

• Today:

- ↪ Methods for Compensation
- ↪ Review of Pole/Zero Plots
- ↪ CMOS Op Amp Compensation

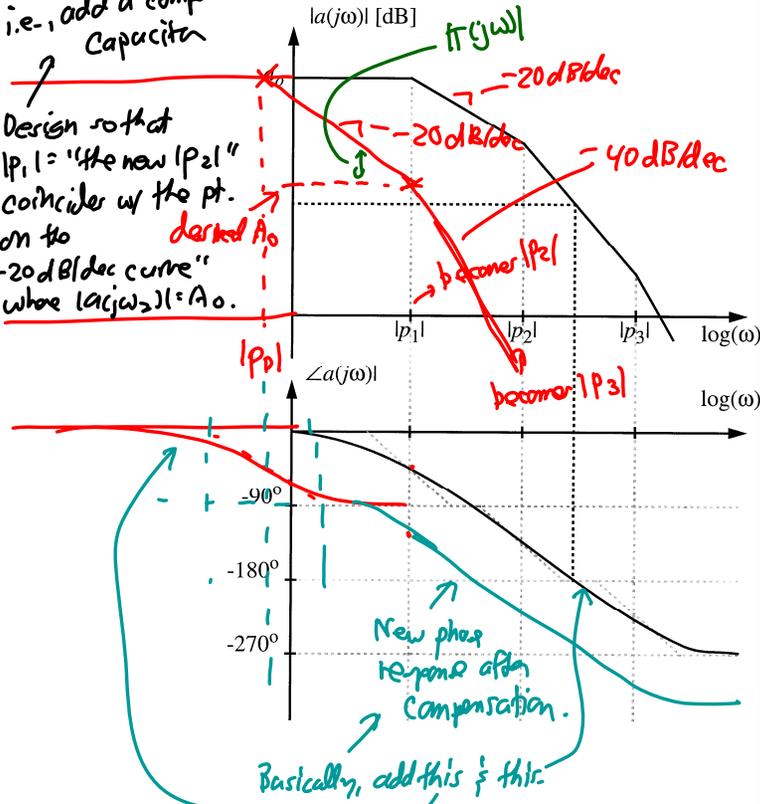
Last Time -

Narrowbanding

→ introduce a pole  $p_D$  so that there is sufficient separation between  $p_D$  &  $p_1$

i.e., add a compensation capacitor

Design so that  $|p_1| = \text{"the new } |p_2| \text{"}$  coincide w/ the pt. on the "20 dB/dec curve" where  $|a(j\omega_0)| = A_0$ .



Remarks on Narrowbanding

- ① Assumption:  $p_1, p_2, p_3$  don't move when  $p_D$  is introduced (often not true, but that movement isn't that big)
- ② Summarize: choose  $p_D$  such that  $|T(j\omega)| = 0\text{dB} = 1$  @  $p_1$  (which becomes the 2nd most dominant pole)  $PM = 45^\circ$  original ( $\text{for } |p_2| \gg |p_1|$ )
- ③ Why do this? Isn't pole-splitting much better? Do it when you have no other choice, e.g., when you have a packaged op amp & have access to only a few terminals (not to the optimum compensation node)

