THE UNIVERSITY OF TEXAS AT DALLAS

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Noise Analysis of Opamps with Feedback

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EE7331-501

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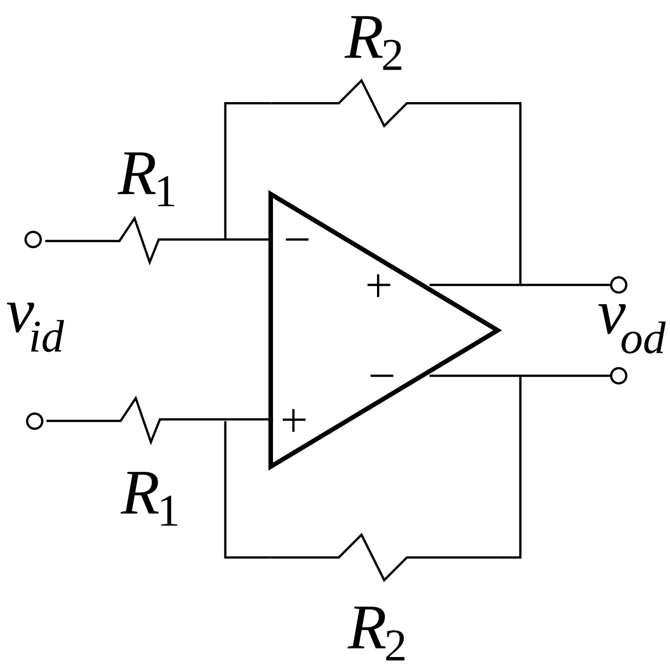
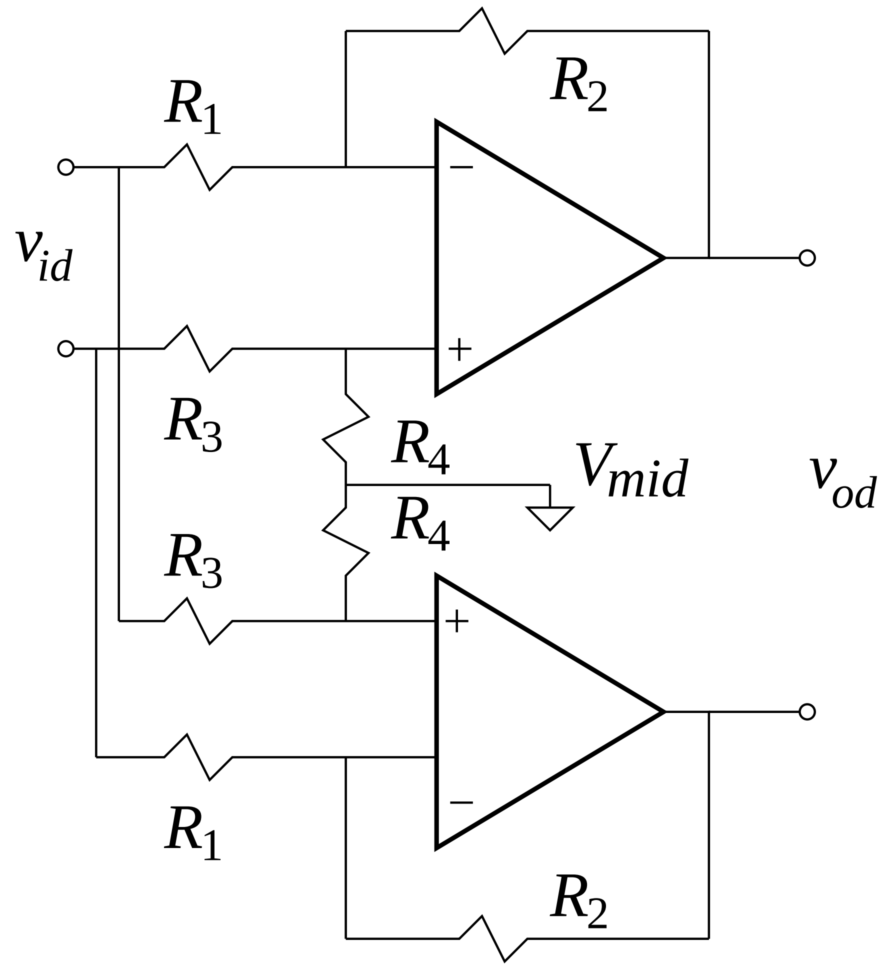
Fall 2007

