Tim Green1 *Sep 25, 2015*

Other Parts Discussed in Post: LMV844

President Ronald Reagan frequently said “trust but verify” when discussing U.S. relations with the Soviet Union. Some say it comes from a Russian proverb, “doveryai no proveryai.”

Trust but verify is exactly what you should do when using SPICE operational amplifier (op amp) macromodels. For op amp stability analysis in the AC domain, you need to verify that both Aol (open loop gain) and Z_O (open-loop output impedance), two key things for op amp stability analysis, are correct for the op amp macromodel.

Figure 1 shows an AC model for an op amp with Aol and Z_O. Since most SPICE op amp macromodels end up being modeled correctly for Aol, I’ll focus on verifying Z_O, which is often not modeled correctly. Note that there is not industry consistency in terminology for open loop output impedance. Both Ro and Zo are used.

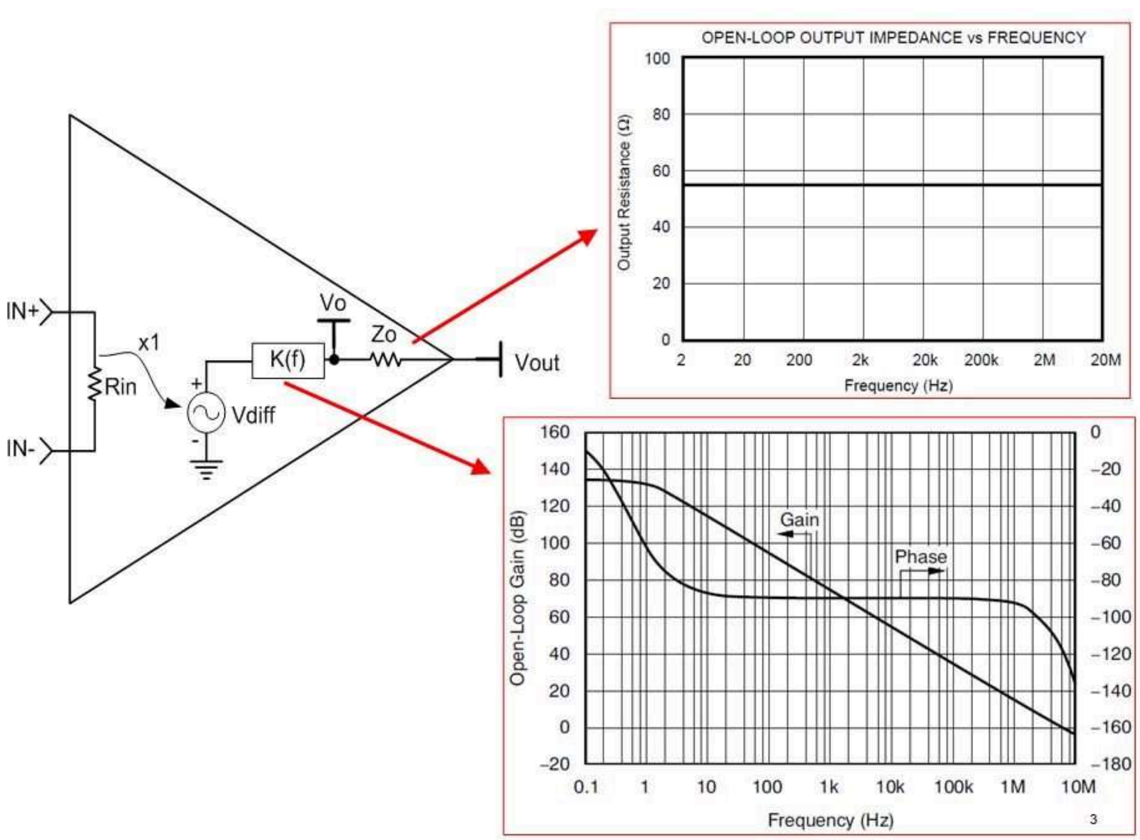

Figure 1: Op amp AC model

Figure 2 illustrates the important differences between Z_O and Z_{OUT}. Z_O is the open-loop output impedance of an op amp. Z_{OUT} is defined as the closed-loop output impedance of an op amp.

Z_O and Z_{OUT} are related. Z_{OUT} is Z_O reduced by loop gain. Figure 2 shows how the relationship between Zo and Zout is derived.

