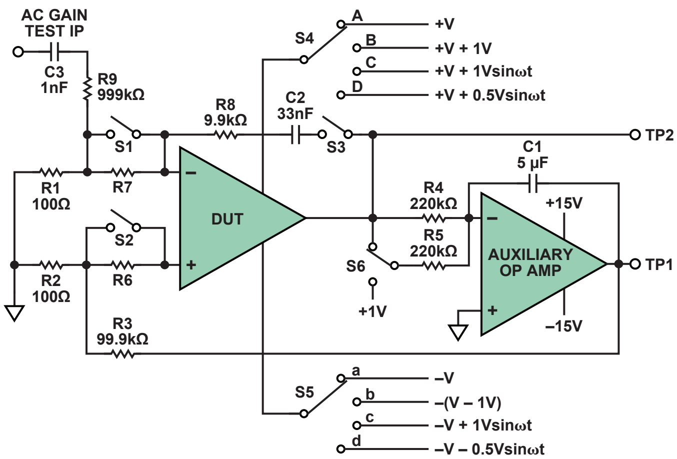
Simple Op Amp Measurements

By James M. Bryant

Op amps are very high gain amplifiers with differential inputs and single-ended outputs. They are often used in high precision analog circuits, so it is important to measure their performance accurately. But in open-loop measurements their high open-loop gain, which may be as great as 10^7 or more, makes it very hard to avoid errors from very small voltages at the amplifier input due to pickup, stray currents, or the Seebeck (thermocouple) effect.

The measurement process can be greatly simplified by using a servo loop to force a null at the amplifier input, thus allowing the amplifier under test to essentially measure its own errors. Figure 1 shows a versatile circuit that uses this principle, employing an auxiliary op amp as an integrator to establish a stable loop with very high dc open-loop gain. The switches facilitate performance of the various tests described in the simplified illustrations that follow.



SWITCH POSITIONS

FIGURE	S1	S2	S3	S4	S5	S6
2	1	1	0	A	a	0
3	0/1	0/1	0	A	a	0
4	1	1	0	A	a	0/1
5	1	1	0	A	a	0
6	1	1	0	A/B	a/b	0
7	1	1	0	A/B	a/b	0
8	1	1	1	C	c	0
9	1	1	1	D	d	0

Figure 1. Basic op amp measurement circuit.

The circuit of Figure 1 minimizes most of the measurement errors and permits accurate measurements of a large number of dc—and a few ac—parameters. The additional "auxiliary" op amp does not need better performance than the op amp being measured. It is helpful if it has dc open-loop gain of one million or more; if the offset of the device under test (DUT) is likely to exceed a few mV, the auxiliary op amp should be operated from ±15-V supplies (and if the DUT's input offset can exceed 10 mV, the 99.9-kΩ resistor, R3, will need to be reduced).

The supply voltages, +V and –V, of the DUT are of equal magnitude and opposite sign. The total supply voltage is, of course, 2 × V. Symmetrical supplies are used, even with "single supply" op amps, with this circuit, as the system ground reference is the midpoint of the supplies.

The auxiliary amplifier, as an integrator, is configured to be open-loop (full gain) at dc, but its input resistor and feedback capacitor limit its bandwidth to a few Hz. This means that the dc voltage at the output of the DUT is amplified by the full gain of the auxiliary amplifier and applied, via a 1000:1 attenuator, to the noninverting input of the DUT. Negative feedback forces the output of the DUT to ground potential. (In fact, the actual voltage is the offset voltage of the auxiliary amplifier—or, if we are to be really meticulous, this offset plus the voltage drop in the 100-kΩ resistor due to the auxiliary amplifier's bias current—but this is close enough to ground to be unimportant, particularly as the changes in this point's voltage during measurements are unlikely to exceed a few microvolts).

The voltage on the test point, TP1, is 1000 times the correction voltage (equal in magnitude to the error) being applied to the input of the DUT. This will be tens of mV or more and, so, quite easy to measure.

