

Op-Amp Simulation – Part II

EE/CS 5720/6720

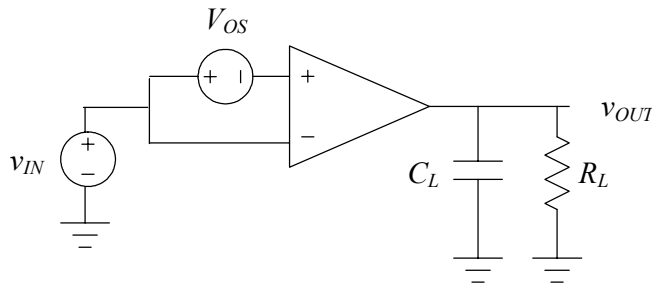
This assignment continues the simulation and characterization of a simple operational amplifier. Turn in a copy of this assignment with answers in the appropriate blanks, and Cadence printouts attached. **All problems to be turned in are marked in boldface.**

For the following problems, use the two-stage op amp you simulated in the previous assignment, using the same value of C_C and the same lead compensation transistor you arrived at. For all simulations below, load the amplifier with $R_L = 1\text{M}\Omega$ in parallel with $C_L = 30\text{pF}$.

1. Common-mode gain; CMRR

Common-mode gain measures how much the output changes in response to a change in the common-mode input level. Ideally, the common-mode gain of an op amp is zero; the amplifier should ignore the common-mode level and amplify only the differential-mode signal. Let's measure the common-mode gain of our op amp.

In order to measure the common-mode gain in the open-loop condition, we have to once again “balance” our high-gain op amp very carefully to keep $V_{OUT} \approx 0$, just like we did in the last assignment when we measured the transfer function. Remember, we do this by adding a dc voltage source V_{OS} in series with one of the inputs. This voltage source is set to the input offset voltage so that if no other signal is present, the output voltage will be approximately zero. Now, with this adjustment in place, we tie the two inputs together and apply an ac signal v_{IN} , as shown below.



Plot the common-mode gain (in dB) transfer function of the op amp over the frequency range 1Hz – 100MHz. Plot at least 50 points per decade of frequency for good resolution. **Turn in this plot.**

What is the common-mode gain at 10 Hz? _____

What is the common-mode gain at 100 kHz? _____

An important figure of merit in op amp design is the *common-mode rejection ratio*, or *CMRR*. CMRR is defined as the differential-mode gain divided by the common-mode gain. (Remember, if you express your gains in the logarithmic units of dB, subtraction is

equivalent to division.) For example, if a particular amplifier has a differential gain of 80 dB at 100 Hz and a common-mode gain of 10 dB at the same frequency, then the amplifier's CMRR at 100 Hz is 70 dB. Ideally, an amplifier should have infinite CMRR. Practically, most designers try to get $\text{CMRR} > 60$ dB, though some applications may require much higher values.

Disconnect the negative input of the op amp from v_{IN} and connect it back to ground. Measure the differential-mode gain (in dB) transfer function of the op amp over the frequency range 1 Hz – 100 MHz. (This is the same measurement you did in the last assignment.) Plot at least 50 points per decade of frequency for good resolution. **Turn in this plot.**

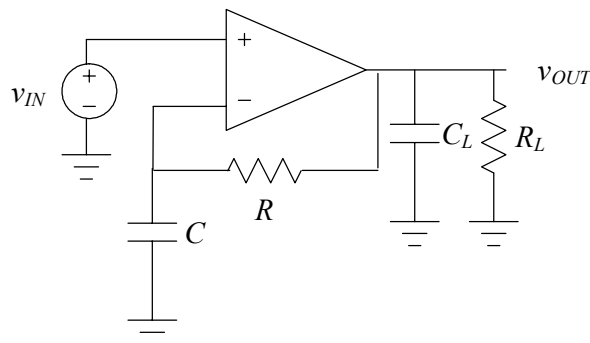
What is the CMRR at 10 Hz (in dB)? _____

What is the CMRR at 100 kHz (in dB)? _____

2. Alternate method for measuring open-loop transfer function

The previous method we used for measuring transfer functions can become slow and tedious if we often make changes to our op amp that affect its dc operating point, because this requires re-measuring the small dc offset voltage, which will have changed. Luckily, changing the value of C_C has no effect on the dc bias point, so we haven't had to repeat the dc offset measurements yet. However, if we make any changes to transistor sizes or bias currents, we would have to repeat the dc sweep to find V_{OS} before measuring the transfer function again.

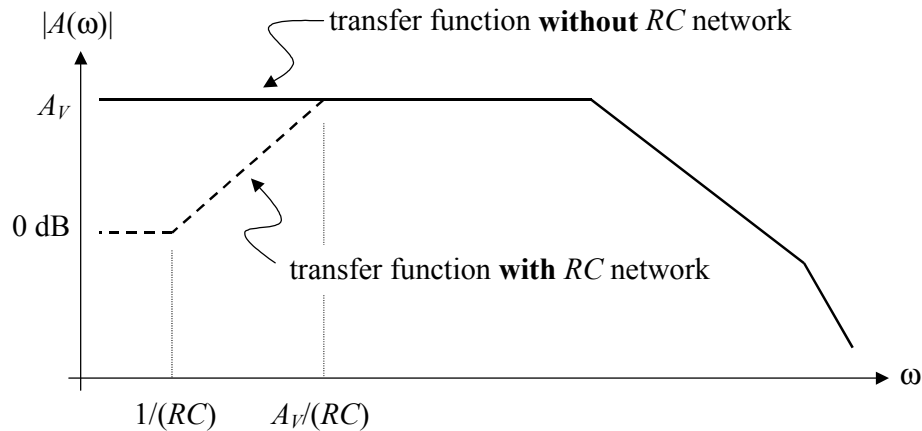
It turns out there is an easier way to measure open-loop transfer functions that does not require us to measure V_{OS} and then “balance” the open-loop op amp. The measurement configuration is shown below.



