Lecture 23: Practical Compensation

- Announcements:
  - None
- Lecture Topics:
  - RHP Zero
  - Nulling the RHP Zero
  - Slew Rate (revisited)
- Last Time:

CMOS 2-Stage Op-Amp Compensation (Summary)

From our previous analysis:

\[ R_1 = \frac{g_m R_s}{g_m R_s + g_m R_C} \quad \text{[} C_c \gg C_t + C_{II} \text{]} \quad \text{[} C_c \gg C_t \text{]} \]

\[ R_2 = \frac{g_m R_C}{C_{II} + C_C (C_{t} + C_{II})} \approx \frac{g_m}{C_C} \quad \frac{1}{C_{t} + C_{II}} \approx \frac{g_m}{C_t} \]

\[ z = \frac{g_m}{C_c} \quad \text{RHP zero (this will cause problems)} \]

Lecture 23w: Practical Compensation

What does the RHP Zero come from?

\[ \frac{V_{oP}}{V_{oN}} \]

\[ a_2 = \frac{V_{oP}}{V_{oN}} \]

\[ V_{oN} = \frac{g_m}{a_2} \]

\[ \text{Current can just feed forward at high freq.} \]

\[ \text{Negative! Should be (+).} \]

\[ \text{Thus \rightarrow instability!} \]

Observation:

The Miller effect (in compensation) requires FB path

\[ \text{But: the feedforward path (that causes the zero) isn't needed} \]

Solution:

1. Kill the feedforward path
2. Keep the FB path

\[ \text{Shunt a unity gain buffer in series w/ } C_c \]
\[ P_1 = -\frac{1}{g_{m2} R_2 R_0 C_c} \quad \text{(same as before)} \]

\[ P_2 \approx -\frac{g_{m2} C_c}{C_{II}(C_I + C_c)} \approx -\frac{g_{m2}}{C_{II}} \quad \left[ C_c \gg C_I \right] \]

\[ P_3 \approx -\frac{1}{R_0 (C_c C_3/C_c + C_c)} \approx -\frac{1}{R_0 C_3} \quad \text{seiner combination of } C_I + C_c. \]

\[ z_e = -\frac{1}{R_0 C_3} \quad \text{(LHP zero)} \]

Remarks:
1. An additional pole \( p_3 = -\frac{1}{R_0 C_3} \) has been created. But since \( R_0 \) is small (in a buffer) and \( C_3 \) is small, \( p_3 \) is at a very high freq. and contributes very little phase @ unity, where \(|T(j\omega)| = 1\).
2. A LHP zero now emerges \( z_e = -\frac{1}{R_0 C_3} \).
   - This helps stability as discussed before.
   - (by contributing \( C_I \) phase shift to PM)

\[ P_1 = -\frac{1}{g_{m2} R_2 R_0 C_c} \quad \text{same as before} \]

\[ P_2 \approx -\frac{g_{m2} C_c}{C_{II} C_3 + C_c (C_I + C_3)} \approx -\frac{g_{m2} C_c}{C_3} \]

\[ P_3 \approx -\frac{1}{R_0 (C_c C_3/C_c + C_c)} \approx -\frac{1}{R_0 C_3} \quad \text{(LHP zero)} \]


\[ p_3 = -\frac{1}{R_2 C_I} \quad \text{pole due to } R_2 \]

\[ z_1 = \frac{1}{C_c \left( \frac{1}{g_{mII}} - R_2 \right)} \quad \text{relocated zero (function of } R_2) \]

Note: The position of the zero depends upon the value of the "nulling resistors" \( R_2 \).

- If \( R_2 < \frac{1}{g_{mII}} \), then \( z_1 \) is in the RHP.
- If \( R_2 > \frac{1}{g_{mII}} \), then \( z_1 \) is in the LHP.

This is great! We can move the zero to a LHP zero!

\[ H(s) = \ldots \]

If \( z_1 = p \),

The Root Locus:

- \( \text{Im}(s) \text{ starts at } C_I \text{, but not } R_2 \)

Zero Placement Strategies:

1. \( \lim_{s \to \infty} z_1 = \frac{1}{C_c \left( \frac{1}{g_{mII}} - R_2 \right)} \to \infty \text{ when } R_2 = \frac{1}{g_{mII}} \)

   After doing this: \( p_3 \approx \frac{g_{mII}}{C_I} \) usually \( C_d \approx C_I \) these poles are far apart...

   This is good but we can do better...

   So be careful...

