Lecture 14: Vos & Finite Gain-BW

Announcements:
- HW#6 due tomorrow
- HW#7 online soon
- Pre-Lecture materials online
- Midterm will be on the date specified in your syllabus: Thursday, March 21, 3:30-5 p.m. in 390 Hearst Mining Building

Lecture Topics:
- Input Offset Voltage (Vos)
- Op Amp Finite Gain-BW

Last Time:

Vos arises due variations in:
1. $\frac{W_1}{l_1}$ t_1 v_{os,1}
2. $\frac{W_2}{l_2}$ t_2 v_{os,2}

Definition: Vos = Vos needed to get V_{os} = 0V when applying 0V to both inputs.

KVL: $V_{os} - V_{os1} + V_{os2} = 0$
\[ V_{os} = V_{os1} - V_{os2} = \frac{2I_{D1}}{M_1C_{ox}(W/L)_1} - \frac{2I_{D2}}{M_2C_{ox}(W/L)_2} \]

Vos = $V_{t1} - V_{t2} + \frac{2I_{D1}}{M_1C_{ox}(W/L)_1} - \frac{2I_{D2}}{M_2C_{ox}(W/L)_2}$

\[ \Delta I_D = I_{D1} - I_{D2} \quad \Delta \left( \frac{V}{l} \right) = (\frac{W}{l})_1 - (\frac{W}{l})_2 \]
\[ I_D = \frac{I_{D1} + I_{D2}}{2} \quad \left( \frac{V}{l} \right) = \frac{1}{2} \left[ (\frac{W}{l})_1 + (\frac{W}{l})_2 \right] \]
\[ \Delta V_C = V_{C1} - V_{C2} \quad \Delta R_D = R_{D1} - R_{D2} \]
\[ V_C = \frac{V}{2} (V_{t1} + V_{t2}) \quad R_D = \frac{1}{2} (R_{D1} + R_{D2}) \]
Now, go through bipolar mismatch prepared material.
**Finite Op Amp Gain & Bandwidth**

For an ideal op amp, \( A = \infty \).

In reality, the gain is given by: \( A(s) = \frac{A_0}{1 + s\frac{R_1}{R_2}} \).

![Graph showing gain vs frequency]

\( \omega_T \) is unity gain frequency, the freq. at which \( |A(j\omega)| = 1 \) (0 dB).

At \( \omega_T \):

\[ |A(j\omega_T)| = 1 = \frac{A_0}{1 + \frac{\omega_T}{\omega_b}} \]

\[ \omega_T = \frac{\omega_b}{\frac{A_0}{\omega_T}} \rightarrow \omega_T = A_0\omega_b \]

- **Gain-Bandwidth Product**

For \( \omega \gg \omega_b \):

\[ A(s) = A_0 \frac{\omega_b}{s} = \frac{\omega_T}{s} \frac{\omega_T}{\omega_b} \]

The unity gain bandwidth, \( f_T \), is usually specified on op amp data sheets. Knowing \( f_T \), one can easily determine the op amp gain at a given frequency \( f \).

**Frequency Response of Closed Loop Amplifier**

**Example: Non-Inverting Amplifier**

\[ N_i = \frac{N_o - N_e}{N_e} \]

\[ N_o = \frac{N_i}{A(s)} \]

\[ V_o = N_i = \frac{N_o}{A(s)} \]

Find an expression for the gain as a function of frequency.

1. **Brute force derivation**:

   \[ \frac{N_o - N_e}{R_2} \rightarrow \frac{N_o}{R_2} : N_e \left( \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1}} \right) \]

2. **More insightful way to do this**:

   - Gain block diagram
   - \( N_i = \frac{N_o - N_e}{N_e} \)
   - \( N_o = \frac{N_i}{A(s)} \)
   - \( V_o = N_i = \frac{N_o}{A(s)} \)

\[ N_i = \frac{N_o - \beta N_e}{N_e} \]

\[ V_o = M_i = \frac{N_o - N_e}{N_e} \]

\[ V_e = N_i = N_e + \beta \]

\[ N_i = N_e \frac{M_i}{\beta} \]

\[ N_i \]
Observations:

1. Closed loop DC gain $= \frac{A_0}{1+\beta A_0} = \frac{A_0}{1+T_o} \approx \frac{A_0}{T_o}$
   
   i.e., the closed loop gain is reduced from the open loop gain by $1+T_o$. Show this on graph.

2. Alternatively, closed loop DC gain $\approx \frac{A_0}{\beta A_0} = \frac{1}{\beta}$

3. $\omega_{3dB}$ has increased from $\omega_b \rightarrow \omega_b (1+\beta A_0) = \omega_b (1+T_o)$

   To draw the Bode plot, just find the DC gain, draw a horizontal line across, then follow the open loop response. Often running into it!

4. Gain-BW Product: $= \frac{A_0}{1+\beta A_0} \omega_b (1+\beta A_0) = A_0 \omega_b = \omega_f$

   :: the Gain-BW product remains the same for the open & closed loop FB cases!