HANDS-ON RADIO

Experiment #73 — Choosing an Op Amp

Lots of circuits use operational amplifiers (op amps), those handy little packages of gain drawn as simple triangles on schematics. Lots of different op amps. For example, searching for op amps in Jameco's online catalog (**www.jameco.com**) returned over 18,000 part numbers! How is a circuit designer supposed to pick the right one? Whittling the problem down to a manageable size depends on understanding what characteristics of the op amp are most important to your circuit.

Basic Properties

Let's review the basic properties of op amps. An introduction to op amps is provided in Hands-On Radio experiment #3.[1] The perfect op amp has infinite gain, infinite bandwidth, infinite input impedance, and zero output impedance. In demanding applications, however, the actual characteristics of real op amps, in which infinite turns into "high" and zero into "low", become important in how the circuit functions.

The specifications section of a typical op amp data sheet will list at least a couple of dozen parameters. Which of those parameters are important depends on what the circuit is supposed to do. This experiment will demonstrate some of the parameters that most effect common ham radio op amp circuits. Start by downloading the data sheet for a 741 op amp from **www.national.com/ds/LM/LM741.pdf**. On page two you'll find its *Table of Electrical Specifications* — use the columns for the 741A version. We're going to use this venerable part, in production for more than 40 years now, because its limitations are easy to observe. You can extend what you learn to its more modern descendants.

Gain-Bandwidth Product

Voltage gain, A_V, is the ratio of output voltage to input voltage. Any real-world amplifier, whether we're referring to an op amp or a big power amplifier, only delivers gain over a finite range of frequencies. The higher the frequency, the lower the gain. Above a few Hz, as frequency rises and gain falls, the op amp behaves as if the product of *open-loop gain,* A_{VD} ("Large Signal Voltage Gain") and bandwidth is a constant. This is the op amp's *gain-bandwidth product* or *GBW*. For example, if an op-amp has an A_{VD} of 10,000 at 100 Hz, then GBW = 10,000 × 100 = 1 MHz. Knowing GBW, you can predict what the op amp's open-loop gain will be at different frequencies. At 1 kHz, A_{VD} = GBW / f = 1 MHz / 1 kHz = 1000. GBW is specified as a minimum guaranteed value with a typical and maximum value often specified, as well. (The 741 data sheet shows GBW as "Bandwidth" in MHz.)

Figure 1 shows a general frequency response typical of all op amps. The circuit in the figure is a non-inverting amplifier with $A_V = 1 + R_f/R = 10 = 20$ dB. Build the circuit using a bipolar ±12 V power supply. You can use any version of the 741.

Input a 100 mV_{P-P} sine wave from a function generator and verify that the circuit gain is 10 at 100 Hz. (Use an oscilloscope, not a voltmeter, to avoid coloring the results with the voltmeter's frequency response.) Now increase the frequency of the input signal, keeping its amplitude constant, until the output voltage drops to 0.71 of the value at 100 Hz (–3 dB). This is the bandwidth of the amplifier, its decreasing gain acting as a low-pass filter. Calculate GBW. It should be higher than the minimum value for GBW in the data sheet. Find the unity-gain frequency by increasing the input signal frequency until gain drops to unity or 0 dB. Plot gain versus frequency at several values between 10 Hz and the unity-gain frequency using the frequency response spreadsheet developed for experiment #18. You should see a curve that looks a lot like the one in Figure 1.

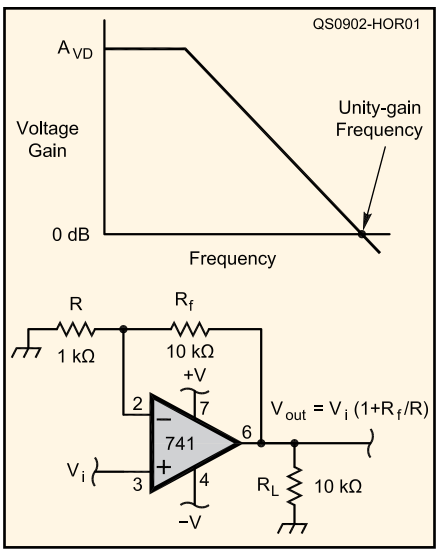


Figure 1 — An op amp's gain decreases linearly (in dB) with frequency, reaching a gain of 0 dB at the unity-gain frequency. Gain-Bandwidth Product (GBW) is the product of gain and bandwidth in this region. The non-inverting amplifier circuit shown is used to evaluate GBW and other op amp parameters.