Two Different Styles of Diff Amps



Case 1



Case 2

Noise Analysis of Case 1 Differential Amp

All noise sources for Case 1 are independent and therefore superposition can be used to directly sum the noise power at the output as

$$\overline{v_{od}^2} = \overline{v_{amp}^2}|H_a|^2 + 2\overline{v_{R_1}^2}A_v^2 + 2\overline{v_{R_2}^2}$$

where $\overline{v_{amp}^2}$ is the total noise integrated over the noise bandwidth f_{NB} of the circuit and $|H_a|^2 \equiv (1 + R_2/R_1)^2$ is the transfer function for the opamp's noise to the output. The closed loop gain from the inverting input is $|A_v| = R_2/R_1$. The input referred noise is found by

$$\overline{v_{id}^2} \equiv \frac{\overline{v_{od}^2}}{A_v^2} = \overline{v_{amp}^2}\left(1 + \frac{R_1}{R_2}\right)^2 + 2(4k_BTR_1f_{NB})\left(1 + \frac{R_1}{R_2}\right)$$

Summary of Case 1

It is a common mistake to think that the single-ended noise at one output of the differential amplifier is just multiplied by $\sqrt{2}$ to get the differential result. Actually this would be the case for an ideal diff amp, but real differential amplifiers have embedded a common-mode feedback amp which contributes noise to each output. The common-mode amps noise can be larger than the input stage. The single-ended noise is

$$\overline{v_{op}^2} = \overline{v_{a_{se}}^2}|H_a|^2 + \overline{v_{R_1}^2}A_v^2 + \overline{v_{R_2}^2} + \overline{v_{a_{cm}}^2}|H_{cm}|^2$$

The common-mode noise is not "seen" in the differential output because it is correlated with itself
(i.e. $\overline{[e_1 + e_3 - (e_2 + e_3)]^2} = \overline{e_1^2} + \overline{e_2^2}$).

Noise Analysis of Case 2

Using superposition the noise at the output of the diff amp in case 2 can be calculated. There are many more components than case 1, but symmetry can simplify the problem.

$$\overline{v_{od}^2} = 2\left[\overline{v_{amp}^2}|H_a|^2 + \overline{v_{R_1}^2}|H_1|^2 + \overline{v_{R_2}^2} + \overline{v_{R_3}^2}|H_3|^2 + \overline{v_{R_4}^2}|H_4|^2\right]$$

where $\overline{v_{amp}^2}$ is the total differential noise integrated over the noise bandwidth, f_{NB}, of the circuit and $|H_a|^2 \equiv (1 + R_2/R_1)^2$ is the transfer function of the opamp's noise to the output. $\overline{v_{R_i}^2} = 4k_BTR_if_{NB}$ is the total noise voltage of the i^{th} resistor. The transfer functions are

$$|H_1|^2 = \left[\frac{R_2}{R_1}\right]^2, \qquad \text{for } R_1$$

$$|H_3|^2 = \left[\left(\frac{R_4}{R_3+R_4}\right)\left(\frac{R_1+R_2}{R_1}\right)\right]^2, \quad \text{for } R_3$$

$$|H_4|^2 = \left[\left(\frac{R_3}{R_3+R_4}\right)\left(\frac{R_1+R_2}{R_1}\right)\right]^2, \quad \text{for } R_4$$

