

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
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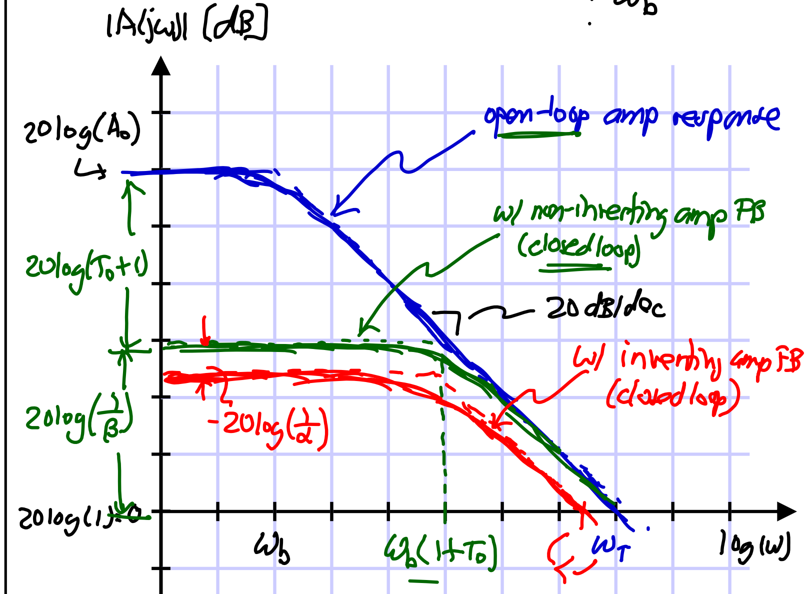
- Lecture Topics:
  - Closed Loop Amplifier Freq. Response Using Finite Gain-BW Op Amps
    - —Non-Inverting Amplifier
    - —Inverting Amplifier
- --
- Last Time:
- Non-inverting amplifier using finite gain-BW op amp
- Now, continue with this …

Non-Ideal Op Amps

Finite Op Amp Gain & Bandwidth

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

In reality, the gain goes as: $A(s) = \dfrac{A_o}{1+\frac{s}{\omega_b}}$



$\omega_T \triangleq$ unity gain frequency: freq. @ which $|A(j\omega)| = 1$ $(=0\,dB)$

At ω_T, $|A(j\omega_T)| = 1 = \dfrac{A_o}{\sqrt{1+\left(\frac{\omega_T}{\omega_b}\right)^2}} \Rightarrow \dfrac{A_o}{\frac{\omega_T}{\omega_b}} = 1 \rightarrow \boxed{\omega_T = A_o\omega_b}$

$[\omega_T \gg \omega_b]$

gain Bandwidth

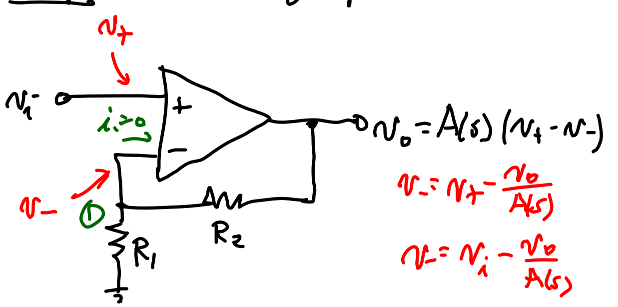
[For $\omega \gg \omega_b$] $\Rightarrow$ $A(s) = \dfrac{A_o}{\frac{s}{\omega_b}} = \dfrac{A_o\omega_b}{s} = \dfrac{\omega_T}{s} \Longrightarrow \dfrac{f_T}{f}$

ω_T in datasheets

(an op amp ultimately is an integrator w/ time constant $\tau = \frac{1}{\omega_T}$)

$\boxed{\text{Frequency Response of Closed Loop Amplifier}}$

Example. Non-Inverting Amplifier



$v_- = v_+ - \dfrac{v_o}{A(s)}$

$v_- = v_i - \dfrac{v_o}{A(s)}$

Find an expression for gain as a function of freq.

