Midterm exam statistics: all students

Lowest IQ’s overall: 2.7 μA, 3.9 μA, 5.3 μA, 6.7 μA, … a total of 17 designs met all specs
Midterm exam statistics: ECEN4827 only

ECEN4827 lowest IQ: 75.7 μA, a total of 2 designs met all specs
Finding complete $A(s)$ using NEET

NEET = “N-Extra-Element-Theorem”


$$A(s) = \frac{v_o}{v_i} = A(0) \frac{1 + b_1 s + \ldots + b_m s^m}{1 + a_1 s + \ldots + a_n s^n}$$

Low-frequency small-signal model (linear)

$v_i$  

$C_1$  

$C_2$  

$C_n$  

$+$  

$-$  

$v_o$  

$\text{all found separately}$

$a_i = \Sigma C_i R_i \text{ at ops.}$
Example: source follower $A(s)$

\[ A(0) = \frac{g_m}{g_m + g_{ms}} = \frac{5}{6} \]

For DC: $a_1 = C_{gd} R_{in} + C_L \frac{1}{g_m + g_{ms}} + C_{qs} R_{in} \frac{g_{ms}}{g_m + g_{ms}}$

already done
\[ a_2 = C_{gd} R_{in} C_L \left( \frac{1}{g_{m} + g_{mb}} \right) + C_{gd} R_{in} C_{gs} \left( \frac{1}{g_{m} + g_{mb}} \right) + C_L \frac{1}{g_{m} + g_{mb}} \cdot C_{gs} \left( R_{in} \right) = R_{in} \frac{1}{g_{m} + g_{mb}} \left( C_{gd} C_L + C_{gd} C_{gs} + C_{ddgs} \right) \]
\[ a_3 = 0 \]
\[ b_1 = C_{gd}(0) + C_{qs}(\frac{1}{g_m}) + C_L(0) \]
\[ b_2 = \frac{C_{gs}}{g_m} \cdot C_{gd} \cdot \Theta + \frac{C_{gs}}{g_m} \cdot C_L \cdot \Theta + C_{gd} \cdot 0 \cdot C_L \cdot \Theta = 0 \]
Source-follower $A(s)$

$$A(s) = A(0) \frac{1 + \frac{C_s s}{2m}}{1 + a_1 s + a_2 s^2} = A(0) \frac{1 + \frac{s}{\omega_2}}{1 + \frac{1}{Q} \frac{s}{\omega_0} + \left(\frac{s}{\omega_0}\right)^2}$$

$$f_z = \frac{9m}{2\pi C_q} \rightarrow \text{high.}$$

$\text{ZVC: } \text{BW } \approx \frac{1}{\pi a_1} \approx 5 \text{ kHz.} \quad \text{(?)}$ (based on dominant pole approximation)

$A(s)$ does not have a dominant pole.

$f_0 \approx 5.5 \text{ MHz}$

$\quad f_0 = 5.1 \text{ MHz}$
Summary

ZVTC allows simple BW estimation, which is accurate for transfer functions that include a dominant-pole

NEET is an approach to finding a complete transfer function

More worked-out NEET examples can be found in the notes posted on the calendar page
Reminder: NMOS and PMOS models in LTspice

(1) place nmos_035 symbol
The same applies to pmos_035

(2) CTRL-right click to open Attribute Editor

(3) Change Prefix to X to use the subcircuit model with automatic adjustments of AS, PS, AD, PD, which affect the values of $C_{sb}$ and $C_{db}$ capacitors

To get credit for LTspice simulation problems (e.g. S10 and S11 in HW9), all devices must use the subcircuit (X) models
Feedback Circuits

- Feedback theorem (due to Prof. David Middlebrook, Caltech)
  - Closed-loop response as a function of
    - Ideal closed loop gain
    - Loop gain
    - Direct transmission through the feedback path
- Frequency responses of feedback circuits based on op-amps with approximately single-pole open-loop response
  - Op-amp gain-bandwidth product, GBW
  - Cross-over frequency $f_c$ and closed-loop bandwidth $BW_{CL}$
- Stability and compensation of feedback circuits
  - Loop-gain magnitude and phase responses
  - Phase margin, gain margin
  - Relationship between phase margin and closed-loop responses: how much phase margin is required?
  - Compensation
- 2-stage CMOS op-amp: dominant-pole ("Miller") compensation
- Large-signal dynamic responses limitations: slew-rate
A Single-Loop Feedback System

Objective: find closed-loop response \( A_{cl} = G = \frac{v_o}{v_i} \) with \( v_x = 0 \)
Middlebrook’s Feedback Theorem*

\[ G = G_\infty \frac{T}{1+T} + G_o \frac{1}{1+T} \]

\[ G = \left. \frac{v_o}{v_i} \right|_{v_x=0} \]

\[ T = \text{loop gain} = \left. \frac{v_x}{v_i} \right|_{v_i=0} \]

\[ G_\infty = \text{ideal closed loop gain} \]

\[ G_o = \text{direct transmission through feedback path} \]

*For derivation, see notes posted on the course website.