Notes on Pre-Lab 4: Differential Amplifiers

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About this assignment

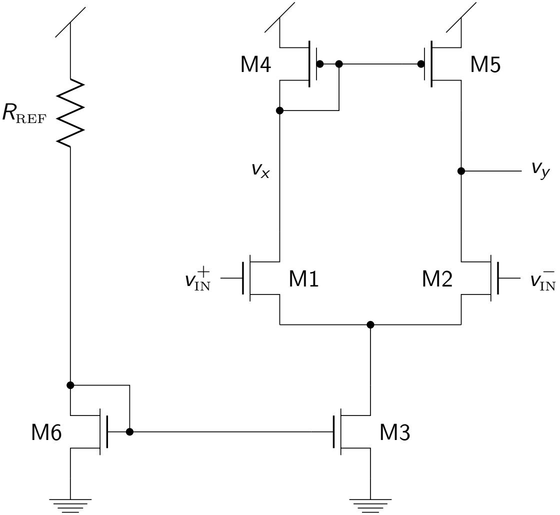
This assignment asks you to analyze and simulate two differential amplifier configurations.

You will explore the following topics:

- Gain and output resistance.
- Input Common Mode Range (ICMR) and Output Swing.
- The Gain-Bandwidth tradeoff.
- Buffering for feedback configurations.
- Resistive loading and its effect on open- and closed-loop gain.
- Distortion reduction in closed-loop feedback configurations.

The Operational Transconductance Amplifier

Your first ciruit is the OTA:



OTA Gain and Output Resistance

The circuit has three device groups:

1. The differential pair (DP) devices M1 and M2.
2. The PMOS current mirror devices M4 and M5.
3. The NMOS bias mirror devices M3 and M6.

The output resistance is the equivalent resistance seen at the output terminal,

$$R_{\mathrm{OUT}} = r_{o2} \parallel r_{o5},$$

and the open-circuit gain is given by

$$A_{vo} = g_{m2} R_{\mathrm{OUT}}.$$

Solving the DC operating point

In order to compute g_m and r_o for the respective devices, you need to know the DC bias current for each device. For M3 and M6, the bias current is equal to I_{REF}, found by equating two expressions for the v_{GS} of M6:

$$V_{\mathrm{DD}} - i_{\mathrm{REF}} R_{\mathrm{REF}} = V_{\mathrm{ThN}} + \sqrt{\frac{2i_{\mathrm{REF}}}{K_n}}.$$

The remaining devices, M1, M2, M4 and M5, all have DC bias current equal to $i_{\mathrm{REF}}/2$.

Calculating the ICMR

The input common-mode range is given by the minimum and maximum values of v_{ICM}. Analyze this by supposing $v_{\mathrm{in}}^{+} = v_{\mathrm{in}}^{-} = v_{\mathrm{ICM}}$.

The potential appearing at the drain of M3 is $v_{DS3} = v_{\mathrm{ICM}} - v_{GS1}$. In order to keep M3 in saturation, we need $V_{DS3} > V_{ov3}$, therefore

$$v_{\mathrm{ICM}} > V_{ov3} + V_{GS1} = \sqrt{\frac{2i_{\mathrm{REF}}}{Kn}} + \sqrt{\frac{i_{\mathrm{REF}}}{Kn}} + V_{\mathrm{ThN}}.$$

In theory, with this circuit v_{ICM} can go all the way up to V_{DD} and the devices should function properly in saturation.

The Output Swing

Similar to the ICMR analysis, the output swing is limited by the v_{DS} values required to keep all devices in saturation. The minimum value is given by the sum of v_{DS}'s for M3 and M2:

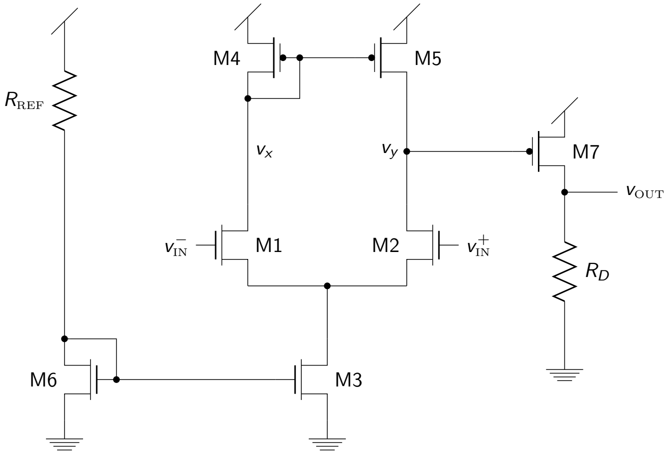
$$v_y > V_{ov3} + V_{ov2} = \sqrt{\frac{2i_{\mathrm{REF}}}{Kn}} + \sqrt{\frac{i_{\mathrm{REF}}}{Kn}}.$$