This simplified op amp model focuses solely on the basic DC characteristics of an op amp. A high input resistance (100mΩ to GΩ), R_{DIFF} develops an error voltage across it, V_E, due to the voltage differences between -IN and +IN. The error voltage, V_E, is amplified by the open-loop gain factor Aol and becomes V_O. In series with V_O to the output, V_{OUT}, is Z_O, the open-loop output impedance. Using standard circuit analysis, the resulting relationship between Z_O and Z_{OUT} is shown.

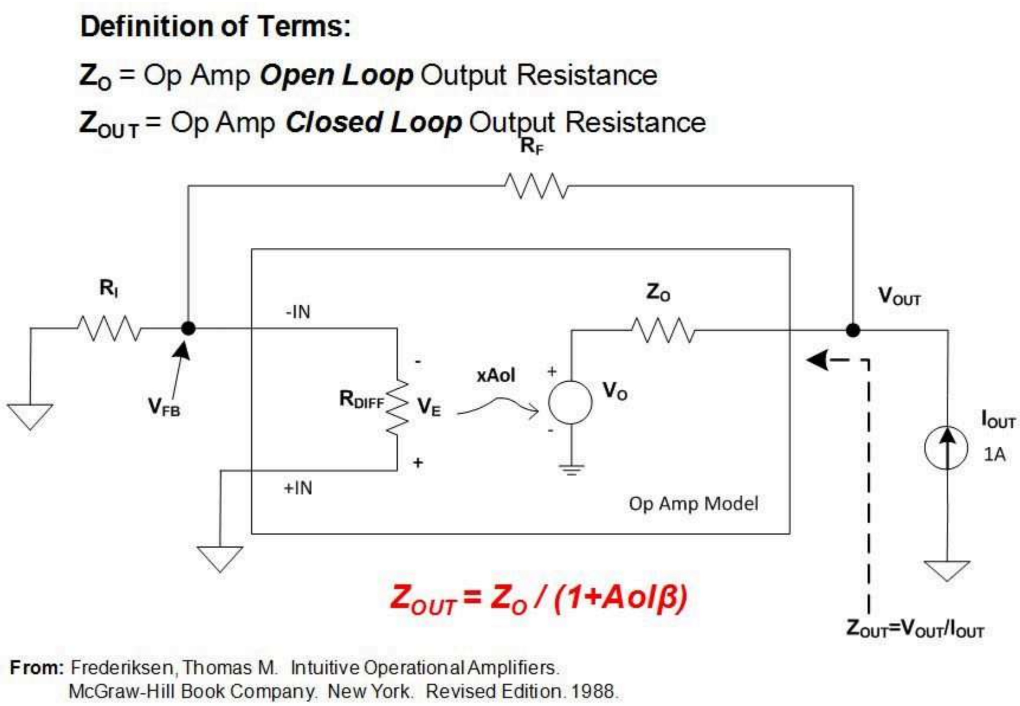

Figure 2: Z_O vs. Z_{OUT}

Figure 3 is the SPICE circuit for testing the Z_{OUT} of an op amp. An AC current source, I_{OUT}, with the DC portion set to zero is injected into the op amp output. You do not want any DC current injected into the op amp output, since Z_{OUT} becomes lower with current in the output. The worst-case stability problems almost always occur with the highest Z_{OUT}.

For this test, I set the op amp closed-loop gain to 1 to check against the Gain = 1x test data in the data sheet. SPICE performed a DC analysis before it ran the AC analysis. You must confirm that the amplifier is not in output saturation for the DC analysis or else the AC analysis will not be meaningful.

- DC analysis showed the output of the LMV844 to be 500µV for a gain = 1, which reflects an expected input offset voltage for this part. If Aol in the op amp macromodel matches the data sheet, then you know Z_O is correct based on Figure 2. V_{OUT} will become Z_{OUT} since the AC analysis will report all voltage probes relative to I_{OUT}, the excitation. The AC analysis will compute $V_{OUT} = I_{OUT} * Z_{OUT}$ and report this as a gain of $V_{OUT}/I_{OUT} = Z_{OUT}$.

