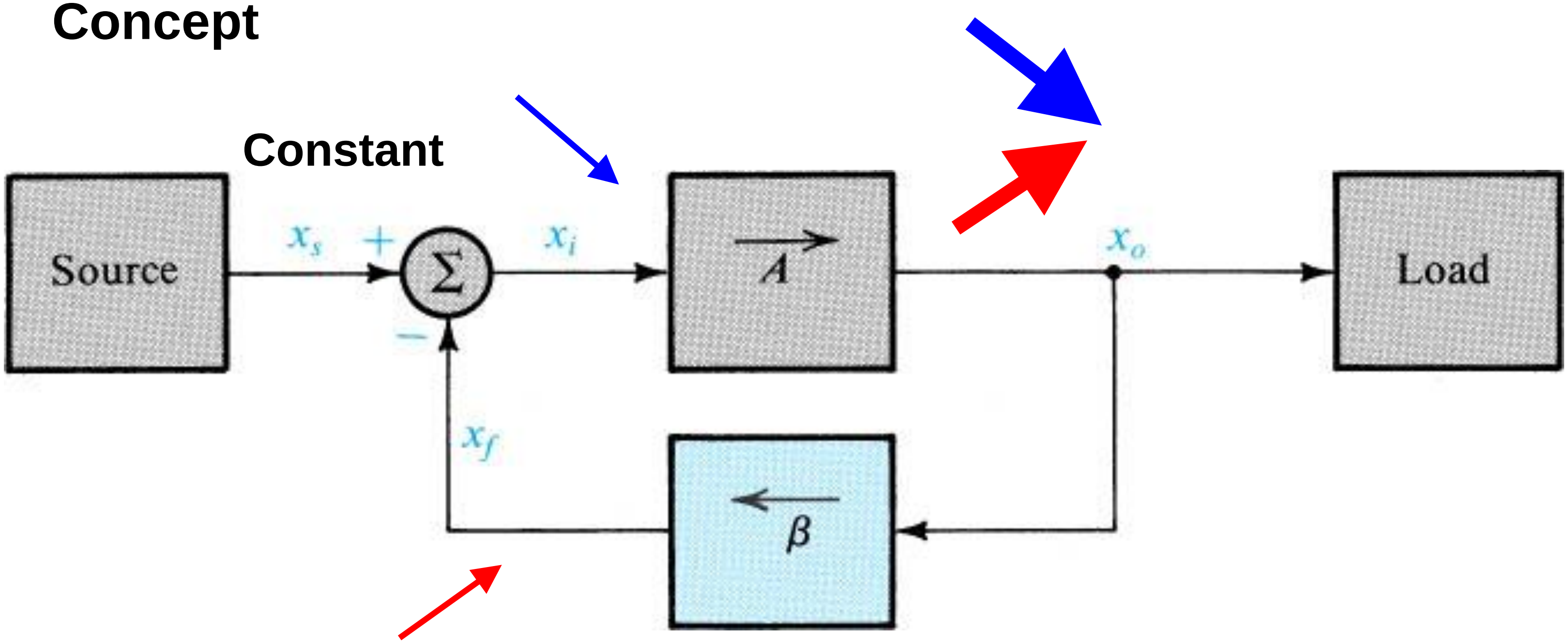
Chapter 10 Feedback

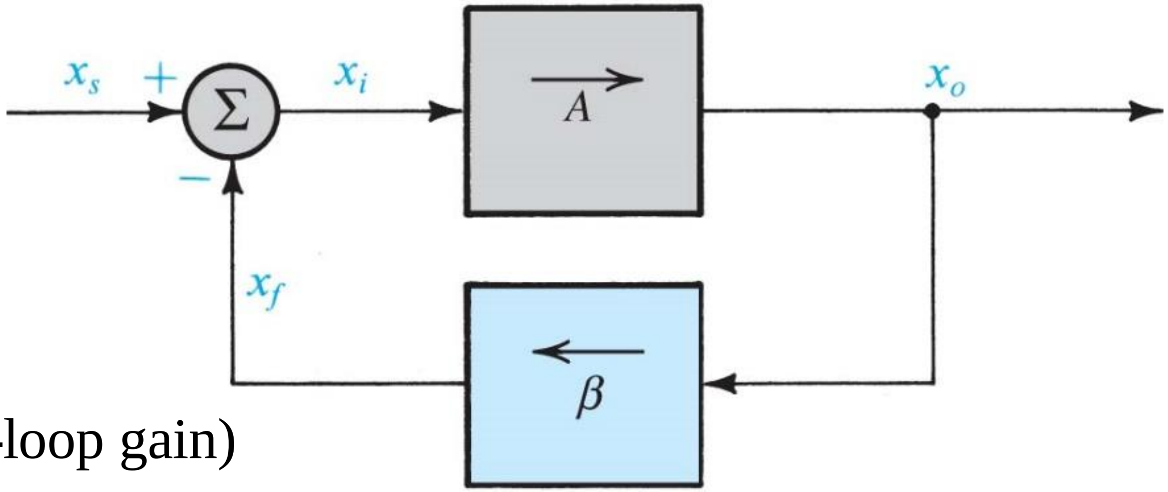
10.1 The General Feedback Structure
10.2 Some Properties of Negative Feedback
10.7 The Stability Problem
10.8 Effect of Feedback on the Amplifier Poles
10.9 Stability Study Using Bode Plots
10.10 Frequency Compensation

Concept



- Assume Xo increases in magnitude →Xf increases, too →Xi decreases →Xo decreases
- In the steady state, Xo will be constant, too.