The maximum output value is limited by M5:

$$v_y < V_{\mathrm{DD}} - V_{ov5} = V_{\mathrm{DD}} - \sqrt{\frac{i_{\mathrm{REF}}}{Kp}}.$$

A Common-Source Output Buffer

Next you're asked to introduce the output buffer as shown below. You should find that the output resistance is significantly reduced by introducing this buffer. The output swing is also improved.



Estimating the DC Operating Point for the CS stage

The properties of the CS stage depend on the DC bias point of V_Y, but that depends on v_{ICM}, which can vary. In order to proceed with an analysis, we may assume that V_y is biased near its lowest allowed value:

$$V_Y \approx V_{ov3} + V_{ov2}.$$

Then the transconductance is

$$g_{m7} \approx K_p \left(V_{\mathrm{DD}} - V_Y - |V_{\mathrm{ThP}}|\right).$$

and the device's drain-source resistance is

$$r_{o7} \approx 2\left[\lambda_p K_p \left(V_{\mathrm{DD}} - V_Y - |V_{\mathrm{ThP}}|\right)^2\right]^{-1}.$$

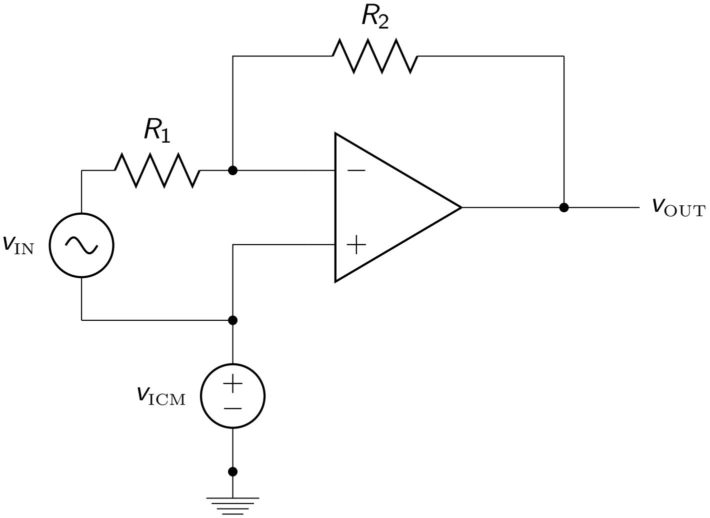
The output resistance is the parallel combination of resistances appearing at the output terminal:

$$R_{\mathrm{OUT}} = r_{o7} \parallel R_D.$$

Finally the open-circuit gain of the CS stage is

$$|A_{vo2}| = g_{m7} R_{\mathrm{OUT}}.$$

The last circuit involves an inverting amplifier configuration:



Loading Effects in the Feedback Configuration

Now that the circuit is being used as an op amp, the inverting input terminal acts as a virtual small-signal ground. Therefore the output terminal is loaded by R_2, which affects the gain of the common-source stage:

$$A_{vl2} = A_{vo2}\left(\frac{R_2}{R_2 + R_{\mathrm{OUT}}}\right).$$

Note that since the OTA stage has a much higher output resistance, the loading effect would be much higher if the CS stage were not present. The total loaded open-loop gain of the op amp circuit is

$$A_{vl} = A_{vo1}A_{vl2}.$$

Gain of the closed-loop configuration

When an ideal op amp is used in an inverting configuration, the expected gain is

$$G^* = \frac{v_{\mathrm{out}}}{v_{\mathrm{in}}} = -\frac{R_2}{R_1}.$$

With a real op amp, however, the actual gain is affected by the finite loaded open- loop gain, like this:

$$G = G^* \left(\frac{A_{vl}}{1 + |G^*| + A_{vl}} \right).$$

Organizing your pre-lab work

Since the pre-lab involves a few repetitive analyses, I recommend that you organize your calculations into a Matlab/Octave script that performs all the above calculations and generates the requested plots from SPICE data.

Two sample scripts are provided, called `predictions.m` and `analysis.m`. You need to modify `predictions.m` to perform the appropriate calculations (look for the comments that say "FILL IN THE SOLUTION" and replace them with your calculations).