① Brute Force Determination:

KCL①: $\dfrac{v_o - v_-}{R_2} = \dfrac{v_-}{R_1} \rightarrow \dfrac{v_o}{R_2} = v_-\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right)$

$\dfrac{v_o}{R_2} = \left(v_i - \dfrac{v_o}{A(s)}\right)\left(\dfrac{1}{R_1} + \dfrac{1}{R_2}\right) \rightarrow \dfrac{v_o}{v_i}(s) = \dfrac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A(s)}\left(1 + \frac{R_2}{R_1}\right)}$

$\left[A(s) = \dfrac{A_o}{1 + \frac{s}{\omega_b}}\right]$ → *

* $\dfrac{v_o}{v_i} = \dfrac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A_o}\cancel{\left(1 + \frac{R_2}{R_1}\right)}} \; \dfrac{1}{1 + \dfrac{s}{\omega_b}\dfrac{\frac{1}{A_o}\left(1 + \frac{R_2}{R_1}\right)}{1 + \frac{1}{A_o}\cancel{\left(1 + \frac{R_2}{R_1}\right)}}}$ } finite gain & BW

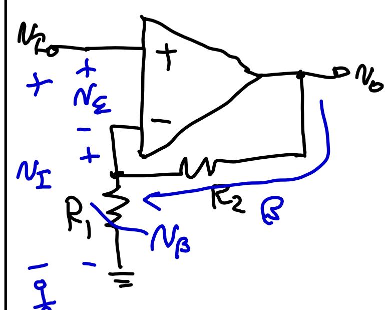
$\left[A_o = \text{large} \rightarrow \frac{1}{A_o}\left(1 + \frac{R_2}{R_1}\right) \ll 1\right]$ → Here, we're essentially saying that the op amp gain is close to ideal & that the non-ideality is mainly finite BW.

$$\boxed{\frac{v_o}{v_i}(s) = \left(1 + \frac{R_2}{R_1}\right)\frac{1}{1 + \dfrac{s}{A_o\omega_b\left(\frac{R_1}{R_1+R_2}\right)}}}$$

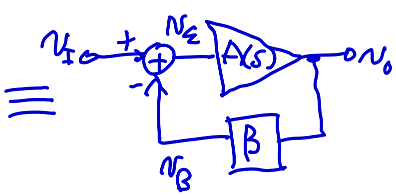
Near Ideal Gain, but Finite BW

$= \checkmark$ **

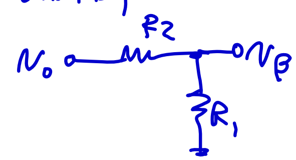
② More insightful way to do this.



$\equiv$



What is β?



$$\boxed{\beta = \frac{v_\beta}{v_o} = \frac{R_1}{R_1 + R_2}}$$

Recall of previous FB analysis:

$$\frac{v_o}{v_i}(s) = \frac{A(s)}{1+\beta A(s)}$$

$$\left[A(s) = \frac{A_o}{1+\frac{s}{\omega_b}}\right] \rightarrow \frac{v_o}{v_i}(s) = \frac{\frac{A_o}{1+\frac{s}{\omega_b}}}{1+\beta\left(\frac{A_o}{1+\frac{s}{\omega_b}}\right)}$$

$$\frac{v_o}{v_i}(s) = \underbrace{\frac{A_o}{1+\beta A_o}}_{\substack{\text{DC gain term}\\ \text{(midband gain)}}} \; \underbrace{\frac{1}{1+\frac{s}{\omega_b(1+\beta A_o)}}}_{\text{Frequency Shaping Term}}$$

$$\frac{A_o}{T_o+1} \qquad \uparrow \ \beta A_o$$

$T_o = \beta A_o \triangleq$ "loop gain" @ $\omega = 0$ (i.e., @ DC)

If $A_o \to \infty$ or if $\beta A_o >> 1$ } $\Rightarrow$ DC gain $= \frac{1}{\beta}$