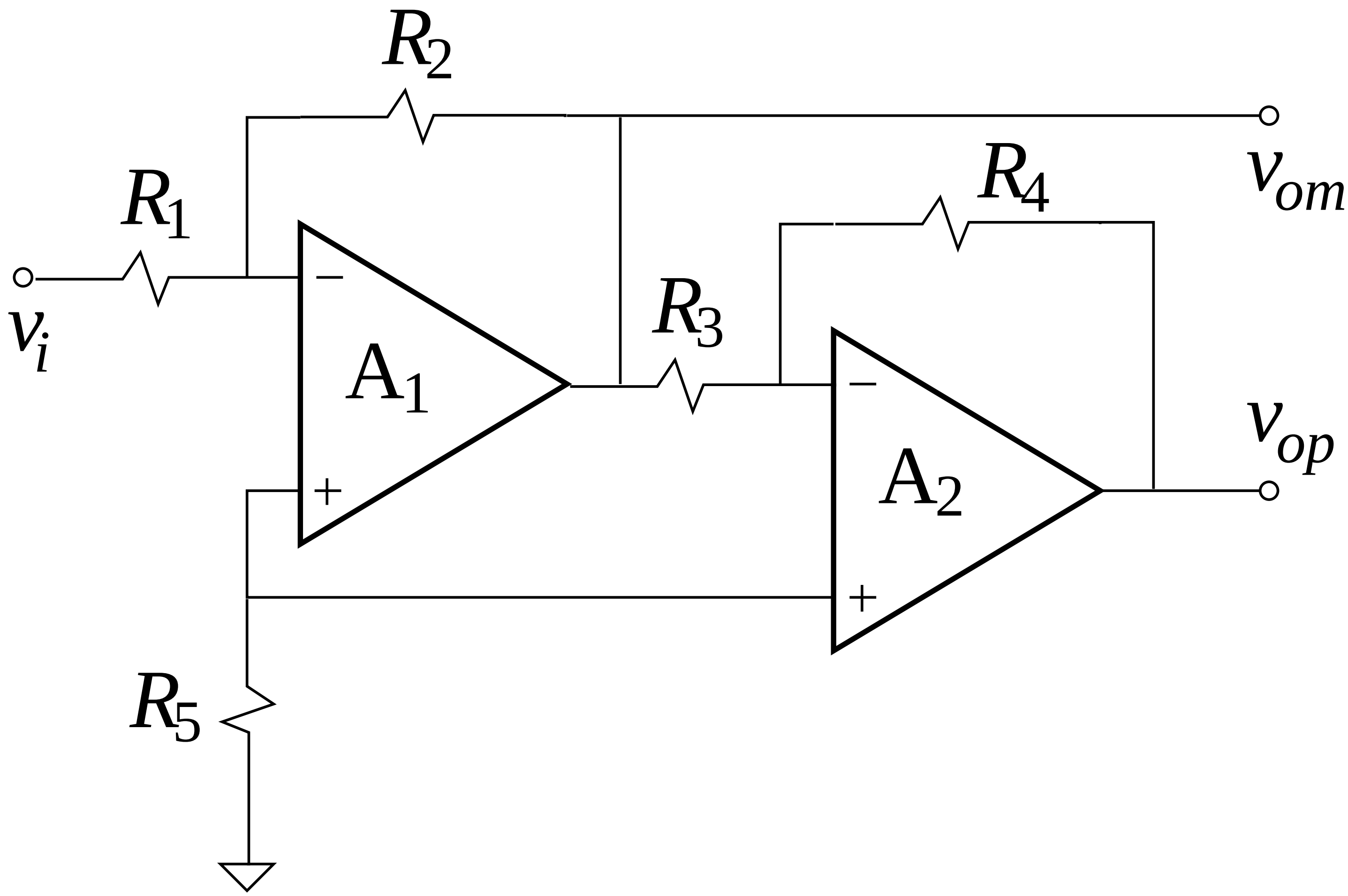
Noise Analysis of Case 2 (continued)

