In part 1 of this series, we introduced you to three op-amp test circuits: A self-test circuit, a two-op-amp loop, and a three-op-amp loop. The circuits let you test $V_{os}$ (offset voltage), CMRR (common-mode rejection ratio), PSSR (power-supply rejection ratio), and $A_{ol}$ (amplifier open-loop gain). In part 2, we focused on measuring input bias current. Now, we present the circuit configurations for the self-test and two operational amplifier circuits. Both can exist in one circuit design through different relay configurations. The circuit lets you test using whatever method is best for a given op amp.

The basic combined circuit is shown in Figures 1 through 13. These figures show how to open and close relays to select the desired test. Figure 1 shows the overall test circuit. In Figures 2 through 13, the signal path is shown in red, making it easy to compare with the methods we discussed in the two previous articles.

Figure 1. This circuit integrates the self-test and two-op-amp loop for op-amp testing. Click on figure to enlarge.
Voltage offset measurement (two amplifier loop)

The loop output can go directly to an ADC (analog-to-digital converter) or DMM in the configuration of K22 shown. If, however, filtering is needed to reduce noise during measurements, K22 can be closed. The RC network of R5 and C7 can filter the noise. Choose the values for R5 and C7 for the given test environment.

The input offset voltage for each amplifier of the DUT (device under test) is measured using the following method. The output of the DUT amplifier is forced to 0.0 V by the null-amplifier. When this happens, the null amplifier immediately adjusts the loop output to zero at the DUT output. The input node voltage of the DUT now equals \( V_{OS} \), so the loop output will be 1000 \( V_{OS} \).

A load can be connected to the output if needed. The offset is then measured for the DUT. The voltage offset is given in the following equation, where the Gain is set by K10 to either 100 or 1000. Figure 2 shows the circuit paths for a \( V_{OS} \) test using the two-amplifier loop. The red lines show the circuit paths.

\[
V_{OS} = \frac{\text{Loop OUTPUT}}{\text{Gain}}
\]

Figure 2. This circuit configuration lets you measure offset voltage (VOS) test using the two-amplifier loop. 
Click on figure to enlarge.
Voltage offset measurement (self-test method)

The measurement method is the same for the self-test loop. Looking at Figure 3, observe the loop amplifier is configured as a unity gain buffer so it won’t oscillate or go into one of the power-supply rails. Use this configuration when making $V_{OS}$ measurements with the self-test loop method.

![Figure 3](image_url) These relay settings select a circuit for $V_{OS}$ measurements using the self-test method. Click on figure to enlarge.

Input bias current positive (loop control, capacitive method)

For both the loop control and self-test loops, use the capacitor method that we discussed in part 2 of this series. Figure 4 shows the test circuit for measuring positive input bias current, $I_{B+}$. Keep in mind that the input bias-current tests are most likely to cause oscillations. Always observe the output of the loop when developing the test.
Figure 4. A circuit configuration for an $I_{B+}$ measurements uses a two-amplifier loop and capacitors.
Click on figure to enlarge.

Figure 5 shows the configuration for measuring $I_{B+}$, the input bias current positive, using the self-test, capacitive method.

Figure 5. A circuit configuration for $I_{B+}$ measurements uses the self-test and capacitor method.
Click on figure to enlarge.
The circuit in **Figure 6** lets you measure input bias current negative, $I_{B-}$, using loop control with the capacitive method.

![Figure 6](image)

**Figure 6.** This circuit configuration for $I_{B-}$ measurements uses the two-amplifier loop and capacitor method.  
[Click on figure to enlarge.]

The circuit in **Figure 7** lets you measure input bias current negative, $I_{B-}$, input bias current negative using the self-test, capacitive method.

![Figure 7](image)

**Figure 7.** A circuit configuration for $I_{B-}$ measurements uses the self-test and capacitor method.  
[Click on figure to enlarge.]
Common-mode rejection ratio (loop control)

To measure CMRR, assume that you need to measure CMRR between two voltages, $V_{CM1}$ and $V_{CM2}$, for a part that runs on power supplies $VS$ in Figure 8. For the first measurement required at $V_{CM1}$, program the positive supply to $+VS - V_{CM1}$ and the negative supply to $-VS - V_{CM1}$. Program the loop control to $-V_{CM1}$. Then measure the offset voltage at the loop output. This measurement is CMRR_A.