Plug in β:

$$[\beta A_o >> 1] \Rightarrow \frac{v_o}{v_i}(s) \simeq \frac{1}{\beta}\,\frac{1}{1+\frac{s}{\omega_b \beta A_o}}$$

$$= \left(1+\frac{R_2}{R_1}\right)\frac{1}{1+\frac{s}{\omega_b A_o\left(\frac{R_1}{R_1+R_2}\right)}} \rightarrow **$$

Observations:

① Closed loop DC gain $= \frac{A_o}{1+\beta A_o} = \frac{A_o}{1+T_o} \approx \frac{A_o}{T_o}$ ↑ $[T_o >> 1]$

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 $\approx \frac{A_o}{\beta A_o} = \frac{1}{\beta}$ $[T_o >> 1]$

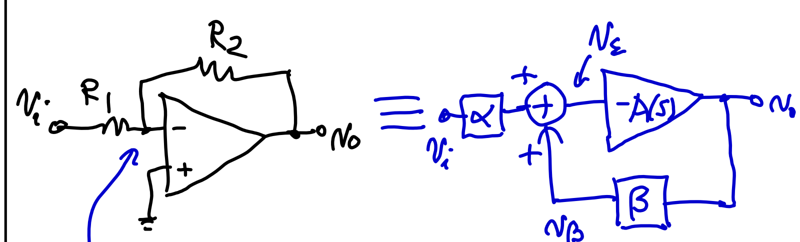
③ ω_{-3dB} has increased from $\omega_b \rightarrow \omega_b(1+A_o\beta) = \omega_b(1+T_o)$

↳ To draw the Bode plot, just find the dc gain, draw a horizontal line across, then follow the open loop response after running into it!

④ Gain-BW Product $= \frac{A_o}{1+\beta A_o}\,\omega_b(1+\beta A_o) = A_o\omega_b = \omega_T$

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

Example: Inverting Amplifier



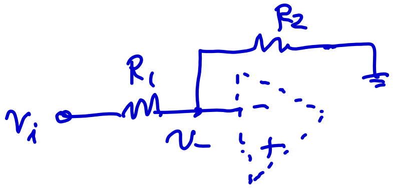
Signals from v_o & v_I sum here

how much of each appears depends on α & β

Determine α:

① Ground output & open loop

② Feed v_i forward to get T.F.

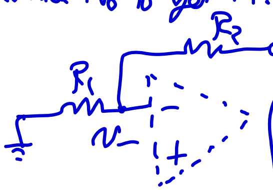


$$\boxed{\frac{v_-}{v_i}(s) = \frac{R_2}{R_1+R_2} = \alpha}$$

Determine β:

① Ground input, open loop

② Feedback v_o to get T.F.



$$\boxed{\frac{v_-}{v_o}(s) = \frac{R_1}{R_1+R_2} = \beta}$$

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

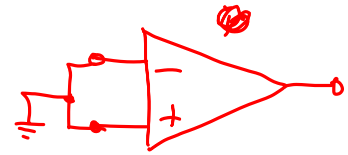
$$\left.\begin{aligned} v_o &= -A(s)v_\varepsilon \\ v_\varepsilon &= \alpha v_i + \beta v_o \end{aligned}\right\} \quad \begin{aligned} v_o &= -\alpha A(s)v_i - \beta A(s)v_o \\ v_o(1+\beta A(s)) &= -\alpha A(s)v_i \end{aligned}$$

$$\therefore \frac{v_o}{v_i}(s) = -\frac{\alpha A(s)}{1+\beta A(s)}$$

$$\left[A(s) = \frac{A_o}{1+\frac{s}{\omega_b}}\right] \Rightarrow \frac{v_o}{v_i}(s) = \frac{-\alpha\frac{A_o}{1+\frac{s}{\omega_b}}}{1+\frac{\beta A_o}{1+\frac{s}{\omega_b}}}$$

$$\boxed{\frac{v_o}{v_i}(s) = \frac{-\alpha A_o}{1+\beta A_o} \cdot \frac{1}{1+\frac{s}{\omega_b(1+\beta A_o)}}}$$

V_{OS} for Lab:



$v_o = A(s)(v_+ - v_-) =$ expect $= 0V$

But actually get $\neq 0V$

↓ non-ideal