GBW is important primarily in high-gain ac circuits, such as narrow audio filters in which insufficient gain results in poor filter performance. For example, in a Sallen-Key active filter, the op amp must have $A_{VD} \geq 90 \times Q^2$. For a sharp filter with a Q = 100, the A_{VD} of the op amp must be at least 900,000 or 119 dB.[2] Why would our 741A not be usable in such a circuit?

Slew Rate

Regardless of gain, the op amp's output circuitry can only supply a limited amount of current. This limits how fast the op amp's output voltage can change for a given load. This maximum rate of output voltage change is called *slew rate, SR*, and it is measured in units of voltage over time. In the data sheet, you'll find slew rate specified as a guaranteed minimum value of V/µs.

Input a 0.5 V_{P-P}, 1 kHz square wave to the amplifier circuit and verify that the output is a 5 V_{P-P} square wave. Trigger the 'scope on the output signal's rising edge and display both the input and output signals. Increase the sweep speed until you can clearly see the rising edge of the output signal. It will appear somewhat like the drawing in Figure 2.

Assuming your function generator's output has a higher slew rate than that of the 741, the output signal's rising edge will be more slanted than that of the input signal. Measure the op amp's slew rate by measuring the total voltage swing divided by the amount of time it takes the signal to make that swing, as shown

[1]Previous Hands-On Radio columns are available to ARRL members at **www.arrl.org/tis/info/HTML/Hands-On-Radio**.

[2]Maxim Semiconductor Application Note 1762, *A Beginner's Guide to Filter Topologies*, 2002; **www.maxim-ic.com/appnotes.cfm/an_pk/1762**.

H. Ward Silver, NØAX ♦ PO Box 927, Vashon, WA 98070 ♦ n0ax@arrl.org

Table 1
Popular Op Amp Specifications

Part Number	*Application*	*A_{VD} (V/mV)*	*GBW (MHz)*	*Slew Rate (V/µs)*	*Output Voltage Swing (2 kΩ load)*
741A	General purpose	50	0.437	0.3	Within 5 V of power supply
LM324A	Low power	25	1	Not specified	Within 1.5 V of power supply
LF356	Wide bandwidth	15	5	7.5	Within 5 V of power supply
TL071	Low noise	15	3	5	Within 5 V of power supply
TLC2772	Rail-to-rail	15	2.18	1.7	Within 750 mV of power supply

in the figure. This value should be greater than the minimum specified slew rate.

Now increase the input signal frequency. You'll see that the slew rate doesn't change because it's not a function of the op amp's gain. Lower the input voltage and you'll see that doesn't affect slew rate, either.

Increase the input signal frequency until you can see both the rising and falling edges of the input square wave. Keep increasing frequency until you reach a point at which the output waveform is unable to reach a maximum before the input signal's falling edge occurs. The op amp has turned a square wave into a triangle wave.

If you intend to use an op amp circuit for signals with fast rising and falling edges, such as for digital data or video, you'll need to consider slew rate. For example, in a 9600 baud system, each data bit is about 10 µs long. If the signal's amplitude is 5 V and the rise or fall time are to be less than 5% of the total bit period, the op amp must have a slew rate of no less than 5 V / 0.5 µs = 10 V/µs. The specs indicate that the 741A op amp is not suitable for this application.

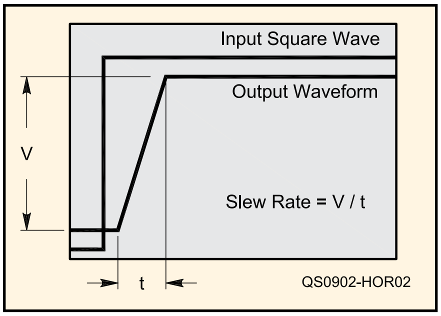


Figure 2 — An op amp's slew rate (SR) can be measured with a square wave input signal and triggering a dual trace 'scope on the input signal's rising edge. The slope of the output signal in V/µs is the op amp's slew rate.

