4. Offset voltage and open-loop gain: they are cousins

Everyone knows what offset voltage is, right? In the simplest G = 1 circuit of **Figure 9a**, the output voltage is the offset voltage of the operational amplifier (op amp). The offset voltage is modeled as a direct current (DC) voltage in series with one input terminal. In unity gain, the offset is passed directly to the output with G = 1. In the high-gain circuit (**Figure 9b**), the output voltage is 1000 Vos. Right?

Well, nearly so, but not quite. Understanding the "not quite" can help you understand errors in your op amp circuits.

In the first case, the output voltage was very near midsupply (assuming dual supplies). This is the output voltage at which TI defines and tests offset voltage. But in the second case, the output may be several volts, assuming several millivolts of offset. That requires a small additional differential voltage at the input of the op amp to create the output swing (according to the open-loop gain of that particular amplifier).

Let us run some numbers. "If the DC open-loop gain is 100 dB, that amounts to 1/10^(100 dB/20) = 10 µV/V. So for every volt of output swing from midsupply, the input voltage must change by 10 µV. Think of it as an offset voltage that changes with the DC output voltage. With 9 V of output swing, that is a 90-µV change. Maybe that is insignificant in your circuits, maybe not.

The point is that thinking of finite open-loop gain as a changing offset voltage with a change in output voltage provides an intuitive way to size up the error. And the character of that error may matter, too. To test offset voltage and open-loop gain, use a fancy two-amp loop circuit. With it, you can control the output voltage and measure the offset voltage. If you sweep the output voltage through its full output range, the change in offset voltage often looks something like **Figure 10**.

Note that the greatest change in offset voltage tends to occur at the output extremes, near the positive and negative rail. The op amp is "straining" to produce its maximum output. The incremental open-loop gain is higher in the middle and falls where the output nears the rails. As you plan your circuits, expect that this will be the case. Offset voltage will increase more dramatically as you push the op amp to its swing limits.

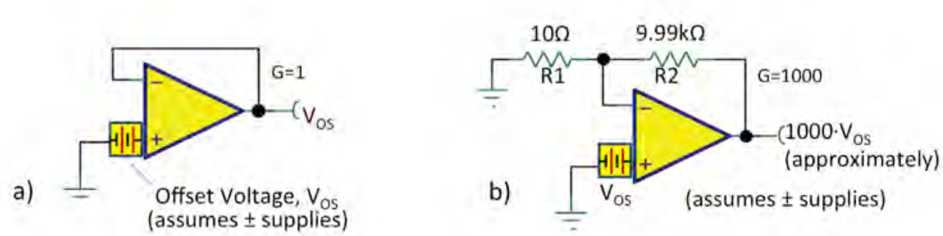

Figure 9: Output offset voltage where G = 1 V/V (a) and G = 1,000 V/V (b).

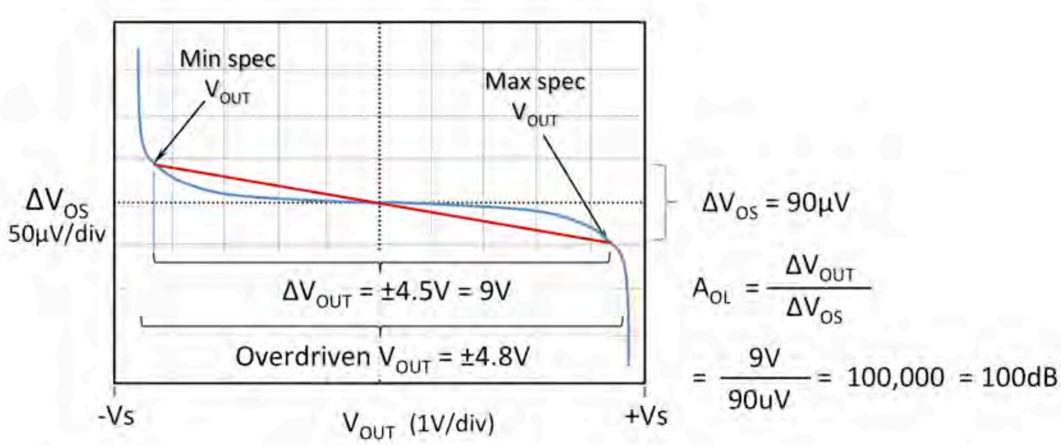

Figure 10: Offset-voltage change shown as a function of output voltage.

Not all op amp manufacturers specify A_{OL} the same way. TI tests its precision op amps for open-loop gain, which is averaged over a generous output-swing range for good linear operation (the red line in **Figure 10**). In the specifications table, it looks like **Table 2**.

When the amplifier is overdriven (creating a larger offset voltage), the output will swing closer to the rails. Sometimes output swing differs from the conditions in **Table 2**. The output swing in **Table 3**, for example, shows the output voltage with the input overdriven. My op amp development group at TI affectionately called this a "slam spec," meaning that the input is overdriven and slammed as far as it can go to the rail.

Both types of specs are useful, depending on the requirements of your application. The key is to understand and carefully interpret the specifications.