10.1 The General Feedback Structure
10.1.1 Signal Flow Graph 10.1.2 The Closed-Loop Gain



$x_o = A \cdot x_i$ (A: open-loop gain)

Let $x_f = \beta x_o$, β feedback factor

$\Rightarrow$ $x_i = x_s - x_f$ (x_i: error signal)

by $x_o = A \cdot (x_s - \beta x_o)$

$\Rightarrow$ closed-loop gain $A_f \equiv \frac{x_o}{x_s} = \frac{A}{1+\beta A}$

where A : the open-loop gain;

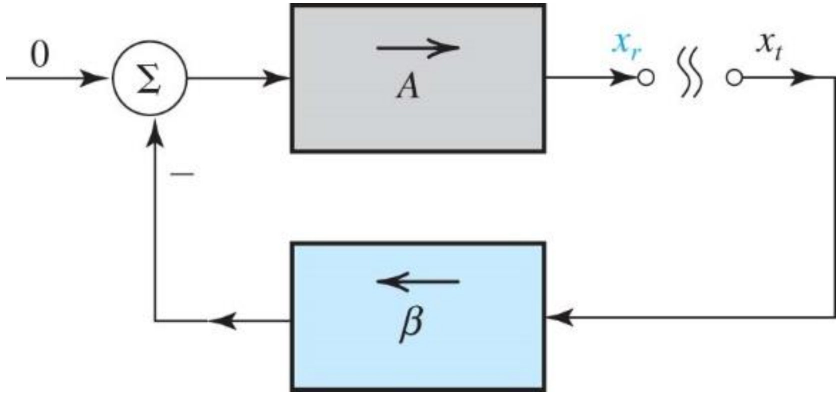
$\beta \cdot A$: loop gain

$1+\beta \cdot A$: amount of feedback

if $\beta \cdot A >> 1$

$\Rightarrow$ $A_f \approx \frac{1}{\beta}$ (independent of A !)

10.1.3 Loop Gain



1. Let $x_s = 0$

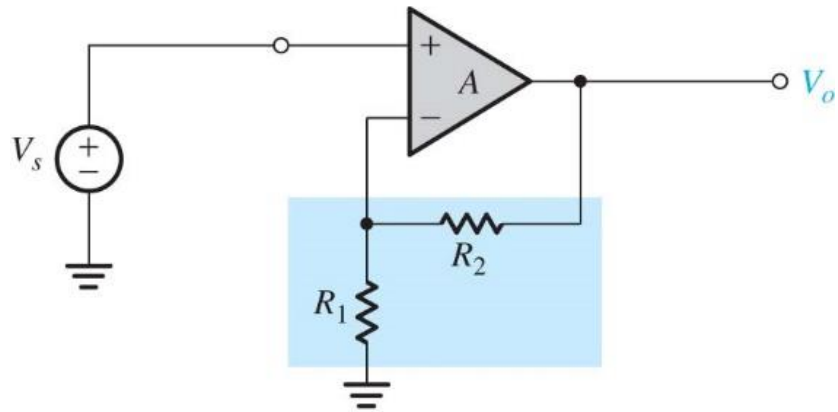
2. $x_r = -\beta \cdot A \cdot x_t$

(negative feedack $\Rightarrow$ x_r and x_t are out of phase)

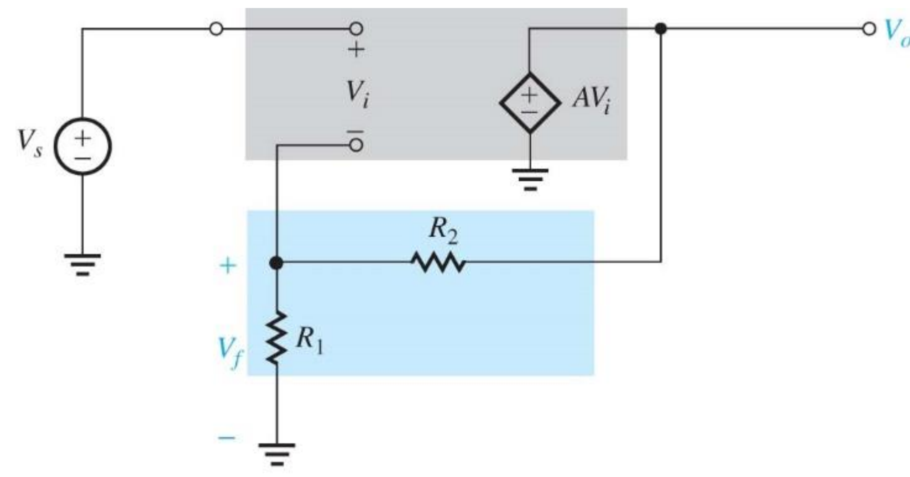
3. $\beta \cdot A \equiv -\dfrac{x_r}{x_t}$

($\beta \cdot A$ is positive for negative feedback systems)

Example 10.1



(a)



(b)

$$\beta = \frac{V_f}{V_o} = \frac{R_1}{R_1 + R_2}$$

$$A_f = \frac{A}{1 + A\beta}$$

(a) If $A=10^4$ and $A_f = 10 \Rightarrow$ find R_2 / R_1?