An ideal op amp has zero offset voltage (V_{OS}); that is, if both inputs are joined together and held at a voltage midway between the supplies, the output voltage should also be midway between the supplies. In real life, op amps have offsets ranging from a few microvolts to a few millivolts—so a voltage in this range must be applied to the input to bring the output to the midway potential.

Figure 2 shows the configuration for the most basic test—offset measurement. The DUT output voltage is at ground when the voltage on TP1 is 1000 times its offset.

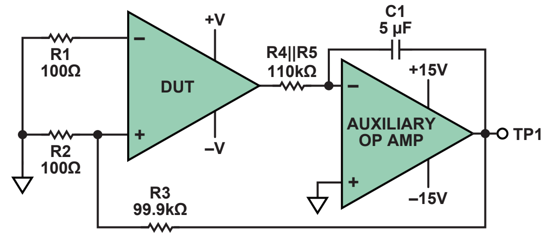


Figure 2. Offset measurement.

The ideal op amp has infinite input impedance and no current flows in its inputs. In reality, small "bias" currents flow in the inverting and noninverting inputs (I_{B-} and I_{B+}, respectively); they can cause significant offsets in high-impedance circuits. They can range, depending on the op amp type, from a few femtoamperes (1 fA = 10^{-15} A—one electron every few microseconds) to a few nanoamperes, or even—in some very fast op amps—one or two microamperes. Figure 3 shows how these currents can be measured.

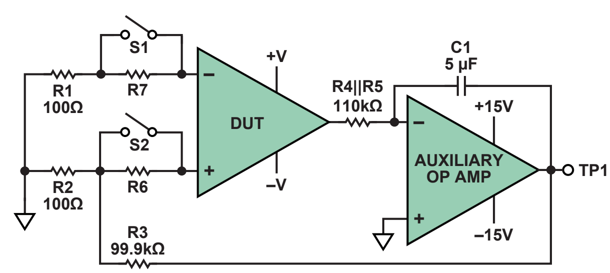


Figure 3. Offset and bias current measurement.

The circuit is the same as the offset circuit of Figure 2, with the addition of two resistors, R6 and R7, in series with the DUT inputs. These resistors can be short circuited by switches S1 and S2. With both switches closed, the circuit is the same as Figure 2. When S1 is open, the bias current from the inverting input flows in R_S, and the voltage difference adds to the offset. By measuring the change of voltage at TP1 (= 1000 $I_{B-} \times R_S$), we can calculate I_{B-}; similarly, by closing S1 and opening S2 we can measure I_{B+}. If the voltage is measured at TP1 with S1 and S2 both closed, and then both open, the "input offset current," I_{OS}, the difference between I_{B+} and I_{B-}, is measured by the change. The values of R6 and R7 used will depend on the currents to be measured.

For values of I_B of the order of 5 pA or less, it becomes quite difficult to use this circuit because of the large resistors involved; other techniques may be required, probably involving the rate at which I_B charges low-leakage capacitors (that replace R_S).

When S1 and S2 are closed, I_{OS} still flows in the 100-Ω resistors and introduces an error in V_{OS}, but unless Ios is large enough to produce an error of greater than 1% of the measured V_{OS}, it may usually be ignored in this calculation.

The open-loop dc gain of an op amp can be very high; gains greater than 10^7 are not unknown, but values between 250,000 and 2,000,000 are more usual. The dc gain is measured by forcing the output of the DUT to move by a known amount (1 V in Figure 4, but 10 V if the device is running on large enough supplies to allow this) by switching R5 between the DUT output and a 1-V reference with S6. If R5 is at +1 V, then the DUT output must move to –1 V if the input of the auxiliary amplifier is to remain unchanged near zero.

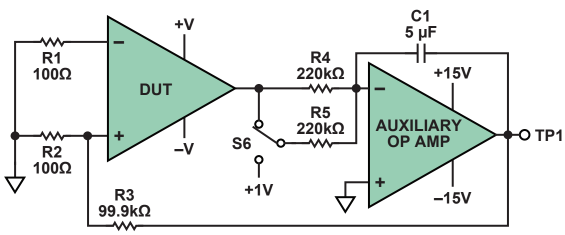


Figure 4. DC gain measurement.