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Open-Loop Gain	Conditions	Min	Typ	Max	Unit
Open-loop gain A_{OL}	$(V-) + 0.5\ V < V_O < (V+) - 0.5\ V,\ R_L = 10\ k\Omega$	100	120	–	dB
	$(V-) + 0.5\ V < V_O < (V+) - 0.5\ V,\ R_L = 2\ K\Omega$	96	116	–	dB

Minimum A_{OL} is assured with an output swing 0.5 V from rails.

Two load conditions shown. Higher A_{OL} with 10 k load.

Table 2: Open-loop gain specifications shown with different loads and output voltage swings.

Output	Conditions	Min	Typ	Max	Unit
Voltage output swing from rails	$R_L = 10\ k\Omega$	0.2	0.15	–	V
	$R_L = 2\ k\Omega$	0.3	0.2	–	V

Table 3: Example of an output voltage swing with the input overdriven.

5. SPICEing offset voltage: how to check the sensitivity of circuits to offset voltage

It may not always be obvious how offset voltage will affect a circuit. "Direct current (DC) offsets are easy to simulate with a simulation program with integrated circuit emphasis (SPICE), but operational amplifier (op amp) macromodels only predict the effects of offset voltage of one unit. What about variation from device to device?

The improved Howland current-source circuit (**Figure 11**) provides a good example. Its feedback to both input terminals may leave you wondering how the input offset voltage (V_{OS}) of the op amp contributes to error. The OPA548 is a hefty power op amp with a 5-A maximum output and 60-V supply capability. It is frequently used in Howland circuits. But how will its 10-mV maximum offset voltage affect the output current of the circuit?

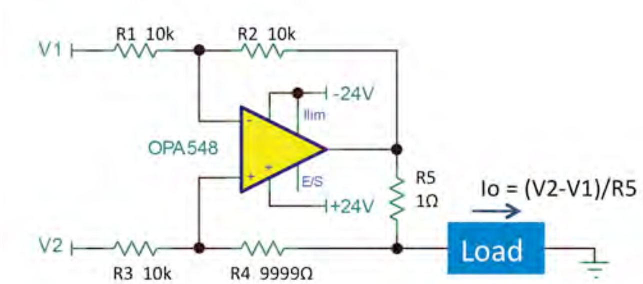

Figure 11: An example circuit—an improved Howland current source.

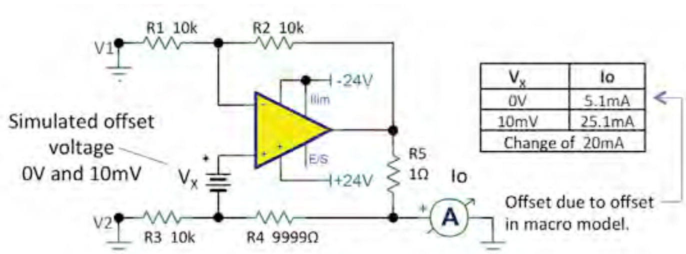

Figure 12: Output offset current due to op amp offset-voltage in an improved Howland current source.

Before simulating, this is an opportunity to exercise best practices with SPICE. What do you think the output current will be with 10 mV of input offset voltage?

Offset voltage is modeled as a voltage source in series with one of the input terminals. So in SPICE, you can merely insert a DC source in series with one of the inputs to induce the effect of varying offset voltage. With V1 and V2 inputs connected to ground, ideally you would expect zero output current. But the offset voltage will supply a small input: a DC simulation with $V_X = 0$ and $V_X = 10$ mV. Note the change in output current due to the change in V_X (**Figure 12**). There may be other sources of offset, so the delta in output current from these two V_X values reveals the contribution of offset voltage. Of course, the offset could also be negative.

The output offset with $V_X = 0$ in the simulation comes from the offset voltage (2.56 mV) included in the OPA548 macromodel – and would not be an additional contributor. Most of TI's macromodels have an offset voltage approximately equal to the typical offset voltage value. In some circuits, other sources of output offsets could come from input bias current and/or input offset current and would be additional contributors to total offset.

What output offset current did you predict? The improved Howland is essentially a difference amplifier (four resistors around an op amp) with an added resistor, R5. This unity-gain difference amplifier (equal resistors) causes the input difference voltage (V2-V1) to be impressed on R5; the resulting current flows to the load. The offset voltage, however, is applied directly to the noninverting input and is amplified by +2 – like a noninverting amplifier (G = 1 + R2/R1). Thus, a 10-mV offset voltage creates 20 mV across R5, producing a 20-mA output current offset. A -10-mV offset would create a -20-mA output current (current sinking from the load).

Maybe you see it intuitively, maybe you don't. Either way, SPICE can provide confirmation.

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6. Where are the trim pins? Some background on offset-voltage trim pins

In 2012, my colleague Soufiane Bendaoud published an article, "Pushing the Precision Envelope." In it, he discussed various technologies that TI uses to "trim" or adjust the offset voltage of its amplifiers to very low values. It got me thinking about offset voltage trim pins. Where do they go?