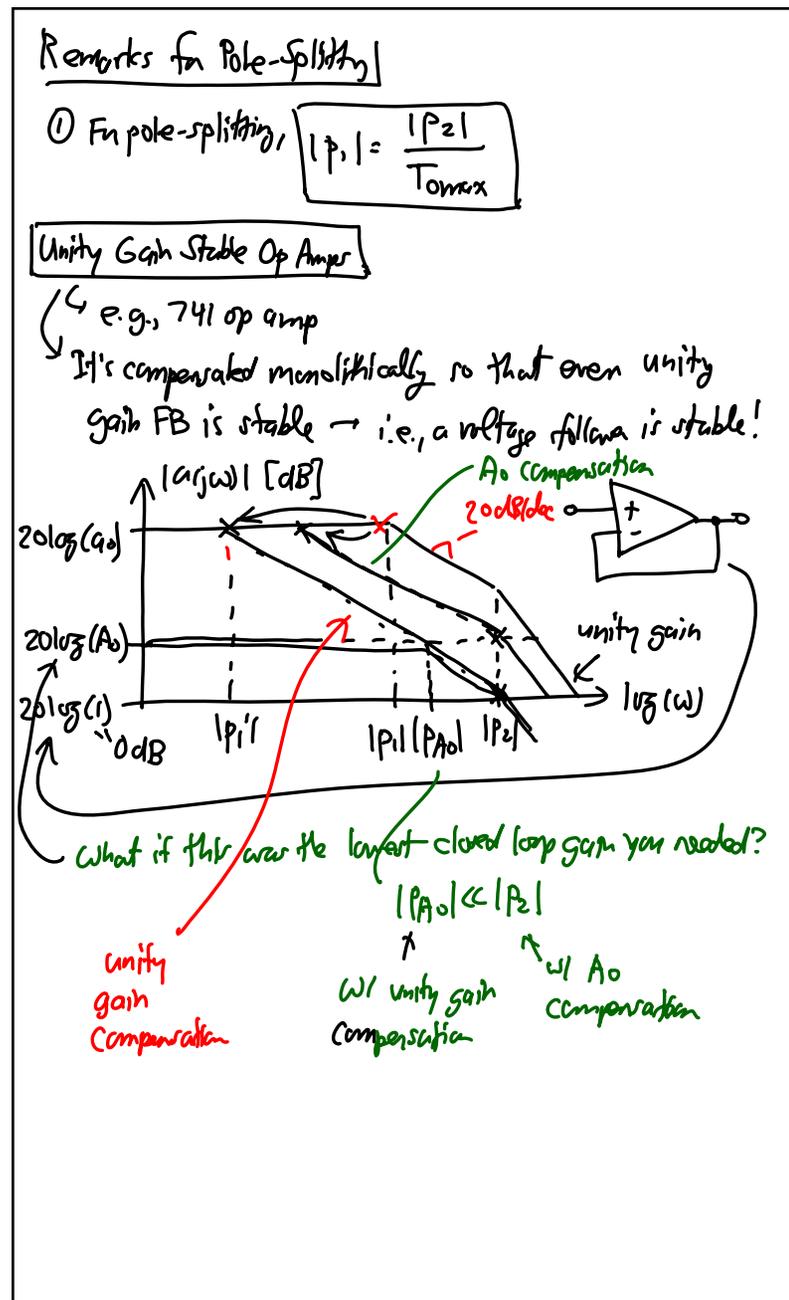
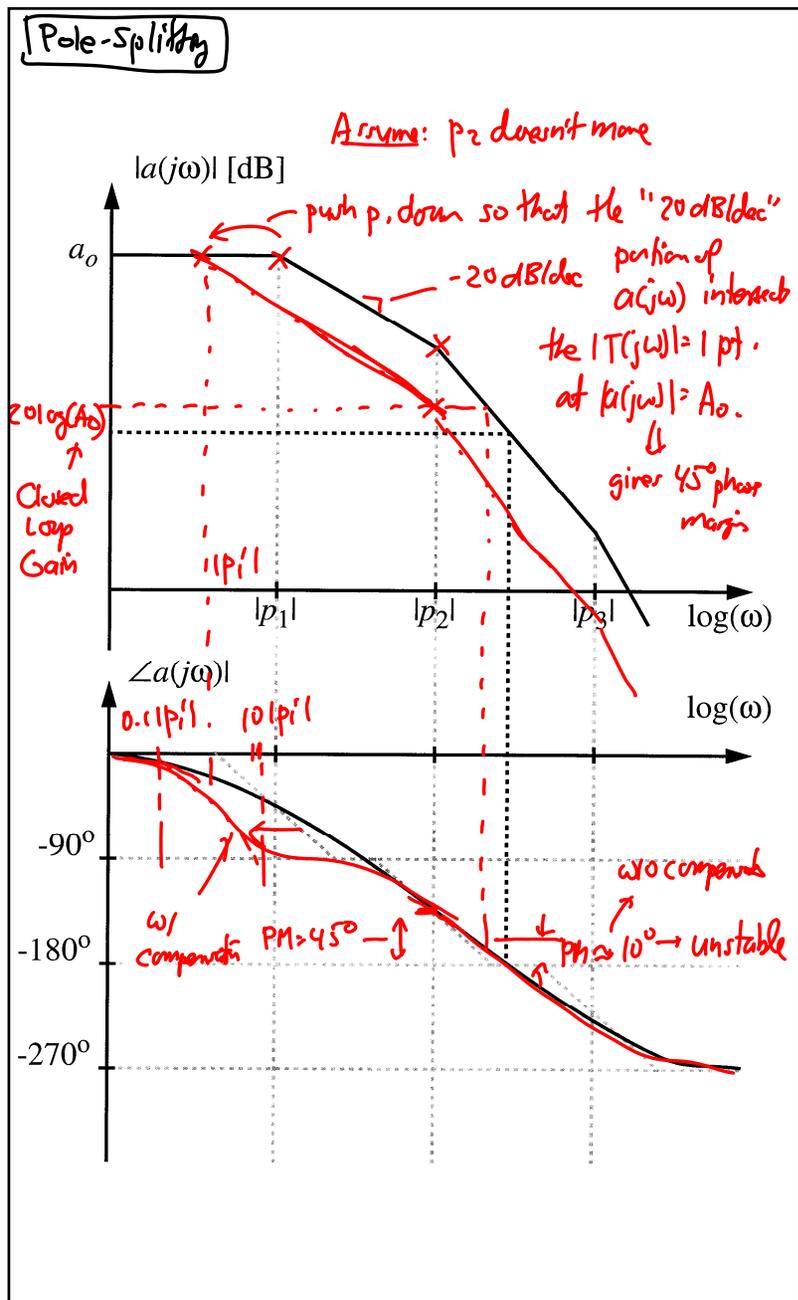
④  $|p_D| = \frac{|p_1|}{T_{max}}$  ← maximum expected/needed loop gain

