Lecture 22: CMOS Op Amp Compensation

Announcements:
- HW#9 due today
- HW#10 online: shorter than usual, since you also have your project (Lab#3) to work on

Lecture Topics:
- Choosing Cc (cont.)
- CMOS 2-Stage Op Amp Poles & Zeros
- RHP Zero
- Nulling the RHP Zero

Last Time:

Choosing Cc (assume no RHP zeros $|p_3| >> |p_2|$)

$\Rightarrow \text{assume}\ \frac{1}{SC_c} \ll \text{significantly below @ high freq.}$

Case: Two-Stage Amplifier, Miller Compensation

$\frac{V_o}{V_i} = \frac{Gm1}{2C_c}\frac{1}{a_2}$

of op amp transconductance $\rightarrow$ (N-1) gain compared to output @ high freq.

$\text{nulling the RHP zero}$

$N_i = \frac{Gm1}{2C_c} \text{ does not hold here but does hold here}$

This is also that method for phase margin determination!

$\left|\frac{N_o}{N_i}(j\omega)\right| \cdot \frac{Gm1}{2C_c} \Rightarrow \text{this should equal } A_o @ Kc$
For PM = 45°:

\[ \omega_{\text{ult}} = \omega_0 \left| \frac{A_{\text{jw}}}{A_{\text{jw}} F} \right| = 1 \]

\[ \omega_{\text{ult}} \text{ "ult" = "unity loop transmission"} \]

For PM = 45°, \[ \omega_{\text{ult}} \approx \omega_2 \approx \text{freq. of 2nd pole in } a_{\text{jw}} \]

\[ \left| \frac{N_{0,1}(j\omega)}{N_{1,1}(j\omega)} \right| = A_{0,1} = \frac{G_{m1}}{\omega_2 C} \]

Closed-loop gain

For PM = 60°:

\[ \omega_{\text{ult}} = \frac{\omega_2}{1.73} \]

\[ \left| \frac{N_{0,1}(j\omega)}{N_{1,1}(j\omega)} \right| = A_{0,1} = \frac{G_{m1}}{\left( \omega_2 \frac{C}{1.73} \right) C} \]

\[ C_c = \frac{1.73 G_{m1}}{\omega_2 A_0} \text{ for PM = 60°.} \]

\[ \text{Review: To make sure everyone understands} \]

\[ 20 \log |a_{\text{jw}} F| \]

\[ 20 \log (a_0) \]

\[ \text{comp. op amp} \]

\[ \text{open-loop op amp} \]

\[ \text{connected 20 \log (A_0)} \]

\[ \text{closed-loop op amp} \]

\[ \text{PM = 60° } \omega = \frac{W_{p2}}{1.73} \]

\[ A_0 = \frac{a_0}{1 + a_0 F} = \frac{1}{F} \]

\[ f_c = \frac{R_1}{R_1 + R_2} \]

Got at least 80% thumbs up!
Case (2): Two-Stage Amplifier, Shunt $C_c$ Compensation

\[ V_i = \frac{G_m V_i}{s C_c} \quad \therefore V_o = a_2 V_i \]

\[ V_o = a_2 V_i, \quad \therefore V_o = \frac{G_m a_2}{s C_c} V_i \]

\[ N_i = \frac{G_m V_i}{s C_c} \]

\[ N_o = a_2 N_i \]

\[ A_0 \text{ must again intersect this curve at the right watt for a given PM} \]

For PM $= 45^\circ$:

\[ \left( \frac{N_o}{N_i} \right) (s = jW_{ult}) = a_2 = \frac{G_m a_2}{W_{ult} C_c} \]

\[ \frac{C_c}{\omega_2 A_0} \]

For PM $= 60^\circ$:

\[ C_c = \frac{1.73 G_m a_2}{\omega_2 A_0} \]

\[ \text{For PM } = 60^\circ, \quad C_c = \frac{1.73 G_m a_2}{\omega_2 A_0} \]

Case (3): Single-Stage Amplifier, Shunt $C_c$ Compensation

\[ \begin{align*}
N_i & = \frac{G_m V_i}{s C_c} \\
N_o & = \frac{G_m V_i}{s C_c} \\
N_o & = \frac{G_m V_i}{s C_c} \\
\end{align*} \]

\[ \text{Thus}, \quad C_c = \frac{G_m a_2}{\omega_2 A_0} \]

This is the final $\omega_2$ after $C_c$ is inserted.
CMOS 2-Stage Op Amp Compensation

\[ V_{BB} \]

\[ C_C \]

\[ g_{m1} V_i + g_{m2} (V_i - V_o) \]

\[ V_o = \left( \frac{g_{m1}}{R_I} \right) V_i + \left( \frac{g_{m2}}{R_{II}} + \frac{N_0}{N_0 - N_i} \right) N_C \]

\[ + \frac{1}{s} \left( \frac{g_{m1}}{R_I} R_{II} + \frac{g_{m2}}{R_{II}} R_I \right) \]

\[ \frac{1}{s} \left( \frac{g_{m1}}{R_I} R_{II} + \frac{g_{m2}}{R_{II}} R_I \right) \]

\[ \left\{ \begin{align*}
N_C &= \frac{g_{m2}}{R_{II} + g_{m2} R_I + g_{m2} R_I R_{II} C_C}
\end{align*} \right. \]

\[ N(s) \]

\[ \frac{N(s)}{D(s)} \]

\[ \text{The pole:} \quad 2 = \frac{g_{m2}}{C_C} \]

\[ 2 = s \]

\[ \text{The zero:} \quad N(s) = 0 \quad \Rightarrow \quad 2 = \frac{g_{m2}}{C_C} \]

\[ \text{Thus:} \quad p_1 = \frac{1}{(C_{II} + C_{C}) R_{II} + (C_{I} + C_{C}) R_I + g_{m2} R_I R_{II} C_C} \]

\[ \text{Thus:} \quad p_2 = \frac{1}{(C_{II} + C_{C}) R_{II} + (C_{I} + C_{C}) R_I + g_{m2} R_I R_{II} C_C} \]

\[ \text{Thus:} \quad \frac{1}{p_2} = \frac{g_{m2} C_C}{C_{II} + C_{C} + C_{I} + C_{C}} \]

\[ p_2 \approx \frac{g_{m2}}{C_{II} + C_{C}} \]
When $C_c \uparrow$, this becomes a shift! $M_6$ becomes "dubiously useful!"  

$$w_2 = \frac{1}{2C_c} \frac{1}{j\omega C_c} = \frac{1}{(g_m)(C_c + C)} = \frac{g_m}{C_c + C}$$

**CMOS 2-Stage Op Amp Compensation**  
**Summary**

- $g_{m1}: g_{m2}$
- $g_{mB}: g_m$
- $R_1 = \text{bias resistor}$
- $R_2 = \text{feedback resistor}$

From our previous analysis:

$$p_1 = \frac{1}{g_{m2}R_1R_2C_c} \left[ \frac{C_c}{C_c + \beta C} \left[ c_c \gg c_1 \right] \right]$$

$$p_2 = \frac{g_{m2}C_c}{C_c + C_c(c_c + C_2)} \approx \frac{g_{m2}}{C_c + C_2} \approx \frac{g_{m2}}{C_2}$$

$$z = \frac{g_{m2}}{C_c} \implies \text{RHP zero} \quad \text{(this will cause problems)}$$