Using the analysis script

The `analysis.m` script plots your SPICE results. In order to use the script, you need to save your output data into a text file. For exercises 3, 4 and 10, SPICE will report tables like the one shown below. Simply copy the table (excluding headers) and paste it into text files with names like `ex3.dat`. Then modify the `analysis.m` script with the appropriate filename to complete each exercise.

Index	vicm	iref	gain	gaindb	bw	gmn	gmp	ron	rop
0	0.000000e+00	8.766407e−13	8.333338e−02	−2.76042e+01	0.000000e+00	9.128974e−12	1.181224e−10	5.825397e+12	4.396446e+11
1	2.500000e−01	1.406455e−10	1.648671e−01	−2.16779e+01	2.434395e+01	1.538101e−09	1.730658e−09	3.260300e+10	3.233262e+10
2	5.000000e−01	2.501083e−08	8.864908e+00	1.293289e+01	5.954460e+03	2.705686e−07	2.931819e−07	1.850115e+08	2.171761e+08
3	7.500000e−01	5.385711e−06	9.317349e+00	1.336525e+01	1.829653e+06	6.696575e−05	3.936264e−05	2.142306e+06	4.538080e+06
4	1.000000e+00	5.034414e−05	9.271199e+00	1.332212e+01	6.478253e+06	1.874068e−04	1.041148e−04	6.119816e+05	1.222976e+06
5	1.250000e+00	1.129684e−04	9.243679e+00	1.329630e+01	1.107992e+07	2.778012e−04	1.518077e−04	3.628159e+05	7.320976e+05
6	1.500000e+00	1.801911e−04	9.222524e+00	1.327640e+01	1.510336e+07	3.499078e−04	1.888576e−04	2.569871e+05	5.353842e+05
7	1.750000e+00	2.427910e−04	9.205734e+00	1.326057e+01	1.833698e+07	4.064633e−04	2.171572e−04	1.999166e+05	4.355970e+05
8	2.000000e+00	2.919145e−04	9.193374e+00	1.324890e+01	2.111600e+07	4.469824e−04	2.367240e−04	1.660991e+05	3.825475e+05
9	2.250000e+00	3.166184e−04	9.187424e+00	1.324328e+01	2.326607e+07	4.678630e−04	2.458654e−04	1.465565e+05	3.611302e+05
10	2.500000e+00	3.206687e−04	9.181599e+00	1.323777e+01	2.411549e+07	4.737566e−04	2.472635e−04	1.346978e+05	3.580188e+05

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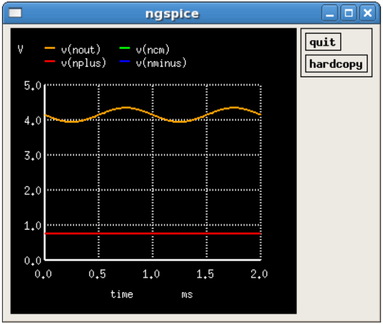
Exercises 3, 4 and 10

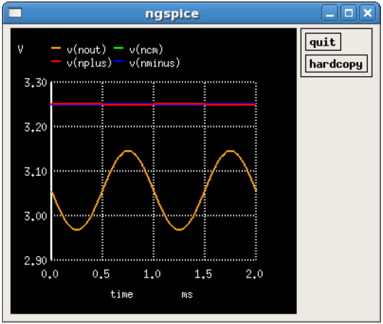
If all goes well, when you run ex3.sp you should see a series of transient simulation plots representing difference values of v_{ICM}:

Low v_{ICM}



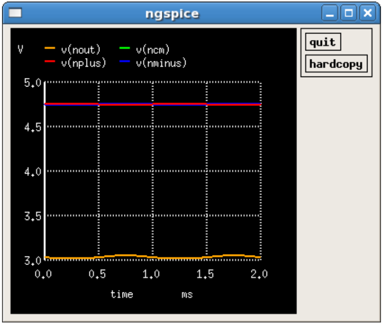
If all goes well, when you run ex3.sp you should see a series of transient simulation plots representing difference values of v_{ICM}:

Middle v_{ICM}



If all goes well, when you run ex3.sp you should see a series of transient simulation plots representing difference values of v_{ICM}:

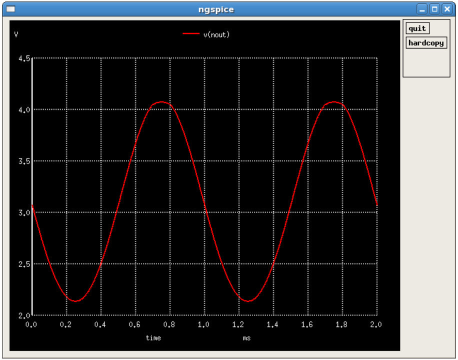
High v_{ICM}



Exercises 5, 6 and 10

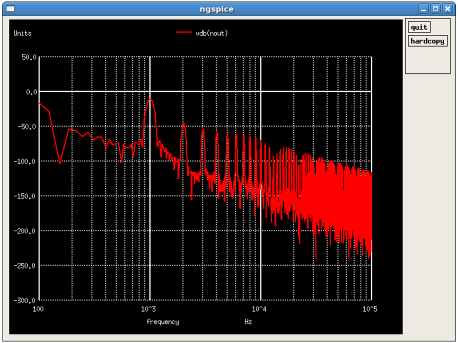
When simulating the distortion analyses, you should get two plots:

A transient simulation result



When simulating the distortion analyses, you should get two plots:

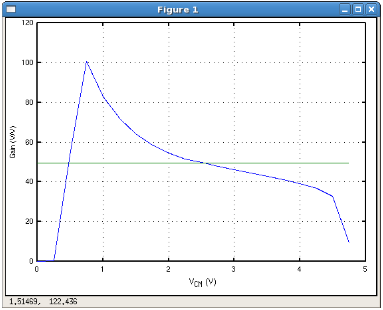
The FFT result



Note: You can measure the fundamental and harmonic lobes by clicking on the point you want to measure. The x and y values are then printed in the NGSpice terminal.

Matlab (or Octave) Analysis (Open Loop)

The Matlab analysis should reveal interesting features about the circuit's behavior. There are three plots:



This plot clearly shows the input common mode range (the amplifier doesn't work if v_{ICM} is too high or too low). It also reveals that within the valid ICMR range, the gain varies considerably depending on v_{ICM}. Was this predicted by your analysis? How can you explain it?

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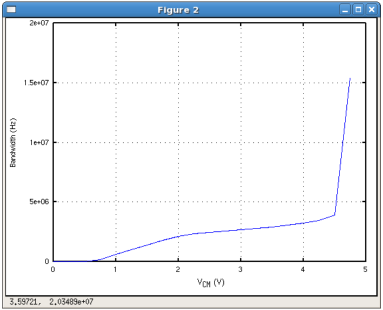

Here we see that the BW varies opposite to the gain. As gain goes down, BW goes up.

Matlab (or Octave) Analysis (Open Loop)

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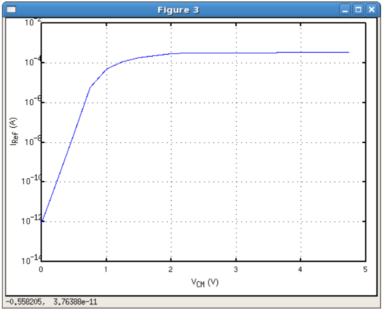
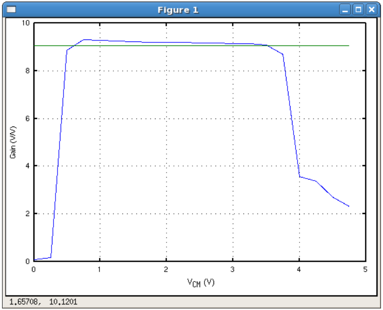


This plot shows what's happening to bias current as v_{ICM} is varied. It should provide some hint as to the gain/bw behavior (hint, consider the relationship between gain and bias current).

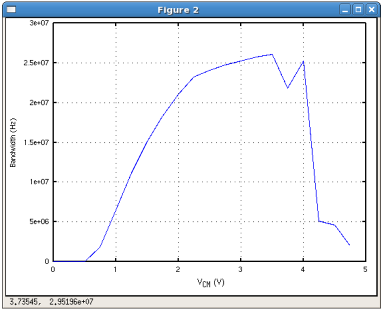
For the closed-loop case, you should notice some key differences:



The closed loop gain is nearly the same across the entire ICMR range. Having a very flat gain improves distortion. Can you explain why distortion is improved?

Matlab (or Octave) Analysis (Closed Loop)

For the closed-loop case, you should notice some key differences:



The BW is much higher for the closed-loop case. Why?