If $A\beta >> 1 \Rightarrow A_f \approx 1/\beta \Rightarrow \frac{R_1 + R_2}{R_1} = 10$

$$\Rightarrow \frac{R_2}{R_1} = 9$$

Exactly $\beta = 0.0999$

$$\Rightarrow \frac{R_2}{R_1} = 9.01$$

(b)if A is reduced by 20%; $A=0.8 \cdot 10^4$

$$A_f = \frac{A}{1 + A\beta}$$

$$= \frac{0.8 \cdot 10^4}{1 + 0.8 \cdot 10^4 \cdot 0.0999} = 9.9975 \quad V/V$$

$\therefore A_f \quad 10 \Rightarrow 9.9975 \Rightarrow 0.025\%$

Table 10.1 Summary of the Parameters and Formulas for the Ideal Feedback-Amplifier Structure of Fig. 10.1

- Open-loop gain $\equiv A$
- Feedback factor $\equiv \beta$
- Loop gain $\equiv A\beta$ (positive number)
- Amount of feedback $\equiv 1 + A\beta$
- Closed-loop gain $\equiv A_f = \dfrac{x_o}{x_s} = \dfrac{A}{1 + A\beta}$
- Feedback signal $\equiv x_f = \dfrac{A\beta}{1 + A\beta} x_s$
- Input signal to basic amplifier $\equiv x_i = \dfrac{1}{1 + A\beta} x_s$
- Closed-loop gain as a function of the ideal value $\dfrac{1}{\beta}$: $A_f = \left(\dfrac{1}{\beta}\right) \dfrac{1}{1 + 1/A\beta}$
- For large loop gain, $A\beta \gg 1$,

$$A_f \simeq \frac{1}{\beta} \qquad x_f \simeq x_s \qquad x_i \simeq 0$$

10.2 Some Properties of Negative Feedback

1. **Desensitize the gain** : make the gain insensitive to temperature effect.
2. **Reduce nonlinear distortion** : make the gain constant.
3. **Reduce the effect of noise** : minimize the unwanted noise.
4. **Control the input and output impedances** : e.g. increase i/p impedance
   decrease o/p impedance.
5. **Extend the bandwidth of the amplifier**.

All the desirable properties are at the expense of a **reduction in gain**.

The gain reduction factor→ **amount of feedback**

So, negative feedback→ tradeoff gain for the desirable properties

10.2.1 Gain Desensitivity:

Since $A_f = \dfrac{A}{1+\beta A}$

$$\frac{dA_f}{dA} = \frac{1}{1+\beta\cdot A}\cdot 1 + A\cdot\frac{d}{dA}\left(\frac{1}{1+\beta\cdot A}\right)$$

$$= \frac{1}{1+\beta\cdot A} - \frac{\beta\cdot A}{(1+\beta\cdot A)^2}$$

$$= \frac{1}{(1+\beta\cdot A)^2}$$

$\Rightarrow$

$$\frac{dA_f}{A_f} = \frac{1}{1+\beta\cdot A}\cdot\frac{dA}{A}$$ (Note: $\dfrac{dA}{A}$ is the gain variation)

$1+\beta\cdot A$ is known as desensitivity factor

10.2.2 Bandwidth Extension:

An amplifier which has a single pole:

$$\mathrm{A(s)} = \frac{\mathrm{A_M}}{1+\frac{s}{\omega_H}}$$

and

$$A_f(s) = \frac{A(s)}{1+\beta \cdot A(s)} = \frac{\frac{\mathrm{A_M}}{1+\frac{s}{\omega_H}}}{1+\beta \cdot \frac{\mathrm{A_M}}{1+\frac{s}{\omega_H}}} = \frac{A_M}{1+\beta \cdot A_M} \cdot \frac{1}{1+\frac{s}{\omega_H(1+\beta \cdot A_M)}}$$

the midband gain of the feedback amplifier is $\frac{A_M}{1+\beta \times A_M}$;

the equivalent upper-3dB frequency is $\omega_{\mathrm{Hf}} = \omega_H(1+\beta \cdot A_M)$

Bandwidth Extension: (cont.)

the upper 3-dB frequency becomes

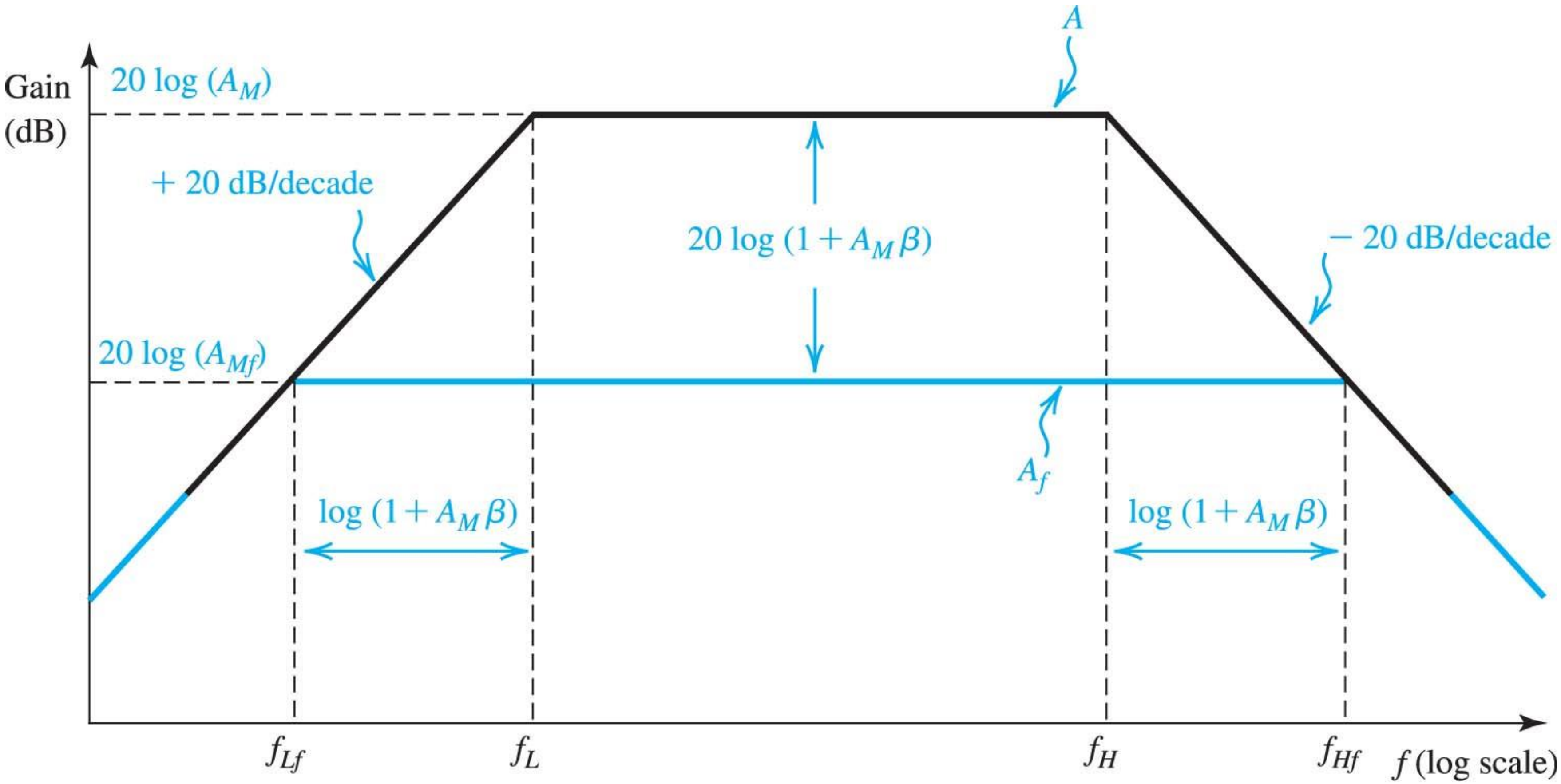
$$\omega_{\mathrm{Hf}} = \omega_H (1 + \beta \cdot A_M)$$