Problem:

- ① often,  $|p_D| \ll |p_1| \therefore f_{-3dB}$  BW of the op amp will be very small
- ②  $\omega_{closed\ loop} = |p_1|$  which isn't that large

Solution: Pole-Splitting

- ↪ move  $|p_1|$  down & either keep  $|p_2|$  still or move  $|p_2|$  up simultaneously
- ↪ after doing this:
  - ①  $\omega_{-3dB} = |p_1|'$
  - ②  $\omega_{closed\ loop} = |p_2|'$



**Choosing  $C_c$**  (assume no RHP zeros &  $|p_3| \gg |p_2|$ )  
 $\Rightarrow$  assume  $\frac{1}{sC_c} \ll$  (surrounding resistances) @ high freq.

① Case: Two-stage Amplifier, Miller Compensation

of op amp of the ground  
 transconductance  $\rightarrow N \rightarrow i$  gain

"virtual ground"

$N_2 = \frac{i_x}{sC_c}$

$a_2 = (-)$

gain of  $a_2$

$i_o = Gm_1 N_1 i$

ideal:  $R_s = 0$

ideal:  $R_L = \infty$

"closer to  $\infty$  than to 0"

$N_2 = \frac{i_x}{sC_c}$

$i_x = Gm_1 N_1 i$

$N_2 = \frac{Gm_1}{sC_c} N_1 i \rightarrow \frac{N_2}{N_1}(s) = \frac{Gm_1}{sC_c}$

This doesn't work for

$\left| \frac{N_2}{N_1}(j\omega) \right|$  [dB]

$A_0$

$|p_2|$

$\hookrightarrow$  for PM=45°

care only about this region

$\left| \frac{N_2}{N_1}(j\omega) \right| = \frac{Gm_1}{\omega C_c} \Rightarrow$  this should equal  $A_0$  @ the freq.  $\omega$  corresponding to the target phase margin

For PM=45°:

$\omega_{ulg} = \omega @ |T(j\omega)| = 1$

"ulg" = "unity loop gain"

For PM=45°  $\rightarrow \omega_{ulg} = \omega_2 \leftarrow$  freq. of the 2nd pole in the  $a(j\omega)$  transfer function

$\left| \frac{N_2}{N_1}(j\omega_2) \right| = A_0 = \frac{Gm_1}{\omega_2 C_c}$

$C_c = \frac{Gm_1}{\omega_2 A_0} \leftarrow$  For PM=45° (provided high-order poles are far away, i.e.,  $|p_3| \gg |p_2|$ )

The frequency response of a given system is completely characterized by knowledge of the poles, zeros, and dc gain factor ( $H_0$ ) of the system in question. In fact, the magnitude & phase of the network can be determined graphically from a pole/zero diagram.

$$H(s) = \frac{(s - \sigma_z)}{(s - \sigma_p - j\omega_p)(s - \sigma_p + j\omega_p)}$$

$$z_1 = \sigma_z$$

$$p_1 = \sigma_p + j\omega_p \quad p_2 = \sigma_p - j\omega_p$$

$\angle = \tan^{-1}\left(\frac{\omega}{-\sigma_z}\right)$   
 $\angle = \tan^{-1}\left(\frac{\omega - \omega_p}{-\sigma_p}\right) = \tan^{-1}\left(\frac{\omega + \omega_p}{-\sigma_p}\right)$   
 $\therefore |H(j\omega)| = \frac{\sqrt{\omega^2 + \sigma_z^2}}{\sqrt{(\omega - \omega_p)^2 + \sigma_p^2} \sqrt{(\omega + \omega_p)^2 + \sigma_p^2}}$   
 $\therefore \angle H(j\omega) = \tan^{-1}\left(\frac{\omega}{-\sigma_z}\right) - \tan^{-1}\left(\frac{\omega - \omega_p}{-\sigma_p}\right) - \tan^{-1}\left(\frac{\omega + \omega_p}{-\sigma_p}\right)$