The voltage change at TP1, attenuated by 1000:1, is the input to the DUT, which causes a 1-V change of output. It is simple to calculate the gain from this (= 1000 × 1 V/TP1).

To measure the open-loop ac gain, it is necessary to inject a small ac signal of the desired frequency at the DUT input and measure the resulting signal at its output (TP2 in Figure 5). While this is being done, the auxiliary amplifier continues to stabilize the mean dc level at the DUT output.

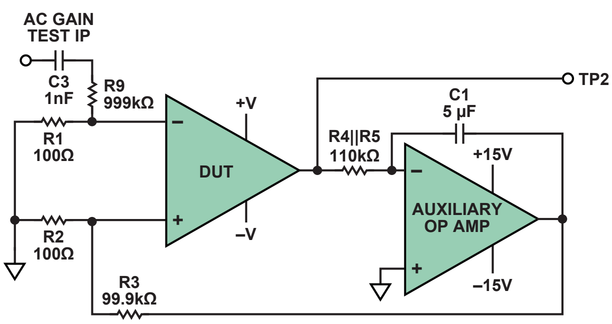


Figure 5. AC gain measurement.

In Figure 5, the ac signal is applied to the DUT input via a 10,000:1 attenuator. This large value is needed for low-frequency measurements, where open-loop gains may be near the dc value. (For example, at a frequency where the gain is 1,000,000, a 1-V rms signal would apply 100 μV at the amplifier input, which would saturate the amplifier as it seeks to deliver 100-V rms output). So ac measurements are normally made at frequencies from a few hundred Hz to the frequency at which the open-loop gain has dropped to unity—or very carefully with lower input amplitudes if low-frequency gain data is needed. The simple attenuator shown will only work at frequencies up to 100 kHz or so, even if great care is taken with stray capacitance; at higher frequencies a more complex circuit would be needed.

The *common-mode rejection ratio* (CMRR) of an op amp is the ratio of apparent change of offset resulting from a change of common-mode voltage to the applied change of common-mode voltage. It is often of the order of 80 dB to 120 dB at dc, but lower at higher frequencies.

The test circuit is ideally suited to measuring CMRR (Figure 6). The common-mode voltage is not applied to the DUT input terminals, where low-level effects would be likely to disrupt the measurement, but the *power-supply* voltages are altered (in the *same*—that is, common—direction, relative to the input), while the remainder of the circuit is left undisturbed.

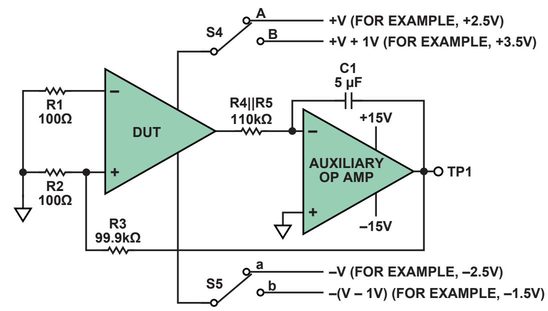


Figure 6. DC CMRR measurement.

In the circuit of Figure 6, the offset is measured at TP1 with supplies of ±V (in the example, +2.5 V and –2.5 V) and again with both supplies moved up by +1 V to +3.5 V and –1.5 V. The change of offset corresponds to a change of common mode of 1 V, so the dc CMRR is the ratio of the offset change and 1 V.

CMRR refers to change of offset for a change of common mode, the total power supply voltage being unchanged. The *power-supply rejection ratio* (PSRR), on the other hand, is the ratio of the change of offset to the change of total power supply voltage, with the common-mode voltage being unchanged at the midpoint of the supply (Figure 7).

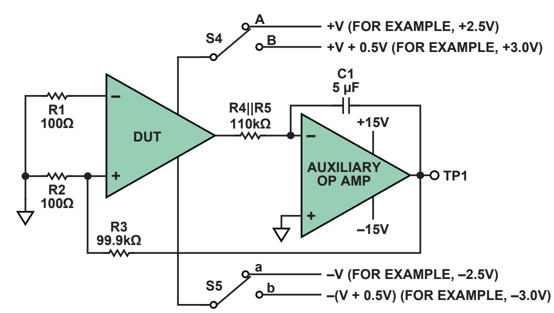


Figure 7. DC PSRR measurement.