Simialrly, the lower 3-dB frequency becomes

$$\omega_{Lf} = \frac{\omega_L}{1 + \beta \cdot A_M}$$

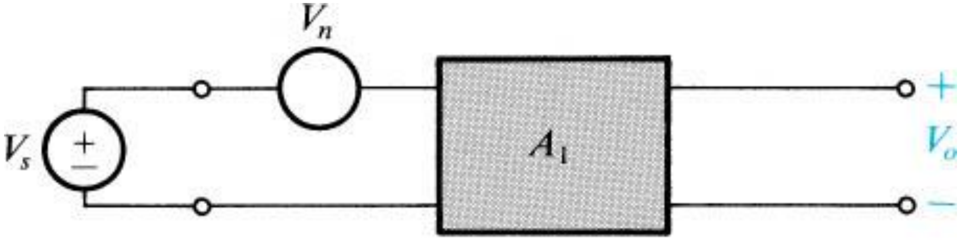
while the gain-bandwidth product is a constant value.

$$\mathrm{A(s)} = \frac{\mathrm{A_M}}{1 + \frac{\omega_L}{s}} \Rightarrow A_f(s) = \frac{A(s)}{1 + \beta \cdot A(s)} \Rightarrow \omega_{Lf} = \frac{\omega_L}{1 + \beta \cdot A_M}$$



$$f_{Lf} = \frac{f_L}{1 + A_M\beta} \qquad A_{Mf} = \frac{A_M}{1 + A_M\beta} \qquad f_{Hf} = f_H(1 + A_M\beta)$$

•10.2.3 Interference Reduction:



(a)

Signal-to-noise ratio $S/N = V_s/V_n$

•Using a "clean" amplifier stage precede the noisy stage!
e.g. low-noise amplifier (LNA)

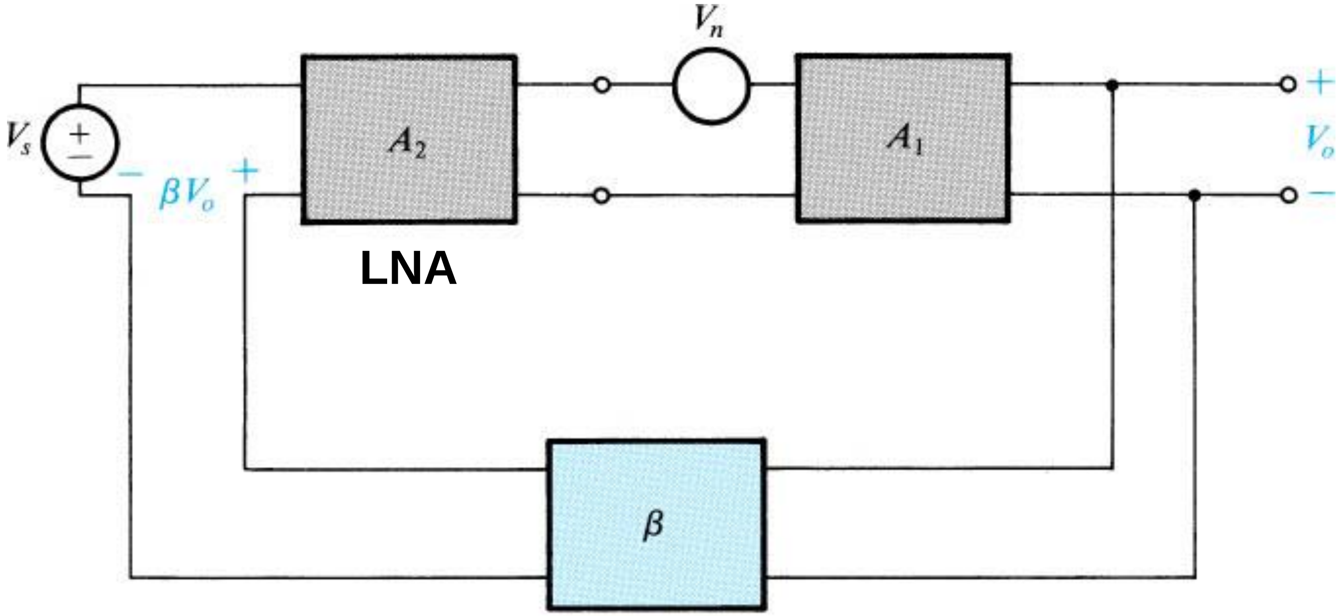
Noise Reduction:

$$V_o = V_s \cdot \frac{A_1 A_2}{1+\beta \cdot A_1 A_2} + V_n \frac{A_1}{1+\beta \cdot A_1 A_2}$$

$$\Rightarrow \quad \frac{S}{N} = \frac{V_s}{V_n} A_2$$

Ex. In audio application:
Power-supply hum issue.