Output Impedance

Another important parameter for many circuits is the op amp's ability to drive a load. Lower values of output impedance allow the op amp to drive lower impedance loads. Output impedance is often specified indirectly as a minimum value or graph of output voltage swing for a given range of load values. You'll find output impedance to be important when using op amps to drive headphones or as drivers of relays or power transistors.

Input a 0.25 V_{P-P}, 1 kHz sine wave and remove the circuit's load resistor, R_L. Measure the circuit's *open circuit output voltage, V_{OOC}*. Replace the load resistor with a 500 Ω potentiometer and lower its resistance until the output voltage is reduced by half. At this point, the resistance of the pot is equal to Z_0.

Voltage Limits

An op amp's ability to produce an output voltage close to the power supply voltages is an important parameter in circuits powered by batteries. The specifications for *output voltage swing* show how close the output voltage can be to the power supply voltages. Op amps with a voltage swing within 1 V or less of the power supply voltages are referred to as *rail-to-rail*. These op amps can operate with lower power supply voltages (weaker batteries, for example) than other op amps.

Return the amplifier circuit's load resistor to the original 10 kΩ and increase the input voltage until the op amp's output waveform flattens at both the positive and negative peaks. Measure the power supply voltage and the voltage of the flattened peaks. They should be well within ±5 V of the power supply voltages.

Popular Op Amps

Even knowing that only a few of these parameters are important, there are still too many different parts for the hobbyist to worry about. How do you actually find one that isn't an exotic or expensive part? Table 1 shows the properties of several popular op amps suitable for Amateur Radio electronics. These op amps are in stock with all major distributors and at least one will be satisfactory for most purposes. Keeping a few of these op amps on hand (including the versions with two or four op amps per package) will let you build a lot of useful circuits. The major semiconductor manufacturers feature part selection guides and online tools on their Web sites, as well.

Recommended Reading

There are many more subtle characteristics of op amps, one of the most widely used analog components. There are plenty of good online sources of information with one of the best being the Texas Instruments reference *Handbook of Operational Amplifier Applications*, downloadable at **focus.ti.com/lit/an/sboa092a/sboa092a.pdf**.

Next Month

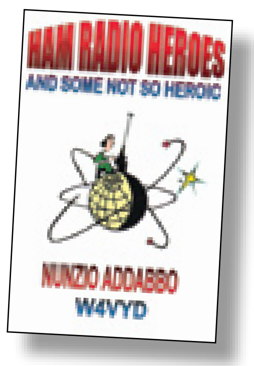
Let's tackle another basic subject next month — the resonant circuit and Q. These deceptively simple circuits virtually define "radio" so it's a good idea to understand them reasonably well.

NEW BOOKS

HAM RADIO HEROES

◊The title *Ham Radio Heroes* is a bit misleading, but not in a negative sense. When most people think of "heroes," they envision individuals who have selflessly sacrificed for worthy causes, or to save the lives of their fellow human beings. To be sure, *Ham Radio Heroes* includes a number of these harrowing and inspiring tales, but the author, Nunzio Addabbo, W4VYD, has broadened the heroic definition considerably. In this book, a ham hero could be a lifesaver, but he or she may also be someone who used Amateur Radio as a means to an unusual or innovative end.

Ham Radio Heroes is a rich 532 page compendium of material culled from a variety of sources, including *QST*. The author refers to the individual stories as "chapters" and there are 110 of them, which gives you some idea of the scope of this book. The stories are relatively short (some only a few pages) and include comments from Addabbo. In many instances Addabbo's observations are every bit as interesting as the tales themselves.



The stories run the gamut from hair raising, to comical, to touching. In *Ham Radio Heroes* you'll read of hams who've saved lives, pioneered new technologies or simply fell in love (literally) over the air. Thanks to the abbreviated format, this is the kind of book that you can dive into, sample a few stories and then return hours or days later. Addabbo has put a great deal of research into *Ham Radio Heroes*, and it shows.

Available from Third Millennium Publishing at **http://3mpub.com/addabbo/ham_radio_heroes.html**; $19.95 softcover, $7 electronic version. *Reviewed by Steve Ford, WB8IMY,* QST *Editor.*