Voltage Amplifier Frequency Response

- Chapter 9 multistage voltage amplifier

Approaches:

1. brute force OCTC -- do for all capacitances in the circuit
2. identify the largest contributor(s) and calculate the Thévenin resistance associated with them

Try second approach: identify four nodes in signal path
Qualitative Evaluation of Time Constants

- Input node: no contribution since $R_S = 0$

- Drain of $M_1$: “low impedance node” since $R_{in(CB)} = 1/g_{m2}$

- Node $X$: extremely high resistance ... could be a big time constant

- Source of $M_3$: “low impedance node” since $R_{out(CD)} = 1/g_{m3}$

- Output node: “low impedance node” since $R_{o(CC)} = 1/g_{m4}$

**Note:** we are *not* considering capacitances *between* nodes here ... since we are doing an approximate analysis, we will use Miller’s theorem to find their effective capacitance to ground
Small-Signal Model of Node X

- Account for all of the capacitances from node X to small-signal ground:
  1. Base-collector capacitance \( C_{\mu 2} \) of \( Q_2 \) (since it is connected to diode-connected transistors \( M_{6B} \) and \( M_{7B} \) that are in turn connected to \( V_{DD} \))
  2. Gate-drain capacitance \( C_{gd6} \) of \( M_6 \) (since it is connected to the same node as \( C_{\mu 2} \))
  3. Gate-drain capacitance \( C_{gd3} \) of \( M_3 \) (since it is connected directly to ground)
  4. Effective capacitance due to \( C_{gs3} \) connected between the input and the output of the common-drain stage:

\[
C_{eff} = C_{gs3} (1 - A_v C_{gs3})
\]

The gain across \( C_{gs3} \) is about 1, but an accurate calculation would include any backgate effect on \( M_3 \) if present.

- Small-signal model with all (non-parasitic) capacitances
Gain-Bandwidth Product

- Considering only the time constant from node $X$

$$\omega_{3dB} \approx \frac{1}{[(\beta_o r_o g_m r_o r_o) g_m (C_{\mu 2} + C_{gd6} + C_{gd3} + (1 - A_v C_{gs}) C_{gs})]}$$

- Approximate low-frequency gain -- from Chapter 9

$$A_{vo} \approx -g_m (\beta_o r_o g_m r_o r_o)$$

- Gain-bandwidth product

$$|A_{vo}| \omega_{3dB} \approx \frac{g_m}{C_{\mu 2} + C_{gd6} + C_{gd3} + (1 - A_v C_{gs}) C_{gs}}$$
Magnitude Bode Plot

- Assuming that the second pole is greater than the unity gain frequency, the Bode plot is

\[
\frac{V_{\text{out}}}{V_s} \approx g_m \frac{1}{\beta o_2 r_2} \left\{ \frac{1}{(r_c \| \beta o_2 r_2) \left( C_{\mu 2} + C_{gd 6} + C_{gd 3} + (1 - A_v 3) C_{gs 3} \right)} \right\} \log \omega
\]

\[
= g_m \beta o_2 r_2 \frac{1}{(r_c \| \beta o_2 r_2) \left( C_{\mu 2} + C_{gd 6} + C_{gd 3} + (1 - A_v 3) C_{gs 3} \right)} \log \omega
\]
Differential Amplifiers

- General structure: two inputs, two outputs

Consider balanced situation: $V_{I1} = V_{I2}$ and $R_{C1} = R_{C2}$ and devices 1 and 2 are in their constant-current modes.

$$I_{BIAS} = I_1 + I_2 = 2(V^+/R_C)$$

Adjust so $V_{O1} = V_{O2}$ are about 0 V (note the dual supplies)
Decomposition of Small-Signal Input Voltages

- Inputs $v_{i1}$ and $v_{i2}$ are not the “natural inputs” to understand how the differential amplifier works ...

- Define two new voltages
  
  differential-mode input voltage $= v_{id} = v_{i1} - v_{i2}$
  
  common-mode input voltage $= v_{ic} = (1/2)(v_{i1} + v_{i2})$

- Expressing the inputs $v_{i1}$ and $v_{i2}$ in terms of $v_{id}$ and $v_{ic}$

  
  $$v_{i1} = v_{ic} + \frac{v_{id}}{2}$$

  $$v_{i2} = v_{ic} - \frac{v_{id}}{2}$$
Example of Signal Decomposition

- $v_{i1} = v_{in}$ and $v_{i2} = 0$ V results in both a differential-mode and a common-mode input to the amplifier

- **Goal:**
  
  determine the response of the differential amplifier to $v_{id}$ and $v_{ic}$ separately and then reconstruct the response
Small-Signal Model of Bipolar Diff. Amplifier

- Define $r_{ob}$ as the internal (source) resistance of the bias current source

- Small-signal model with purely differential inputs

$$
\begin{align*}
&v_+ \\
&+ \\
&\equiv R_C \\
&\equiv R_C \\
&Q_1 \\
&v_{o1} \\
&- \\
&\equiv r_{ob} \\
&Q_2 \\
&v_{o2} \\
&- \\
&v_+ \\
&i_{BIAS}
\end{align*}
$$

$$
\begin{align*}
&v_{i1} \\
&v_{i2} \\
&v_{id} \\
&\frac{v_{id}}{2} \\
&- \\
&- \\
&+ \\
&+ \\
&g_m v_{\pi 1} \\
&g_m v_{\pi 2} \\
&+ \\
&- \\
&v_{\pi} \\
&v_+ \\
&v_{o1} \\
&v_{o2} \\
&v_+ \\
&\equiv r_{ob} \\
&\equiv r_{ob} \\
&- \\
&- \\
&+ \\
&\equiv r_{ob}
\end{align*}
$$
Small-Signal Model with Purely Differential Inputs

- The voltage at $v_x$ must be zero for purely differential inputs --> it can be considered a small-signal or incremental ground reference
- Only need to solve half of the circuit, whose outputs are + or $-v_{od}/2$

\[
\frac{v_{od}}{2} = -g_m R_C \frac{v_{id}}{2}
\]

define differential-mode gain $a_{dm}$ by

\[
a_{dm} = \frac{v_{od}}{v_{id}} = -g_m R_C
\]