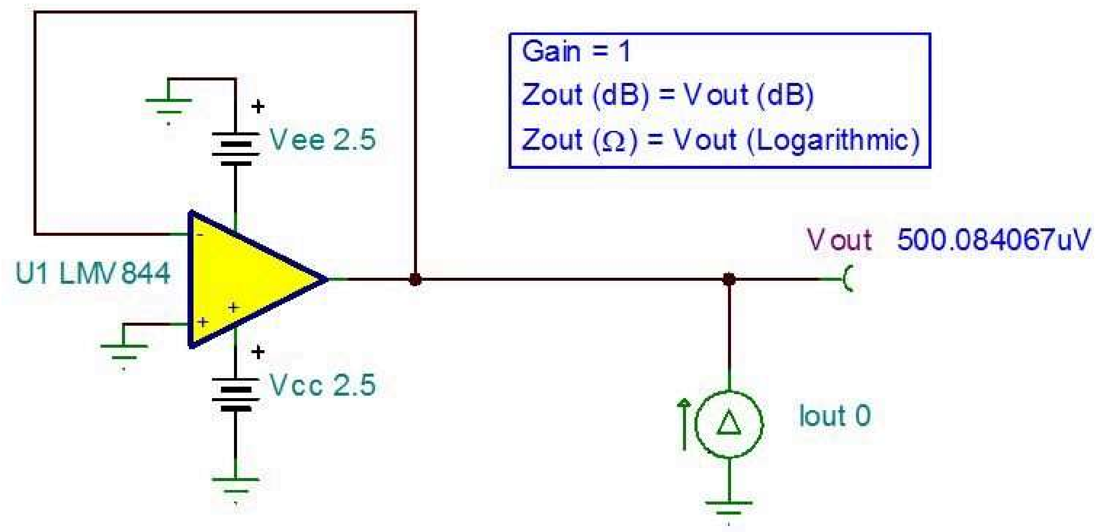

Figure 3: Z_{OUT} SPICE measure

My SPICE test result of the LMV844 macromodel indicates that Z_{OUT} does not match the data sheet for a gain = 1. Figure 4 shows two slopes (+20dB/dec and +40dB/dec) on the data sheet Z_{OUT} for a gain = 1 and only one slope (+20dB/dec) for the macromodel Z_{OUT}. If you see this in your application, you will need to contact the op amp manufacturer to get a SPICE op amp macromodel with the correct Z_{OUT} for stability analysis. Like Zo, there is not industry consistency in terminology for closed loop output impedance. Both Rout and Zout are used.