For the second measurement required at $V_{CM2}$, program the positive supply to $+VS - V_{CM2}$ and the negative supply to $-VS - V_{CM2}$. Program the loop control to $-V_{CM2}$. Then measure the offset voltage at the loop output. This is CMRR_B.

Note that the total supply voltage remains the same, and that the output remains centered between the two supplies. CMRR is then calculated as follows:

$$CMRR = \frac{CMRR_A \cdot CMRR_B}{V_{CM1} - V_{CM2}}$$

Figure 8. This circuit configuration for CMRR measurements uses the two-amplifier loop. Click on figure to enlarge.

Common mode rejection ratio (self-test)

Use the same measurement and calculation method that was described in Figure 8 for the self-test loop CMRR test in Figure 9.
Power supply rejection ratio (loop control)

To test PSRR, the DUT is configured as if we are going to make a $V_{OS}$ measurement. However, for PSRR, the power supply will be varied and the change in the input offset voltage measured. PSRR also can be measured with an output load by closing relay KA101, KA102 or KA103 as in Figure 10.

The loop control should be set to 0 V. For the first measurement, set V+ Force and V- Force to the minimum supply voltage (VP1 and VN1) and measure the loop output. Then set the supplies to the maximum supply voltage (VP2 and VN2) and measure the loop output. Calculate PSRR for the DUT using this equation:

$$PSRR = 20 \times \log \left( \frac{VP2 - VN2}{V1 - V2} \right)$$

$$\frac{loopout 1 - loopout 2}{loopout 1}$$
Figure 10. This circuit configuration for PSRR test uses a two-amplifier loop. Click on figure to enlarge.

Power supply rejection ratio (self-test)

Use the same measurement and calculation method that was described in Figure 11 for the self-test loop PSRR test.

Figure 11. The circuit configuration for PSRR test uses the self-test method. Click on figure to enlarge.
Open loop gain (loop control)

For the open loop gain measurement, the output is moved over a defined DC range and the DC changes on the input are measured. The appropriate load can be set using relays KA101, KA102 or KA103. The loop control voltage is then set to the positive output value desired, such as $V_{OUT1}$, and the change on the input is measured, as in $V_{IN1}$. Then the loop control voltage is set to the negative output value desired, such as $V_{OUT2}$, and the change on the input is measured, such as $V_{IN2}$. The positive and negative output voltages on the DUT can also be used to test the output swing. The DC open loop gain is then calculated as follows:

$$Aol = \frac{V_{OUT1} - V_{OUT2}}{|V_{IN1} - V_{IN2}|} / Gain$$

Since the loop amplifier may need to drive the DUT output to the power supply rails, for example V+ Force and V- Force, it is important to have an amplifier whose common mode input range is capable of handling the swing requirement. This also means that the loop amplifier power supplies need to be much higher than those of the DUT.

![Figure 12. Circuit configuration for Aol test using a two-amplifier loop. Click on figure to enlarge.](image)

Open loop gain (self-test)

The same measurement and calculation method lets you perform the self-test loop Aol test using the circuit in Figure 13.
The circuits in the above figures use mechanical relays because they offer lower on resistance than solid-state relays. Unfortunately, mechanical relays are not as reliable as solid-state relays and they produce heat than can affect sensitive measurements. Furthermore, many relays have no thermal emf specification. You should avoid them because you don't know how much their thermal emfs will affect your measurements. Relays with good thermal characteristics are, however, usually large. Smaller relays can be obtained, but they require precious metals that increase their cost. We believe that it's well worth the cost to achieve measurement repeatability and capability.

In addition to selecting relays with good contacts, we suggest latching relays. When turned on, the coils in non-latching relays will dissipate heat. This heating can increase the thermal emf they generate. The relay power supply can also contribute to leakage problems. If the relay supply is connected to a relay's coil, then there is a potential leakage path from that pin to the relay caused by surface contamination and the isolation resistance of the PCB and the relay's case. Figure 14 shows how to connect--and not to connect--relays to a power supply. We recommend connecting relays to ground rather than to a power supply's high side.
Figure 14. Connect relay coils to ground (right), rather than to a power supply's high side (left). Click on figure to enlarge.

A practical test circuit has been presented for testing the basic DC specifications for an operational amplifier. An inherent challenge with the two-amplifier loop is stability, which we plan to cover in part 4 of this series. T&MW

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