display? Repeat these observations at 30 kHz.

3 Post-Lab

In your lab book, write a summary of your findings, and write a brief report describing your objectives, methods and major findings. Submit this report to the TA or Instructor along with your Lab Book.