First, we make $R \gg R_L$ so that this resistor has no significant loading effect on the op amp. Let's set $R = 100\text{M}\Omega$ in our simulation.

Here's how this configuration works: At dc (and very low frequencies), C is basically an open circuit. Since no current flows into the op amp's inputs (or through C), the current through R is zero. That means the voltage drop across R is also zero, so the voltage at the negative input of the op amp is equal to the output voltage. Thus, at very low frequencies, the op amp is configured at a unity-gain buffer, so $v_{OUT} \equiv v_{IN}$. If we make the dc value of $v_{IN} = 0$, then our output is where we want it to be.

At high frequencies, the reactance of C ($1/j\omega C$) becomes very small relative to the resistance of R (i.e., the capacitor begins to act like a short circuit), and so the negative input is effectively connected to ground, just like in our previous open-loop measurements. The key is to set C sufficiently high so that the effects caused by the RC network occur at frequencies far below what you actually want to measure. The effect of the RC network on the amplifier gain curve is shown below. At very low frequencies, the amplifier starts to act like a unity-gain buffer.



We should set C such that the frequency $A_V/(2\pi RC) \ll f_{min}$, where A_V is the low-frequency gain of the op amp, and f_{min} is the minimum frequency of interest in our transfer functions.

Set $C = 0.1$ F (that's right: one-tenth of a Farad!). Run an ac simulation from 1nHz (that's right: one nanoHertz!) to 100MHz, showing gain (in dB) and phase. **Turn in this plot. On the plot, label the two frequencies shown on the above figure. Do the calculated frequencies match the appropriate points on the curve?** _____

(Remember to convert radians/second to Hz, if necessary.)

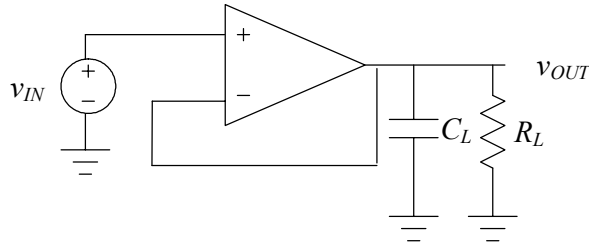
Now run an ac simulation just from 1Hz to 100MHz, showing gain (in dB) and phase. **Turn in this plot.**

How does this gain plot compare with the differential-mode gain curve measured in the previous problem using the traditional method? _____

3. Slew rate

In the previous assignment, we used ac analysis to determine the small-signal bandwidth of the op amp. The speed of amplifiers is often limited by large-signal effects such as slew rate – the maximum speed at which an op amp can charge and discharge its load.

To measure slew rate, configure the op amp as a unity-gain buffer as shown below.



Run a transient simulation where v_{IN} is a 5 kHz square wave going from -1V to +1V. (This qualifies as a large signal.) Look at the output waveform. Does it look like a nice square wave, or do you see significant slewing (a slope less than infinity) on the -1V to +1V transitions? Increase the frequency of the square wave until you can see these sloped regions clearly. (The output should still reach -1V and +1V during each cycle. If it does not, your square wave is too fast.) Make sure your maximum time step is at least 200 times less than your simulation time so you get a high-resolution simulation. **Turn in this plot.**

Now select two points on the rising slope and from these calculate the positive slew rate using units of V/ μ s.

The positive slew rate is _____.

Now select two points on the falling slope and from these calculate the negative slew rate using units of V/ μ s.

The negative slew rate is _____.

Now repeat the above measurements after removing R_L and C_L . **Turn in this slew-rate plot.**

The positive slew rate with no load is _____.

The negative slew rate with no load is _____.

What is the slew rate predicted by Equation 5.15 in Johns & Martin? _____.

How does this compare with the simulation results? _____

4. Output resistance

Now we will estimate the closed-loop output resistance of our op amp in unity gain configuration. Keep the same circuit setup as above, but remove R_L from the circuit and make the input waveform a small 1kHz sine wave with a dc level of zero volts and an amplitude of 1mV. (Use a transient source, not the “AC” source. We will be running transient simulations.) Run a simulation of encompassing 2-3 cycles of the waveform and verify that the output amplitude matches the input amplitude. **Turn in this plot.** If you wish, you can insert a dc V_{OS} source at the input to cancel out any small offset voltage.

Now add $R_L = 1\text{M}\Omega$ back to the circuit. Make sure R_L is connected to ground, not V_{SS} . Run the simulation again.

What is the output voltage amplitude? _____

Now decrease the value of R_L until the output voltage amplitude drops to approximately 0.909mV instead of 1.0mV.

What value of R_L causes an output amplitude of 0.909mV? _____

Based on a simple voltage divider relationship, what must the output resistance of the unity-gain buffer be? _____

Using the low-frequency open-loop gain amplifier gain measured in previous problems, what would you predict the open-loop output resistance of the op amp to be? _____

What would you predict the output resistance of the amplifier to be if it were configured (with an appropriate feedback network) to have a closed-loop gain of 1000? _____