Experiment #3—Basic Operational Amplifiers

Let's give transistors a rest this month and take a look at one of the most popular components in electronics—the op-amp. The most widely used circuits are two simple amplifiers and an adder circuit.

Background

Op-amp is an abbreviation for *operational amplifier*, a term coined 70 years ago. Complicated mathematical equations were then solved by analog computers. Amplifiers were used to add, multiply, integrate, or perform other "operations" on signals. Originally made with vacuum tubes, integrated circuit op amps—such as the 741—started a revolution in electronics.

Op-amps generally have a high voltage gain, a high input impedance and a low output impedance. These properties make designing op-amp circuits easy because they simplify the design equations, as we'll see.

Terms to Learn

Inverting (–) and non-inverting (+)—signals at the inverting input cause the op-amp output to respond in the opposite "direction" and, for signals at the non-inverting input, in the same direction.

Negative feedback—routing some of a circuit's output back to the input in such a way as to oppose the effect of the input signal.

The Operational Amplifier

Figure 1 shows the basic op-amp symbol, including the inverting and non-inverting inputs. *The 2003 ARRL Handbook* incorrectly shows the pin-outs for several popular op-amps on page 24.27—the inverting and non-inverting input connections are *reversed.* The industry standard for single op-amp ICs is that pin 2 is the inverting input (–) and pin 3 the non-inverting input (+).

The bypass or decoupling capacitors (C1, C2) shown in Figure 1 keep the power bus clean and help prevent feedback paths that might cause the op-amp circuit to oscillate. They bypass the power connections to ground, hence "decoupling" ac signals from the circuit.

An op-amp has a huge capacity to amplify—80 dB or more of voltage gain at dc! Most of the time that's far too much gain, but so-called "negative feedback" can control that gain, creating useful behavior. Consider that the op-amp's gain is acting solely on the voltage differential between its two inputs. The trick is to connect components from the output to the inputs so that when the output is doing what we want, the voltages at both input pins are balanced. This is a "correction" or "feedback" signal. It stabilizes the op-amp output by correcting its input. If the input changes—even a little bit—the high gain immediately causes the op-amp to react, changing its output and the feedback signal until its inputs are balanced once again. When feedback is used we refer to the circuit being "closed-loop."

The Non-Inverting Amplifier

Figure 2A shows a non-inverting amplifier. The input signal, V_I, is connected directly to the non-inverting (+) input, while resistors R_f and R form a feedback network. Remember that the op-amp has a very high input impedance, so we can treat the series combination of R and R_f as a voltage divider connected between the output pin and ground. The voltage at the inverting (–) input of the op-amp, V_i, must be:

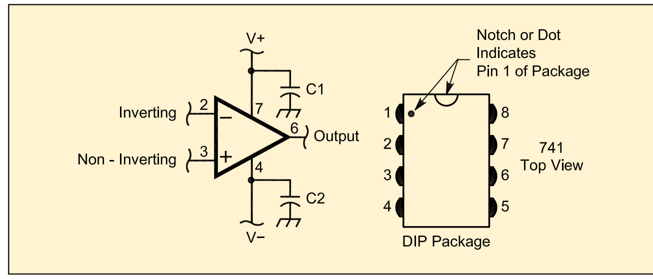

Figure 1—The operational-amplifier schematic symbol and typical package details.

$$V_i = V_{out} R / (R + R_f)$$

Since the op-amp's inputs must balance, $V_i = V_I$ and the circuit's gain, A_v must be:

$$A_v = V_{out} / V_I = (R + R_f) / R = 1 + R_f / R \quad [1]$$

The non-inverting amplifier's gain is always greater than 1 and is determined only by the ratio of R_f and R. There's no magic—the op-amp is just connected so that when its output is the correct amount larger than the input signal, both inputs balance.

Testing the Non-Inverting Amplifier

• Design the amplifier to have a gain of 2. That requires R_f = R. Use a value of 1 kΩ for this first circuit. Your power supply should be set to at least ±12 V (+12 V if you are using a single-polarity supply). Caution—do not apply signals above or below the power supply to the op-amp inputs or you may damage the IC.

• Build the circuit as shown in Figure 2A, including a 10 µF bypass capacitor to ground at each power supply pin. The 1 kΩ potentiometer will serve as an adjustable voltage source for V_I. Set the potentiometer so that the resistance from the wiper to ground is about 100 Ω. After checking all your connections, apply power and measure V_I and V_{out}. V_I should be approximately 1.2 V (one-tenth of V+) and V_{out} should be close to twice the value of V_I.

• The voltage at the inverting input, V_i should follow V_I very closely.

• Adjust the potentiometer output voltage up and down while measuring both V_I and V_{out}.

• You need a ±12 V power supply for this step. Replace the potentiometer with a function generator supplying a 1 V_{p-p}, 1 kHz sine wave. Use the oscilloscope to measure the output—it should be just like the input, but with twice the voltage.

• Experiment by changing the ratio of R and R_f to obtain different gains. (Keep resistor values above 100Ω.)

• Make a unity-gain voltage follower by removing R and replacing R_f with a direct connection as shown in Figure 2B. This circuit is frequently used to isolate a sensitive input or drive a heavy load.

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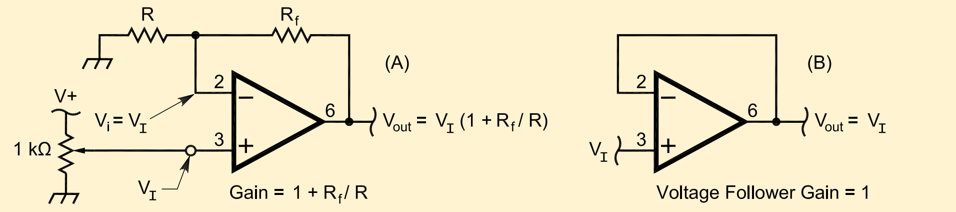

Figure 2—The non-inverting amplifier and a voltage follower.