Pre-amplifier + Power Amplifier!

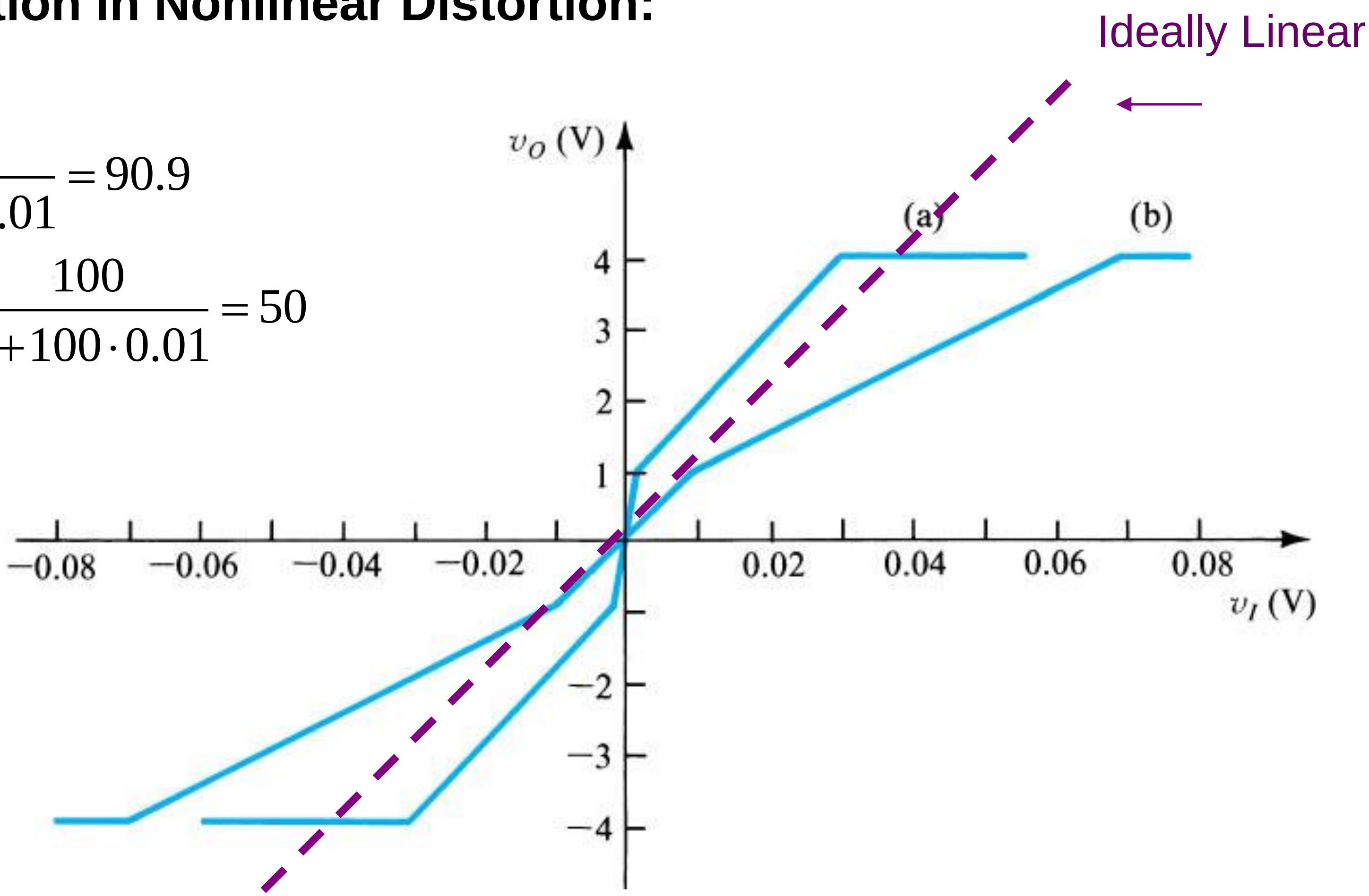


(b)

10.2.4 Reduction in Nonlinear Distortion:

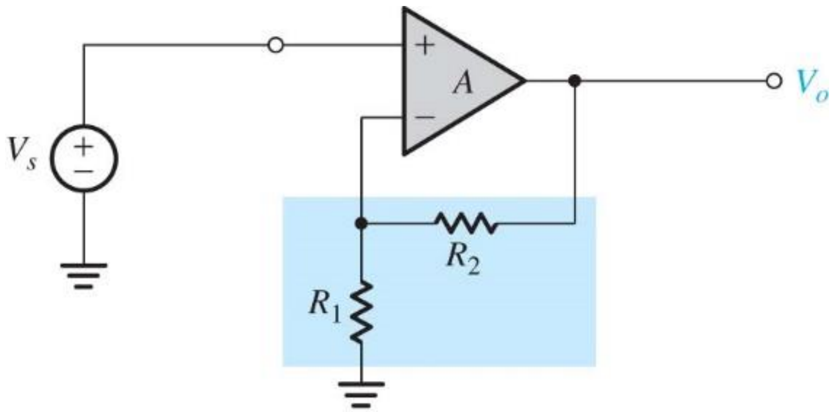
$$A_{f,b1} = \frac{1000}{1+1000 \cdot 0.01} = 90.9$$