2. Eliminate \( p_2 \) by placing \( z_1 \) on top of it:

   \[ z_1 = p_3 \Rightarrow \frac{1}{C_c \left( \frac{1}{g_{mII}} - R_2 \right)} = -\frac{1}{R_2 C_I} \]

   After this:
   - \( p_3 \) gone, \( p_1 \) \& \( p_2 \) left
   - Now, can place \( W_{II} \) at \( p_2 \) \( \approx \) really good
   - \( p_2 \) \text{ also pretty good} \( PM = 45^\circ \)
   - \( p_1 \) \text{ not so bad}
   - \( p_1 \) \text{ not so bad}

   \text{No worrying about the influence of } p_3
Eliminate $p_2$ by placing $Z$ on top of it:

$$Z = p_2 = \frac{1}{C_C \left( \frac{1}{g_{mII}} - R_2 \right)} - \frac{g_{mR}}{C_{II}}$$

$$R_2 = \frac{C_C + C_{II}}{C_C} \left( \frac{1}{g_{mII}} \right) = \frac{1}{g_{mII}} \left( 1 + \frac{C_{II}}{C_C} \right)$$

With this choice of $R_2$:

$$p_2^* = \frac{1}{R_2 C_C} = \frac{1}{(C_C + C_{II}) \left( \frac{1}{g_{mII}} \right) C_C}$$

This is the new $p_2$.

For PM = 45°:

$$C_C = \frac{g_{mII}}{p_2} = \frac{g_{mII}}{p_2 A_0} = \frac{C_{II} (C_C + C_{II})}{C_C A_0}$$

for $C_C \ll C_{II}$.

Remark: If settling time is important, then approach 2 may not be the best approach. The reason is that, if the zero is not exactly equal to the pole, the a "doublet" answer, which actually can hurt the settling time.

Discussed in a handout to be posted on the course website. Also, discussed in Razavi, problem 10.19.
Actual Implementation

- Resistors are too big! Implement using a much smaller MOS resistor!

MOS Resistor: just an MOS Xrista operated in the linear region

\[ I_d = \mu_n C_X \frac{W}{L} \left( V_{gs} - V_t \right) V_{ds} - \frac{1}{2} \frac{V_{ds}^2}{R} \]

\[ \frac{\partial I_d}{\partial V_d} = \mu_n C_X \frac{W}{L} (V_{gs} - V_t) \]

\[ R_s = \left( \frac{dV}{dI} \right)^{-1} = \frac{1}{\mu_n C_X \frac{W}{L} (V_{gs} - V_t - V_d)} \]

\[ \frac{V_{ds}}{C_{lin}} = \frac{1}{\mu_n C_X \frac{W}{L} (V_{gs} - V_t - V_d)} \]

A variable resistor controlled by \( V_{ds} \)

Design:

Need \( V_A \rightarrow V_{G_{in}} \rightarrow |V_{G_{in}}| \), know that \( |V_{G_{in}}| = |V_{G_{in}}| \)

\[ \sqrt{\frac{2 I_{th}}{M_{p} C_X (W/L)_{11}}} \]

\[ \sqrt{\frac{2 I_{oh}}{M_{p} C_X (W/L)_{12}}} \]

\[ I_{th} = \frac{V_{ds}}{C_{lin}} \]

Also, need \( |V_{G_{in}}| \cdot |V_{G_{in}}| \)

Because \( V_A \rightarrow V_{in} \rightarrow |V_{in}| \rightarrow |V_{in}| \)

\[ R_s = M_{p} C_X (W/L) \sqrt{\frac{2 I_{th}}{M_{p} C_X (W/L)_{11}}} \]

Thus:

\[ R_s = \frac{1}{M_{p} C_X (W/L) \sqrt{2 I_{th}}} \]

\[ \frac{2 I_{th}}{M_{p} C_X (W/L)_{11}} \]

\[ \frac{1}{M_{p} C_X (W/L) \sqrt{2 I_{th}}} \]
Case: Eliminate \( p_2 \) by placing \( z_1 \) on \( \tau_p \) of it.

\[
R_2 = \frac{C_s + C_L}{g_{m6} C_c} = \frac{\sqrt{\mu C_{ox} \left( \frac{W}{L} \right) I_{D0}}}{\mu C_{ox} \left( \frac{W}{L} \right) I_{D0}} \sqrt{2 I_{D0}}
\]

\[
\left( \frac{W}{L} \right)_{p} = \sqrt{\left( \frac{W}{L} \right)_{I_{D0}} \frac{I_{D6}}{I_{D0}} \frac{C_L}{C_s + C_L}}
\]

Case: Move \( z_1 \to \infty \).

\[
R_2 = \frac{1}{g_{m6}} \left( \frac{W}{L} \right)_{p} = \sqrt{\left( \frac{W}{L} \right)_{I_{D0}} \frac{I_{D6}}{I_{D0}}}
\]