Lesson 5

Lesson Exercises: **6, B6.10, B6.11**

Recommended Exercises: *B6.24*

Theoretical Issues: **Opamp**

Exercise 6

1. Determine the transfer functions, $H_i = \frac{V_o}{V_{ni}}$, from all the noise sources in the amplifier (one for each transistor) to the output.

2. Calculate the total output noise by $S_{o,tot}(f) = \sum_{1=1}^{7} |H_i| S_i(f)$

3. calculate the equivalent input noise by $S_{i,tot}(f) = \frac{S_{o,tot}(f)}{A_{tot}}$

The noise sources in the differential amplifier have the following transfer functions to the gate of M_7 (the output of stage 1: V_{o1}).

$$\left|\frac{V_{o1}}{V_{n1}}\right| = \left|\frac{V_{o1}}{V_{n2}}\right| = g_{m1}R_{out1}, \left|\frac{V_{o1}}{V_{n3}}\right| = \left|\frac{V_{o1}}{V_{n4}}\right| = g_{m3}R_{out1} \text{ and } \left|\frac{V_{o1}}{V_{n5}}\right| = \frac{g_{m5}}{g_{m3}}$$

where $R_{out1} = r_{ds4} \| r_{ds2}$ and $R_{out2} = r_{ds6} \| r_{ds7}$.

To get the total transfer function to the output the noise voltages are amplified by the gain of stage 2:

$|H_1| = |H_2| = g_{m1}R_{out1} \cdot g_{m7}R_{out2}$, $|H_3| = |H_4| = g_{m3}R_{out1} \cdot g_{m7}R_{out2}$ and

$|H_5| = g_{m5}/g_{m3} \cdot g_{m7}R_{out2}$.

The transfer functions for the transistors in stage 2 are:

$|H_6| = g_{m6}R_{out2}$ and $|H_7| = g_{m7}R_{out2}$.

The total equivalent input noise spectral density is thus given by

$$S_{i,tot}(f) = \sum_{1=1}^{7} \frac{|H_i| S_i(f)}{A_{tot}} = S_1(f) + S_2(f) + \left(\frac{g_{m3}}{g_{m1}}\right)^2 (S_3(f) + S_4(f)) +$$

$$+ \left(\frac{g_{m5}}{g_{m3}A_1}\right)^2 S_5(f) + \left(\frac{1}{A_1}\right)^2 S_7(f) + \left(\frac{g_{m6}}{g_{m7}A_1}\right)^2 S_5(f) \approx$$

$$\approx 2 \cdot S_1(f) + \left(\frac{g_{m3}}{g_{m1}}\right)^2 2 \cdot S_3(f)$$

where $S_i(f) = 4kT\frac{2}{3}\frac{1}{g_{mi}} + \frac{K}{(W/L)_i C_{ox} f}$

Conclusions:

- Noise contributions from M_5-M_7 are small
- Large area for the transistors => small 1/f-noise
- $g_{m1} > g_{m3}$ => small contribution from M_3-M_4.
- Large g_{m1} => Small thermal noise in M_1-M_2.

Exercise B6.10

$$P = (I_{D4} + I_{D3})(V_{dd} - V_{ss}) = 2 \cdot I_{D3} \cdot (V_{dd} - V_{ss}) \Rightarrow I_{D3} = \frac{P}{2(V_{dd} - V_{ss})} = 125\mu\text{A}$$

From p. 271: $I_B = 4 \cdot I_{D5} \Rightarrow I_{D5} = I_{D6} = 25uA$, $I_{D1} = I_{D1} = 100uA$

$g_{m1} = \sqrt{2\mu C_{ox}(W/L)_1 I_{D1}} = 1.9\,\text{mA/V}$. $A_0 = g_{m1} \cdot r_{out}$,

$$|p_1| = \frac{1}{r_{out}C_L} \Rightarrow \omega_u = A_0|p_1| = \frac{g_{m1}}{C_L} = \frac{1.9m}{10p} = 2\pi \cdot 30\,\text{MHz}$$

$$SR = \frac{I_{out,max}}{C_L} = \frac{I_{D3}}{C_L} = \frac{125u}{10p} = 12.5\,\text{V/us}$$

Exercise B6.11

The second pole is approximately given by

$$|p_2| = \frac{g_{m5}}{C_{p2}}$$

where C_{p2} is the total capacitance at the drain of M_2.

$$C_{p2} = C_{dg2} + C_{dg4} + C_{sg4} = C_{gd(overlap)}(W_2 + W_4 + W_5) + \frac{2}{3}W_5 L C_{ox} =$$

$$= 0.2f(300 + 300 + 60) + \frac{2}{3} \cdot 60 \cdot 1.6 \cdot 1.9f = 254\,fF$$

$g_{m5} = \sqrt{2\mu C_{ox}(W/L)_1 I_{D1}} = 0.237\,\text{mV}$ => $|p_2| = g_{m5}/C_{p2} = 2\pi \cdot 148.5\,\text{MHz}$

From p. 237:

$\frac{\omega_t}{|p_2|} = \tan(90° - PM) = \tan(20°) = 0.364 \Rightarrow \omega_t = 2\pi \cdot 54.05\,\text{MHz}$, where ω_t is the unity gain frequency of the loop gain. In this case we are only interested in the transfer function of the opamp which corresponds to $\beta = 1$. For high frequencies the loop gain is given by (p. 237):

$$T(s) = \beta A(s) = \frac{\beta \cdot A_0|p_1|}{s\left(1 + \frac{s}{|p_2|}\right)} = \frac{g_{m1}/C_L}{s\left(1 + \frac{s}{|p_2|}\right)}$$

At the unity gain frequency:

$$T(j\omega_t) = 1 = \frac{g_{m1}/C_L}{\omega_t\sqrt{1+\left(\frac{\omega_t}{|p_2|}\right)^2}} = \frac{g_{m1}/C_L}{\omega_t\sqrt{1+0.364^2}} \Rightarrow C_L = \frac{g_{m1}}{\omega_t\sqrt{1+0.364^2}} = 5.3\,\text{pF}$$

where the value on g_{m1} was calculated in 6.10.

$$SR = \frac{I_{D4}}{C_L} = \frac{125u}{5.3p} = 22.4\,\text{V/us}$$

Exercise B6.24

By breaking the feedback lop we see that the total load capacitance at the output is

$C_L = C_0 + \frac{(C_1/M)\cdot(C_1+C_p)}{C_1/M+C_1+C_p}$ and the feedback factor $\beta = \frac{C_1/M}{C_1/M+C_1+C_p}$.

The unity gain frequency is given by $\omega_u = g_{m1}/C_L$ and according to p. 234

$$\tau = \frac{1}{\omega_{-3dB}} = \frac{1}{|p_1|} = \frac{1}{\beta\omega_u} = \frac{1}{g_{m1}}\left((M+1)C_0 + C_p + \frac{MC_0C_p}{C_1} + C_1\right)$$

$$\frac{\partial\tau}{\partial C_1} = 0 \Rightarrow -\frac{C_0C_p}{C_1} + M = 0 \Rightarrow C_{1,opt} = \sqrt{MC_0C_p}$$