The Inverting Amplifier

The high-impedance of the op-amp input can be used to create an inverting amplifier whose gain is also set by the ratio of two resistors. In Figure 3, R and R_f are again connected to the inverting input, but the input signal is connected to the free end of R and the non-inverting input is grounded. How does this work? Remember that the op-amp inputs are balanced, so the inverting input must also be at ground potential. It's not grounded, it's just at ground potential. This is called a "virtual ground."

With the inverting input at 0 V, the current through R must be $I_I = V_I / R$. Remember, too, that the op-amp input impedance is very high, so the input current must be balanced by the op-amp's output removing just as much current through Rf as flows through R. By Ohm's Law, the output voltage is then:

$$V_{out} = 0 - (I_I)\, R_f = -\,(V_I / R)\, R_f = -V_I\, R_f / R$$

and the gain must be:

$$A_v = V_{out} / V_I = -(V_I R_f / R)/V_I = -\, R_f / R \quad [2]$$

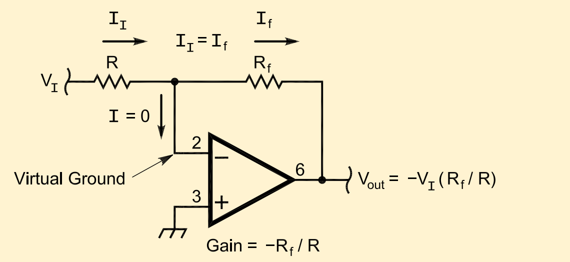

Figure 3—The inverting amplifier.

Testing the Inverting Amplifier

• Design the amplifier to have a gain of –4. Select a value for R of 1 kΩ. This requires R_f to be 4 kΩ. The closest standard value is 3.9 kΩ. You will need a ±12 V power supply to test this amplifier configuration.

• Build the amplifier as shown in Figure 3 and connect a 1 $V_{p\text{-}p}$, 1 kHz sine wave to the input. You should see a 3.9 $V_{p\text{-}p}$ sine wave at the output, but inverted with respect to the input. Look at the inverting input to verify that it is at ground potential.

• Use different resistor ratios to change the gain. (Keep resistor values above 100 Ω to limit how much power the op-amp must supply.) Input a dc voltage by using the 1 kΩ potentiometer as before and see if the circuit output is of the opposite polarity.

The Summing Amplifier

The circuit of Figure 4 shows how more than one signal can be combined and amplified by a summing amplifier. As for the inverting amplifier, the op-amp must balance all of the currents at the inverting input—even if current comes from more than one source!

The current from each input signal equals V_{in} / R, so the total current in R_f must be their sum:

$$I_f = V_{in1} / R_1 + V_{in2} / R_2$$

Using the same reasoning as before, the output voltage must be:

$$V_{out} = -\,(V_{in1} / R_1 + V_{in2} / R_2)R_f \quad [3]$$

The gain for either input signal is still the ratio, $-\, R_f / R$.

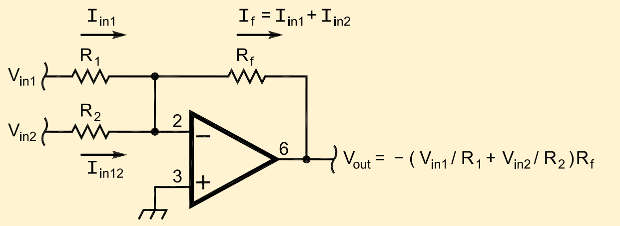

Figure 4—A summing amplifier.

Testing the Summing Amplifier

• Design the amplifier to have a gain of –1 for each input by setting all three resistors (R_1, R_2 and R_f) to 10 kΩ. You will need a ±12 V power supply to test this amplifier configuration.

• Build the circuit and input the 1 $V_{p\text{-}p}$, 1 kHz sine wave to input 1. Use the 1 kΩ potentiometer as before to supply input 2.

• Vary the potentiometer while watching the output on your oscilloscope. You will see the inverted sine wave from input 1 shifted up and down as the dc level at input 2 changes.

• Experiment by altering the ratio of either input resistor and R_f to observe the effect on the addition of signals. Replace R_1 or R_2 (or both) with a 10 kΩ potentiometer and vary the channel ratios independently. Congratulations—you've just built a 2-channel mixer!

Suggested Reading

The 2003 ARRL Handbook, pp 8.32-8.35; Horowitz and Hill, *The Art of Electronics*, chapter 4, sections 4.01-4.08; Ian Poole, G3YWX, "An Introduction to Op Amps," *QST*, Feb 1999, pp 55-56. The ARRL Web site for this series is **www.arrl.org/tis/info/html/hands-on-radio/**. Use it!

Shopping List

You'll need the following components:

• 741 op-amp—The part may be labeled as an LM741CN, MC1741CP1, µA741C, etc. The prefixes and suffixes identify the manufacturer, package style and temperature grade. RadioShack part number 276-007 will fill the bill.

• ¼ W resistors of the following values: 1 kΩ (2 ea), 3.9 kΩ, 10 kΩ (4 ea) and miscellaneous values between 1 kΩ and 10 kΩ.

• 1 kΩ and 10 kΩ potentiometer (single or multi-turn).

• 2—10 µF capacitors with a voltage rating of 25 V dc or more.

Next Month

Op-amps are frequently used as the engine driving an active filter. Sprinkle on a few capacitors and resistors and next month we'll see just how easy creating an audio filter can be.