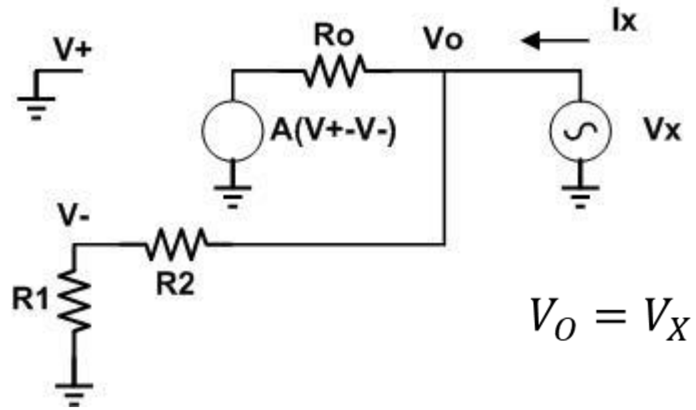
$$A_{f,b2} = \frac{A}{1+\beta A} = \frac{100}{1+100 \cdot 0.01} = 50$$



Illustrating the application of negative feedback to reduce the nonlinear distortion in amplifiers. Curve (a) shows the amplifier transfer characteristic without feedback. Curve (b) shows the characteristic with negative feedback ($\beta = 0.01$) applied.

4. Control the input and output impedances





$$I_X = \frac{V_X - A(V_+ - V_-)}{R_O} + \frac{V_X}{R_1 + R_2} = \frac{V_X - A(0 - \frac{R_1}{R_1 + R_2} V_X)}{R_O} + \frac{V_X}{R_1 + R_2}$$

$$\Rightarrow \frac{V_X}{I_X} = \frac{R_O}{1 + A\frac{R_1}{R_1 + R_2} + \frac{R_O}{R_1 + R_2}} \approx \frac{R_O}{1 + A\frac{R_1}{R_1 + R_2}}$$

$$\Rightarrow \frac{V_X}{I_X} = \frac{R_O}{1 + A\beta}, \quad \beta = \frac{R_1}{R_1 + R_2}$$

10.7 The Stability Problem
10.7.1 Transfer Function of the Feedback Amplifier

A(s) open-loop transfer function

A_f (s) closed-loop transfer function

β(s) feedback transfer function

$$A_f(s) = \frac{A(s)}{1+\beta(s)\cdot A(s)}$$

$$A_f(j\omega) = \frac{A(j\omega)}{1+\beta(j\omega)\cdot A(j\omega)} = \frac{A(j\omega)}{1+L(j\omega)} \quad \text{and} \quad L(j\omega) = \left|\beta(j\omega)\cdot A(j\omega)\right|\cdot e^{j\,\varphi(\omega)}$$

at DC, L=β · A should be a positive number (∵ negative feedback);

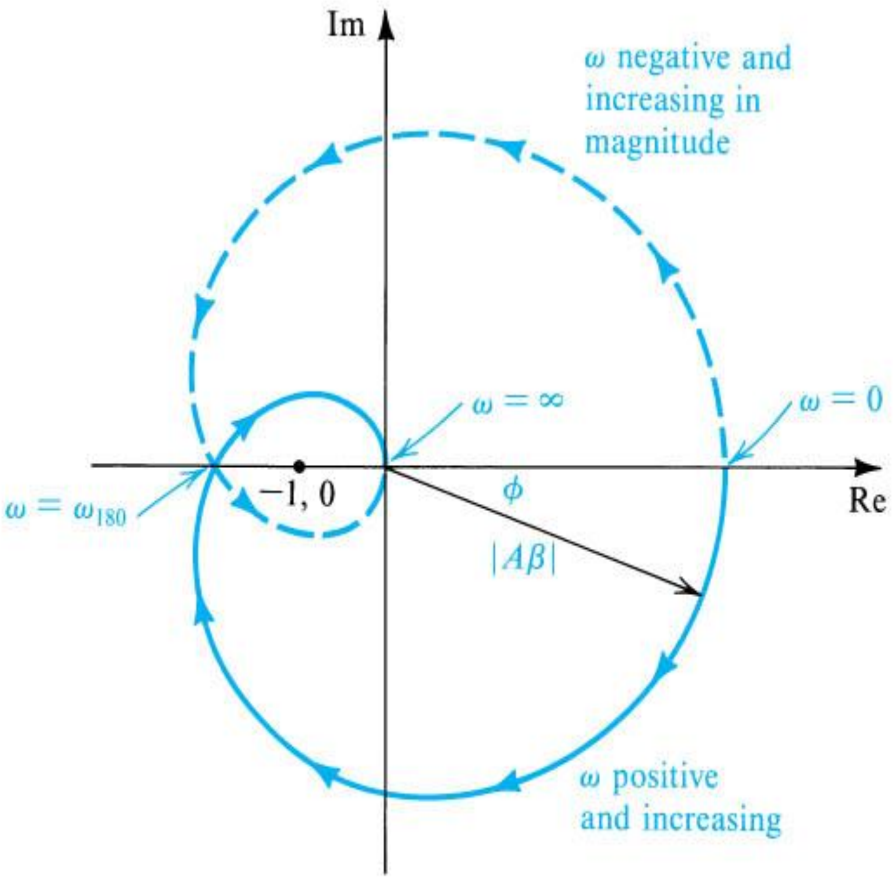
at $\omega = \omega_{180}$, $\phi(j\omega_{180}) = 180^{o}$

$\beta(j\omega_{180})\cdot A(j\omega_{180})$ is real and negative

1. $\left|\beta(j\omega_{180})\cdot A(j\omega_{180})\right| < 1$, **feedback is positive & system is stable**
2. $\beta(j\omega_{180})\cdot A(j\omega_{180}) = -1$, **oscillator (∵ 1+βA=0)**
3. $\left|\beta(j\omega_{180})\cdot A(j\omega_{180})\right| > 1$, **oscillations will grow in amplitude**

10.7.2 The Nyquist Plot

- **How to check at some ω such that |L(jω)|=1 and ϕ=180º.**
- **The Nyquist plot → the polar plot of loop gain (vs. frequency)**



The Loop Gain:

$$L(j\omega) = \left|\beta(j\omega)\cdot A(j\omega)\right|\cdot e^{j\phi(\omega)}$$

The Nyquist plot intersects the negative real axis at frequency ω_{180°.