The standard choice for resistors in this case is $R_3 = R_1$ and $R_4 = R_2$, Then the closed loop gain of this circuit is $|A_v| = 2(R_2/R_1)$. Therefore, the input referred noise is

$$\overline{v_{id}^2} \equiv \frac{\overline{v_{od}^2}}{A_v^2} = \frac{\overline{v_{amp}^2}}{2}\left(1 + \frac{R_1}{R_2}\right)^2 + 4k_B T R_1 f_{NB}\left(1 + \frac{R_1}{R_2}\right)$$

Even though Case 2 has 8 resistors and 2 amps versus half as many components in Case 1, the second case has less input referred noise for either equal value resistors or equal closed-loop gain.

Single-ended Input to Differential Output Amp



Analysis of Single-ended to Differential Amp

There is a subtle problem when calculating the noise at the output of this single-ended to diff amp. The noise power of each element can not be simply summed because there is correlation at the output for certain elements. The following method shows how to handle this case. First the inverting output

$$e_{om} = e_{A_1}\left(1+\frac{R_2}{R_1}\right) + e_{R_1}\left(-\frac{R_2}{R_1}\right) + e_{R_2} + e_{R_5}\left(1+\frac{R_2}{R_1}\right)$$

where $e_R \equiv \overline{v_R^2}^{\frac{1}{2}} = \sqrt{4k_BTRf_{NB}}$. Here all of the terms are independent, therefore the noise is

$$\overline{v_{om}^2} = \overline{v_{A_1}^2}\left(1+\frac{R_2}{R_1}\right)^2 + \overline{v_{R_1}^2}\left(\frac{R_2}{R_1}\right)^2 + \overline{v_{R_2}^2} + \overline{v_{R_5}^2}\left(1+\frac{R_2}{R_1}\right)^2$$

Noise Analysis (continued)

Now the non-inverting output is examined

$$e_{op} = e_{om}\left(-\frac{R_4}{R_3}\right) + e_{A_2}\left(1+\frac{R_4}{R_3}\right) + e_{R_3}\left(-\frac{R_4}{R_3}\right) + e_{R_4} + e_{R_5}\left(1+\frac{R_4}{R_3}\right)$$

Note that the noise at v_{om} is also at the non-inverting output v_{op} multiplied by the closed-loop gain of opamp A_2. Since the noise from R_5 gets to v_{op} through two paths, the resulting noise is correlated. This will give an extra noise term in the non-inverting output over just squaring the individual pieces. The noise at v_{op} due to R_5 only is

$$\overline{v_{op_5}^2} = \overline{v_{R_5}^2}\left[\left(1+\frac{R_4}{R_3}\right)^2 + \left(1+\frac{R_2}{R_1}\right)^2 - 2\left(1+\frac{R_4}{R_3}\right)\left(1+\frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3}\right)\right]$$

Differential Noise at Output

When the difference is taken at the output of the diff amp, then all of the noise terms at v_{om} will be correlated with themselves at v_{op}. This leads to lots of extra noise components. Again looking at just the part due to R_5 gives

$$\begin{aligned}\overline{v_{od_5}^2} = \quad & \overline{v_{R_5}^2}\left\{\left(1+\frac{R_2}{R_1}\right)^2+\left(1+\frac{R_4}{R_3}\right)^2+\left(1+\frac{R_2}{R_1}\right)^2\left(\frac{R_4}{R_3}\right)^2\right. \\ & +2\left(1+\frac{R_2}{R_1}\right)^2\left(\frac{R_4}{R_3}\right)-2\left(1+\frac{R_2}{R_1}\right)\left(1+\frac{R_4}{R_3}\right)\left(\frac{R_4}{R_3}\right) \\ & \left.-2\left(1+\frac{R_2}{R_1}\right)\left(1+\frac{R_4}{R_3}\right)\right\}\end{aligned}$$

$$\overline{v_{od_5}^2} = \overline{v_{R_5}^2}\left(\frac{R_2}{R_1}\right)^2\left(1+\frac{R_4}{R_3}\right)^2$$