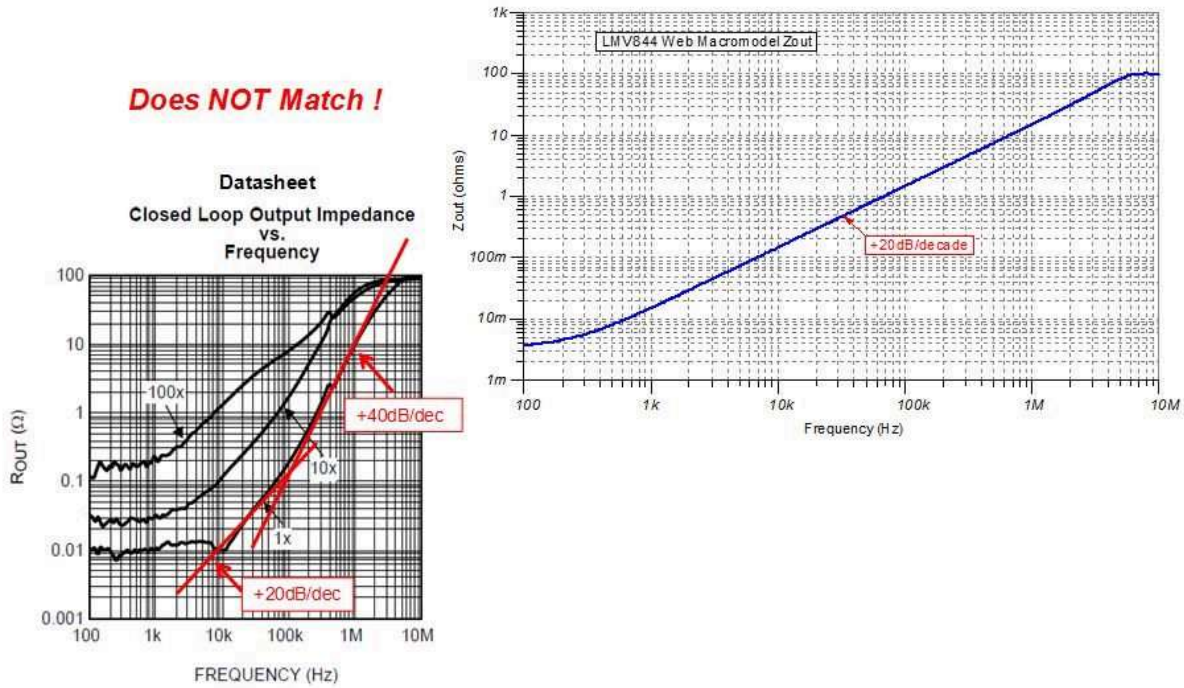

Figure 4: LMV844 macro vs. data sheet

I will use the test circuit in Figure 5 to measure Z_O, open-loop output impedance. SPICE will perform a DC analysis before it runs the AC analysis. You must confirm that the amplifier is not in output saturation for the DC analysis or else the AC analysis will not be meaningful. In the circuit of Figure 5, L1 will act as a short at DC but an open for any frequency of interest. Conversely, C1 will act as an open at DC and a short for any frequency of interest.

DC analysis shows the output of the OPA376 to be at -25.38µV for a gain = 1, which is an expected input offset voltage for this part. Just like the Zout test, use an AC current source, with DC component of it set to zero, to back-drive the output of the op amp. V_{OUT} will become Z_O since the AC analysis will report all voltage probes relative to I_{OUT}, the excitation. The AC analysis will compute $V_{OUT} = I_{OUT} * Z_O$ and report this as a gain of $V_{OUT} / I_{OUT} = Z_O$.

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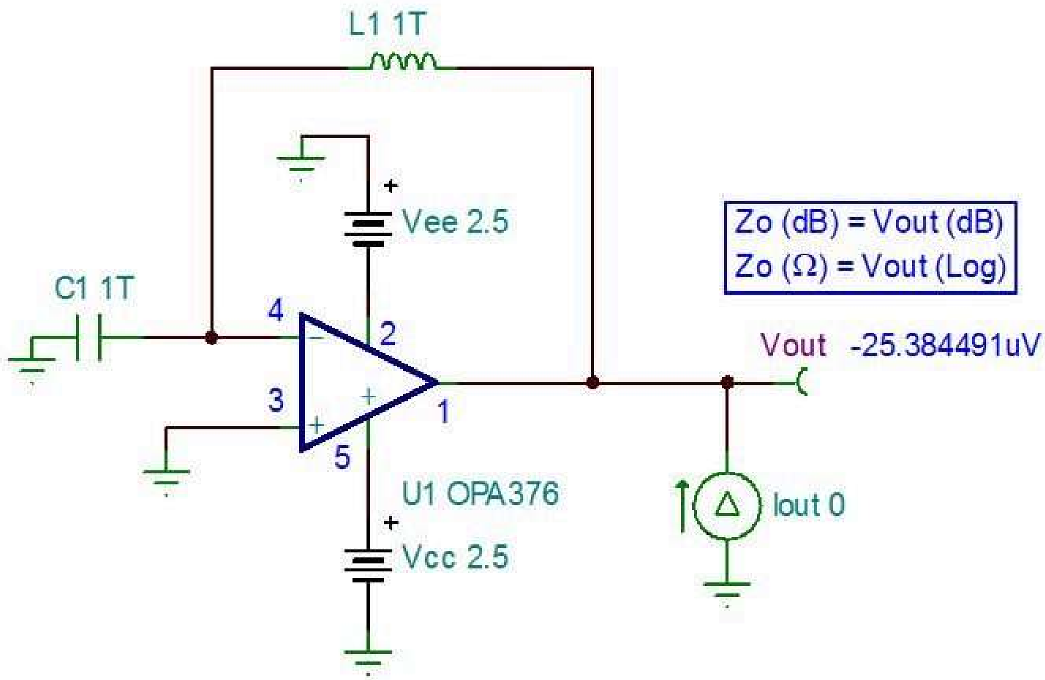

Figure 5: Z_O SPICE measure

Figure 6 confirms that the SPICE op amp macromodel does indeed match the data sheet. There are two curves for Z_O in the OPA376 data sheet. Since I am interested in the unloaded Z_O, output with no load current, I will compare the SPICE simulation against the 400μA load current Ro curvet in the data sheet. Remember that Z_O decreases with current in the output stage. You need to know the largest Z_O, which will almost always cause the worst stability issues.

