Lecture 7: Non-Ideal Op Amp Circuits

• Announcements:
  - HW#3 online and due Friday via Gradescope
  - Late Homework Policy:
    - -10% per day
    - It's -10% one second after Friday noon
    - -20% on second after Saturday noon
    - ...
  - Regrades:
    - Submit HW w/ a note with reason
    - HW will go back to reader, which will take time
  - We will NOT drop a HW
    - It’s only 10% of your grade and it’s better that you at least do some problems in a HW
  - Next Wednesday, 9/12: I will be out of town.
    - So no ground lecture that day
    - Make up will probably need to be by video recording and put online

• Lecture Topics:
  - Closed Loop Amplifier Freq. Response Using Finite Gain-BW Op Amps
    - Non-Inverting Amplifier
    - Inverting Amplifier

• Last Time:
  - Non-inverting amplifier using finite gain-BW op amp
  - Now, continue with this ...

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For an ideal op amp, $A = \infty$.

In reality, the gain goes as:

$$A(s) = \frac{A_0}{1 + \frac{s}{\omega_b}}$$

Non-Ideal OpAmps

Finite Op Amp Gain + Bandwidth

$\omega_t \triangleq$ unity gain frequency = freq. at which $|A(j\omega)| = 1$

At $\omega_t$, $|A(j\omega)| = 1$:

$$A_0 \sqrt{\frac{\omega}{\omega_b}} \Rightarrow \frac{A_0}{\omega_t \omega_b} = 1 \Rightarrow \omega_t = A_0 \omega_b$$

$[\omega_t > \omega_b]$
EE 105: Microelectronic Devices & Circuits
Lecture 7w: Non-Ideal Op Amp Circuits

Frequency Response of Closed Loop Amplifier

Example: Non-Inverting Amplifier

\[ V_o = A(s) (V_i - V_e) \]

Find an expression for gain as a function of freq.

1. **Brute Force Determination:**
   
   \[ G = \frac{V_o}{V_i} = \frac{V_e}{V_i} \]

   \[ \frac{V_o}{V_i} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1} + \frac{1}{A(s)}} \]

   \[ A(s) = \frac{A_0}{\frac{R_2}{R_1} + s} \]

   \[ G = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1} + \frac{1}{A_0(1 + \frac{R_2}{R_1})}} \]

   \[ \text{finite gain} \text{ BW} \]

   \[ A_0 \text{ large} \Rightarrow \frac{1}{A_0(1 + \frac{R_2}{R_1})} \ll 1 \]

   Here, we're essentially saying that the op amp gain is close to ideal as the non-idealities are mainly finite BW.

   Near ideal gain, but finite BW

2. **Insightful Way to Do This:**

   \[ \frac{\alpha_o}{\alpha_i} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1} + \frac{1}{A(s)}} \]

   \[ A(s) = \frac{A_0}{\frac{R_2}{R_1} + s} \]

   \[ \frac{\alpha_o}{\alpha_i} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_2}{R_1} + \frac{1}{A_0(1 + \frac{R_2}{R_1})}} \]

   \[ \text{finite gain} \text{ BW} \]

   What is \( \beta \)?

   \[ \beta = \frac{\alpha_B}{\alpha_i} = \frac{R_1}{R_1 + R_2} \]

   \[ \text{finite BW} \]
Recall previous FB analysis:

\[ \frac{V_o}{V_i}(s) = \frac{A(s)}{1 + \beta A(s)} \]

\[ A(s) = \frac{A_0}{1 + \frac{s}{\omega_b}} \rightarrow \frac{V_o}{V_i}(s) = \frac{A_0}{1 + \frac{s}{\omega_b}} \frac{1}{1 + \beta \left( \frac{A_0}{1 + \frac{s}{\omega_b}} \right)} \]

DC gain term

Frequency Shaping Term

DC gain with midband gain

\[ T_o = \beta A_0 \times \frac{1}{1+\frac{s}{\omega_b (1+\beta A_0)}} \]

If \( A_0 \rightarrow \infty \text{ or } A_0 \gg 1 \) → DC gain: \( \frac{1}{\beta} \)

Plug in \( \beta \):

\[ [\beta A_0 \gg 1] \rightarrow \frac{V_o}{V_i}(s) = \frac{1}{\beta} \frac{1}{1 + \frac{s}{\omega_b A_0}} \equiv \text{"loop gain" at } \omega = 0 \]

i.e. @ DC

\[ T_o = \beta A_0 \]

Observations:

1. Closed loop DC gain = \( \frac{A_0}{1 + \beta A_0} \approx \frac{A_0}{T_o} \)

   i.e., the closed loop gain is reduced from the open loop gain by \( 1 + T_0 \) → show this on graph

2. Alternatively, closed loop DC gain ≈ \( \frac{A_0}{\beta A_0} = \frac{1}{\beta} \)

3. \( \omega_{3dB} \) has increased from \( \omega_b \rightarrow \omega_b (1 + A_0 \beta) = \omega_b (1 + T_0) \)
   
   To draw the Bode plot, just find the DC gain, draw a horizontal line across, then follow the open loop response after running into it!

4. Gain-BW Product = \( \frac{A_0}{1+\beta A_0} \omega_b (1+\beta A_0) = A_0 \omega_b = \omega_1 \)
   
   \( \therefore \) the Gain-BW product remains the same for the open & closed loop FB cases!

Example: Inverting Amplifier

\[ \frac{V_o}{V_i} \rightarrow R_2 \]

Signals from \( V_o \) & \( V_i \) sum here

How much of each appears depends on \( \alpha \) & \( \beta \)
Determine $\alpha$:
1. Ground output, open loop
2. Feed $V_i$ forward to get T.F.

\[
\frac{V_o}{V_i}(s) = \frac{R_2}{R_1 R_2} = \alpha
\]

Determine $\beta$:
1. Ground input, open loop
2. Feedback $V_o$ to get T.F.

\[
\frac{V_o}{V_o}(s) = \frac{R_1}{R_1 R_2} = \beta
\]

Now, get T.F. to the system block diagram:

\[
\begin{align*}
V_o &= -A(s) V_v \quad \Rightarrow \quad V_o = -A(s) V_v - \beta A(s) V_o \\
V_v &= \alpha V_v + \beta V_o \quad \Rightarrow \quad V_o (1 + \beta A(s)) = -\alpha A(s) V_v \\
\therefore \quad \frac{V_o}{V_v}(s) &= -\frac{A(s)}{1 + \beta A(s)} \\
A(s) &= \frac{A_o}{1 + \frac{s}{2 A_o}} \quad \Rightarrow \quad \frac{V_o}{V_v}(s) = -\frac{A_o}{1 + \frac{s}{2 A_o}}
\end{align*}
\]