The Nyquist plot of an unstable amplifier.

10.8. Effect of Feedback on Amplifier Poes

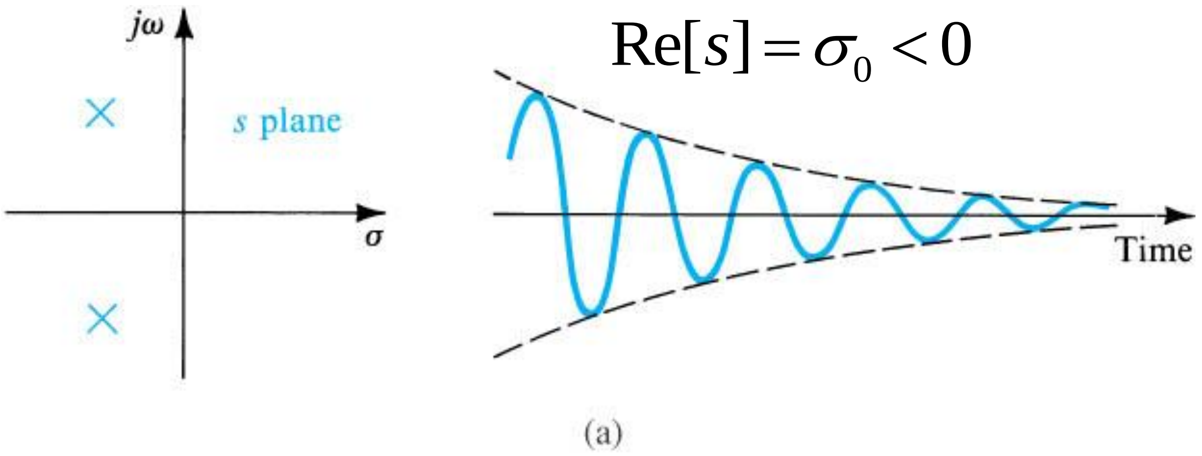
10.8.1 Stability and Pole Location

Consider an amplifier with a pole pair at $s = \sigma_0 \pm j\,\omega_n$

After a disturbance,

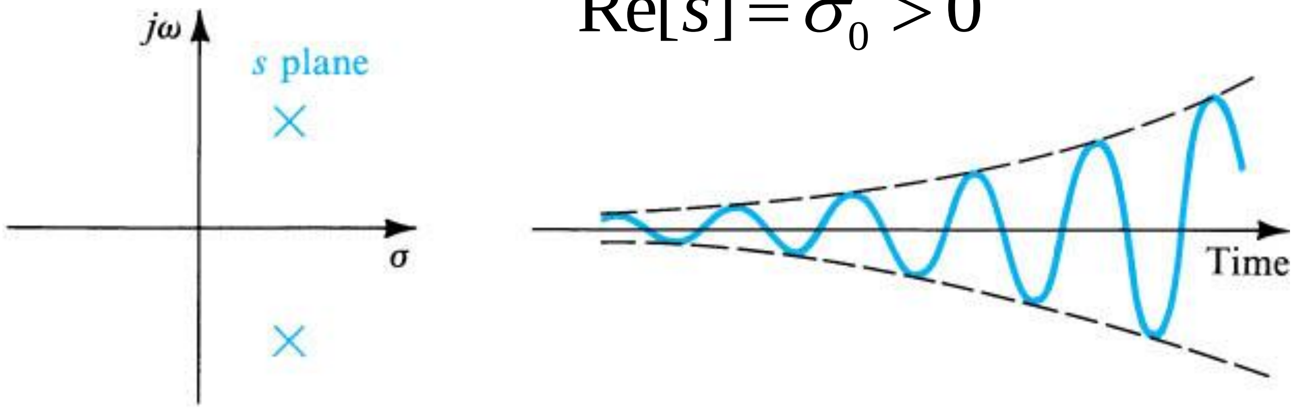
$$v(t) = e^{\sigma_0 t}[e^{+j\omega_n t} + e^{-j\omega_n t}] = 2\,e^{\sigma_0 t}\,\cos(\omega_n t)$$