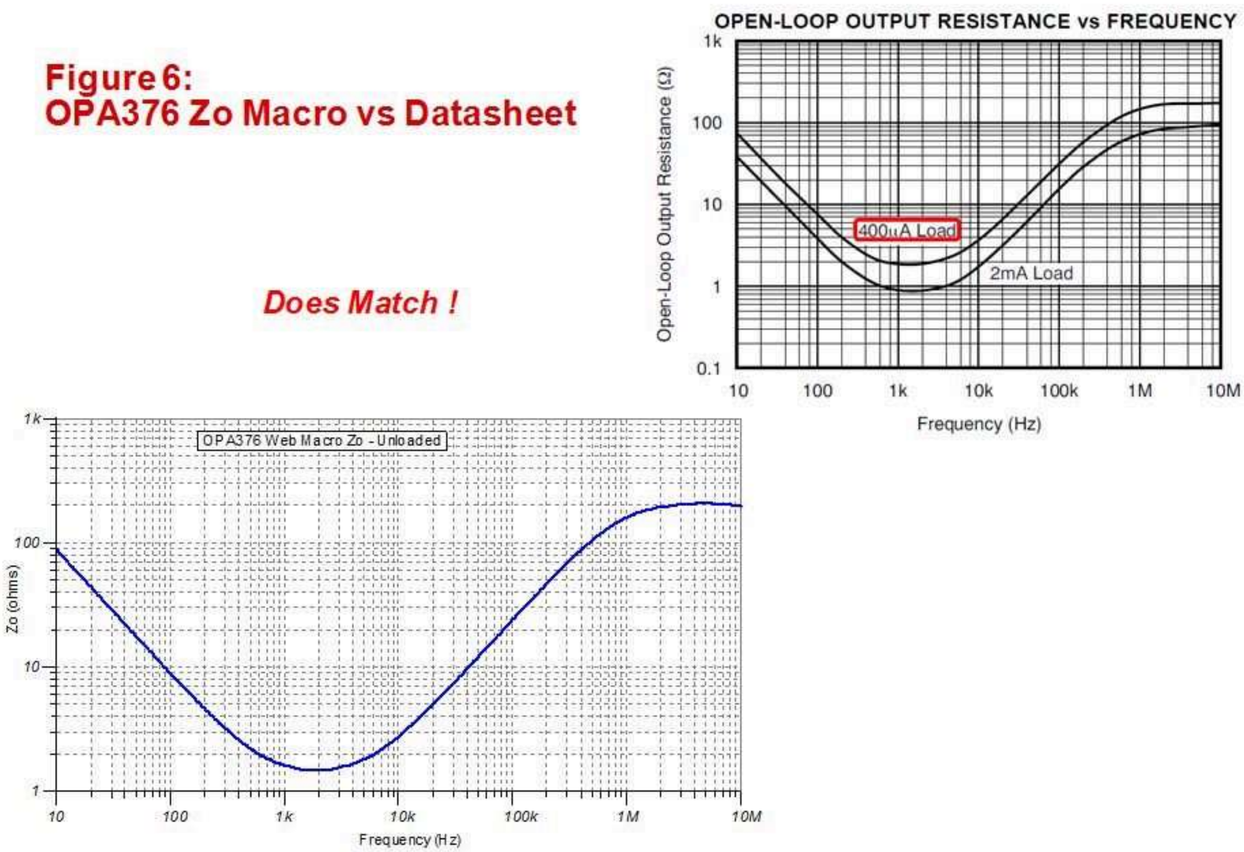

Figure 6: OPA376 macro vs. datasheet

You now have a quick and easy way to trust but verify SPICE op amp macromodels for the proper Z_O or Z_{OUT}. The correct Z_O or Z_{OUT} will allow you to simulate, predict and build stable op amp circuits for your end applications. For more detailed information on op amp stability, check out the resources below.

Additional resoucres

- Learn more about op amp stability on the TI E2E™ forum under Prescision Amplifiers, Precision Amplifier Wiki.
- Check out TI Precision Labs and learn all about precision op amps.
- Take a look at our free TI TINA-TI™ SPICE simulator.
- Learn about TI's entire portfolio of amplifier ICs and find more technical resources.