Newer operational amplifiers (op amps) lack the offset voltage trim pins once found on virtually all op amps. There are many factors at work in this change. Better, lower-offset amplifiers, autocalibrated system designs, pressure to reduce assembly and adjustment costs, tiny surface-mount packages – all combine to reduce the use of offset trim pins. Still, many of our best-selling op amps have trim pins, and knowledge and best practices of how to use (or not use) them are fading.

This much is easy: if you do not use the trim pins, leave them open circuit, with no connection. Do not connect them to ground.

Figure 13 shows a common type of internal trim circuitry. Trim pins connect to a tapped portion of the input-stage load circuitry. Adjusting the potentiometer skews the balance of the load plus or minus a few millivolts of input offset voltage. Datasheets generally recommend a value for the potential, but it is not critical. A much higher resistance potentiometer will cause the change in offset voltage to occur toward the extremes of rotation. Too low a value will reduce the adjustment range. Potentials in the range of +100 percent to 50 percent of the recommended value will likely function satisfactorily.

Notice that the trim circuitry in this example is referenced to the V+ supply. Some op amps have trim circuitry referenced to the V- supply terminal. Connecting the wiper of the potential to the wrong rail or to ground on a dual supply will surely cause problems. Some designers attempt tricky active circuitry to drive these pins. While this is possible, ground-referenced circuitry connected to the trim pins can create power-supply rejection problems.

It is best to use the trim pins only to null the offset of the first amplifier in a signal chain. Generally, that stage has some gain and its offset dominates that of the complete signal chain. If used to correct other large sources of offset in the chain, you could introduce an unwanted temperature drift.

Lacking trim pins, there are other ways to trim offsets in your system. You could inject or sum variable voltages from a potentiometer or other control signal into various points in your signal chain. **Figure 14** shows examples. The trimming voltages shown here should be derived from the power supplies. Regulated supplies are probably sufficient. Unregulated supplies, such as batteries, may not be sufficiently constant or stable.

The improved offset voltage of modern amplifiers often eliminates the need for trimming. Still, there are times when some type of offset adjustment is required. You can be ready with techniques, whether with trim pins or add-on circuitry.

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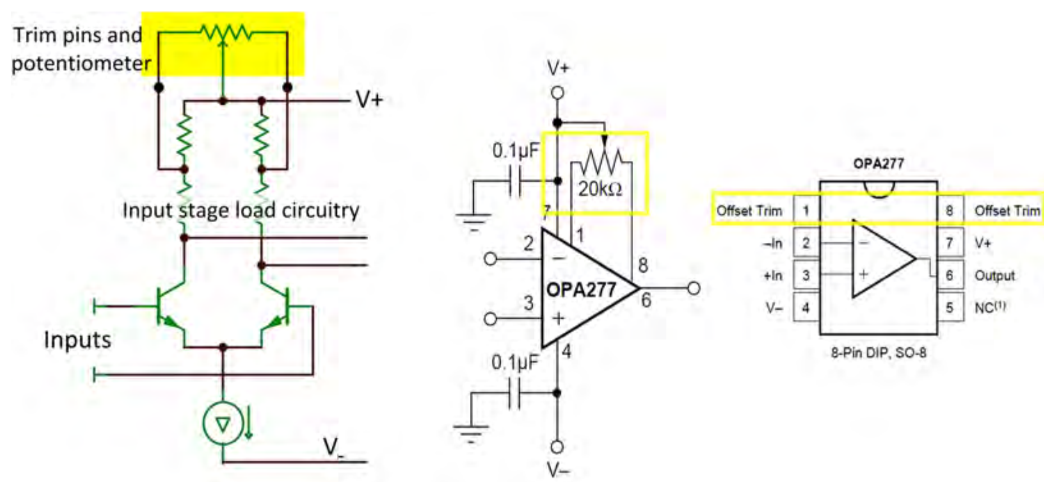

Figure 13: Typical internal circuitry where trim pins connect to the input-stage load circuitry.

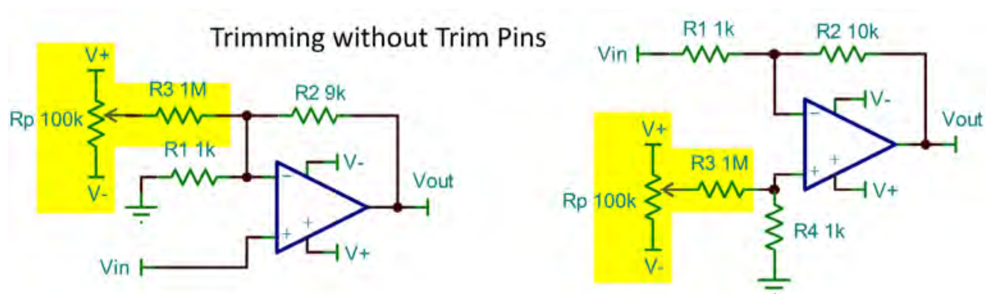

Figure 14: Examples of offset-correction voltages injected into various points of the signal chain.