The circuit used is exactly the same; the difference is that the *total* supply voltage is changed, while the common level is unchanged. Here the switch is from +2.5 V and –2.5 V to +3 V and –3 V, a change of total supply voltage from 5 V to 6 V. The common-mode voltage remains at the midpoint. The calculation is the same, too (1000 × TP1/1 V).

To measure ac CMRR and PSRR, the supply voltages are modulated with voltages, as shown in Figure 8 and Figure 9. The DUT continues to operate open-loop at dc, but ac negative feedback defines an exact gain (×100 in the diagrams).

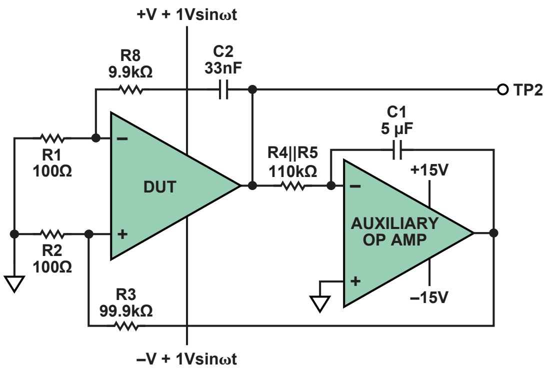


Figure 8. AC CMRR measurement.

To measure ac CMRR, the positive and negative supplies to the DUT are modulated with ac voltages with amplitude of 1-V peak. The modulation of both supplies is the same phase, so that the actual supply voltage is steady dc, but the common-mode voltage is a sine wave of 2 V p-p, which causes the DUT output to contain an ac voltage, which is measured at TP2.

If the ac voltage at TP2 has an amplitude of x volts peak ($2x$ volts peak-to-peak), then the CMRR, referred to the DUT input (that is, before the ×100 ac gain) is $x/100$ V, and the CMRR is the ratio of this to 1 V peak.

AC PSRR is measured with the ac on the positive and negative supplies 180° out of phase. This results in the amplitude of the supply voltage being modulated (again, in the example, with 1 V peak, 2 V p-p) while the common-mode voltage remains steady at dc. The calculation is very similar to the previous one.

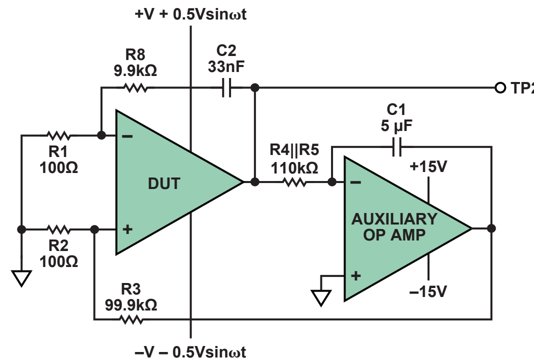


Figure 9. AC PSRR measurement.

Conclusion

There are, of course, many other op amp parameters which may need to be measured, and a number of other ways of measuring the ones we have discussed, but the most basic dc and ac parameters can, as we have seen, be measured reliably with a simple basic circuit that is easily constructed, easily understood, and remarkably free from problems.

Author

James Bryant [james@jbryant.eu] has been a European applications manager with Analog Devices since 1982. He holds a degree in physics and philosophy from the University of Leeds. He is also C.Eng., Eur. Eng., MIEE, and an FBIS. In addition to his passion for engineering, James is a radio ham and holds the call sign G4CLF.

Jan 2018: We changed C1=1uF to C1=5uF. It turned out that the Auxiliary Op Amp integrator still has sufficient gain to cause closed loop peaking of up to 10dB at or about 40Hz turning into a 40Hz Oscillation.

Simulation shows that it can prevented by decreasing the pole frequency by a factor of 5.