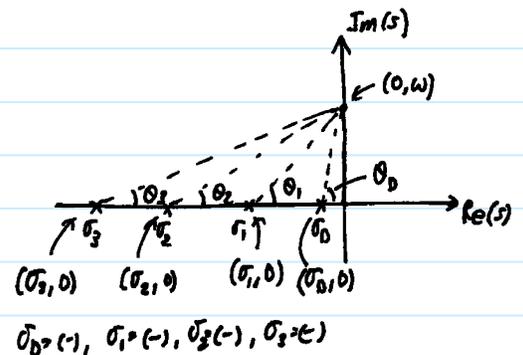
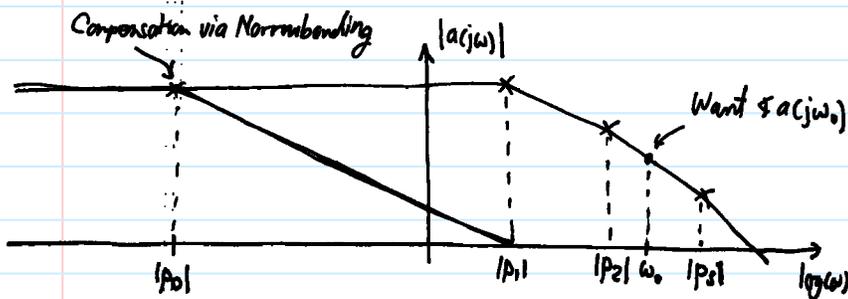
In general:

$$|H(j\omega)| = H_0 \frac{\prod_{j=1}^m (\text{mag. of vectors from zeros to } j\omega)}{\prod_{i=1}^n (\text{mag. of vectors from poles to } j\omega)} = H_0 \frac{\prod_{j=1}^m |j(\omega - \omega_{zj}) - \sigma_{zj}|}{\prod_{i=1}^n |j(\omega - \omega_{pi}) - \sigma_{pi}|}$$

$$\angle H(j\omega) = \sum \text{angles from zeros} - \sum \text{angles from poles} + \angle H_0$$

$z_j = \sigma_{zj} + j\omega_{zj}$   
 $p_i = \sigma_{pi} + j\omega_{pi}$   
 $\angle H_0$  could be  $0^\circ$  or  $180^\circ$   
 $(-)$   $(+)$

Precise Determination of Phase



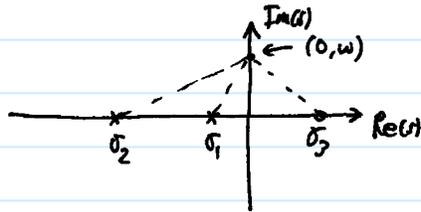
$$\angle a(j\omega) = -\theta_0 - \theta_1 - \theta_2 - \theta_3$$

$$= -\tan^{-1}\left(\frac{\omega}{-\sigma_0}\right) - \tan^{-1}\left(\frac{\omega}{-\sigma_1}\right) - \tan^{-1}\left(\frac{\omega}{-\sigma_2}\right) - \tan^{-1}\left(\frac{\omega}{-\sigma_3}\right)$$

$$\therefore \angle a(j\omega_0) = -90^\circ - 90^\circ - \tan^{-1}\left(\frac{\omega_0}{|p_1|}\right) - \tan^{-1}\left(\frac{\omega_0}{|p_3|}\right)$$

since  $\omega_0 \gg |p_1| \ \& \ |p_3|$

Ex: System w/ 2 poles & 1 RHP zero



$\sigma_1 = (-)$      $\sigma_2 = (-)$  since it's a zero!

$$\angle H(j\omega) = -\tan^{-1}\left(\frac{\omega}{-\sigma_1}\right) - \tan^{-1}\left(\frac{\omega}{-\sigma_2}\right) + \tan^{-1}\left(\frac{\omega}{-\sigma_3}\right)$$

$$= -\tan^{-1}\left(\frac{\omega}{|\sigma_1|}\right) - \tan^{-1}\left(\frac{\omega}{|\sigma_2|}\right) + \tan^{-1}\left(-\frac{\omega}{|\sigma_3|}\right)$$

$\angle H(j\omega) = -90^\circ - 90^\circ + (-90^\circ) \Rightarrow \angle H(j\omega) = -270^\circ$

$\omega \rightarrow \infty$

$$|H(j\omega)| = \frac{\sqrt{\omega^2 + \sigma_3^2}}{\sqrt{\omega^2 + \sigma_1^2} \sqrt{\omega^2 + \sigma_2^2}}$$

Note: The RHP zero contributes a (-) phase shift!