$$\mathrm{Re}[s] = \sigma_0 < 0$$



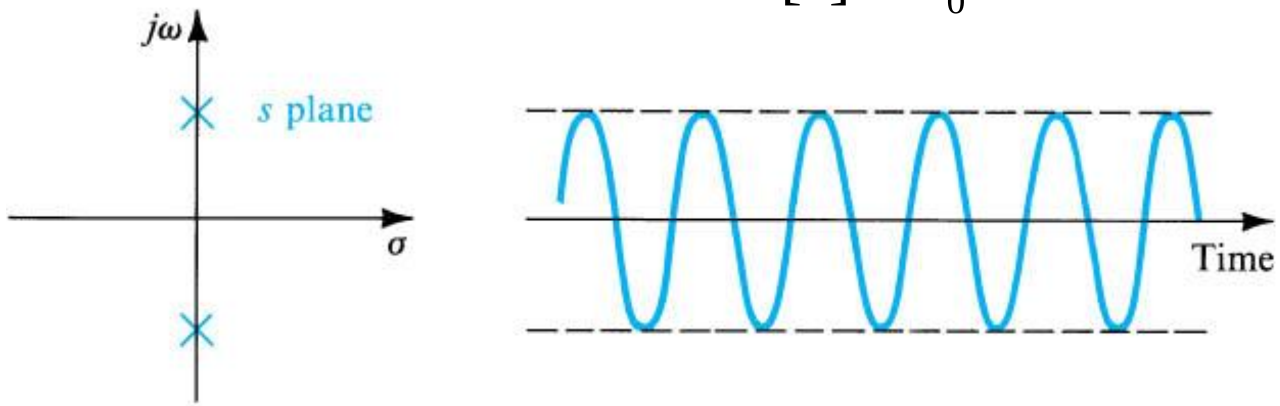
Relationship between pole location and transient response.

$$\mathrm{Re}[s] = \sigma_0 > 0$$



(b)

$$\mathrm{Re}[s] = \sigma_0 = 0$$



(c)

Relationship between pole location and transient response.

10.8.2 Poles of the Feedback Amplifier

The characteristic equation of the feedback loop:

$$1+\beta(\mathrm{s})\cdot \mathrm{A}(\mathrm{s})=0$$

zeros of the characteristic equation $\Rightarrow$ poles of the feedback amplifier.

$$(\because \quad A_f = \frac{A(s)}{1+\beta(s)\times A(s)} \quad \Leftrightarrow \quad \frac{zeros}{poles})$$

10.8.3 Amplifier with a Single-Pole Response

open-loop transfer function : $\mathrm{A(s)} = \dfrac{\mathrm{A}_0}{1+\dfrac{\mathrm{s}}{\omega_\mathrm{p}}}$

closed-loop transfer function: $\mathrm{A_f}(s) = \dfrac{\dfrac{A_0}{1+\beta\cdot A_0}}{1+\dfrac{s}{\omega_p(1+\beta\cdot A_0)}}$

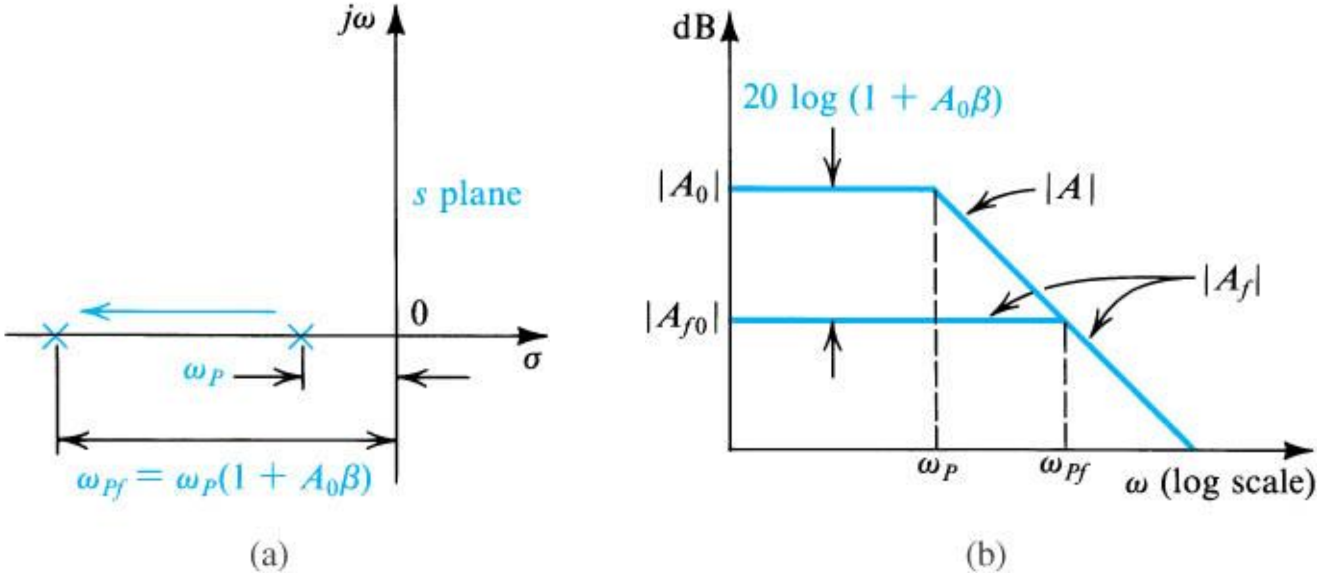
$\Rightarrow$ The feedback moves the pole along the negative real axis to a frequency $\omega_{\rm pf}$, $\omega_{pf} = \omega_p(1+\beta \cdot A_0)$

$\Rightarrow$ At lower frequency, the gain reduction is

$$20\log(A_0) - 20\log(A_f) = 20\log(\frac{A_0}{A_f}) = 20\log(1+\beta \cdot A_0)$$

When $\omega >> \omega_p(1+\beta \cdot A_0)$, $A_f(s) \approx A(s)$ is the voltage gains.

For any β, this amplifier is unconditionally stable.



Effect of feedback on **(a)** the pole location and **(b)** the frequency response of an amplifier having a single-pole open-loop response.

10.8.4 Amplifier with a Two-Pole Response

The open-loop transfer function :

$$\mathrm{A(s)} = \frac{\mathrm{A}_0}{(1+\dfrac{\mathrm{s}}{\omega_{\mathrm{p1}}})(1+\dfrac{\mathrm{s}}{\omega_{\mathrm{p2}}})}$$

The closed-loop poles obtained from $1+\beta \cdot \mathrm{A(s)} = 0$

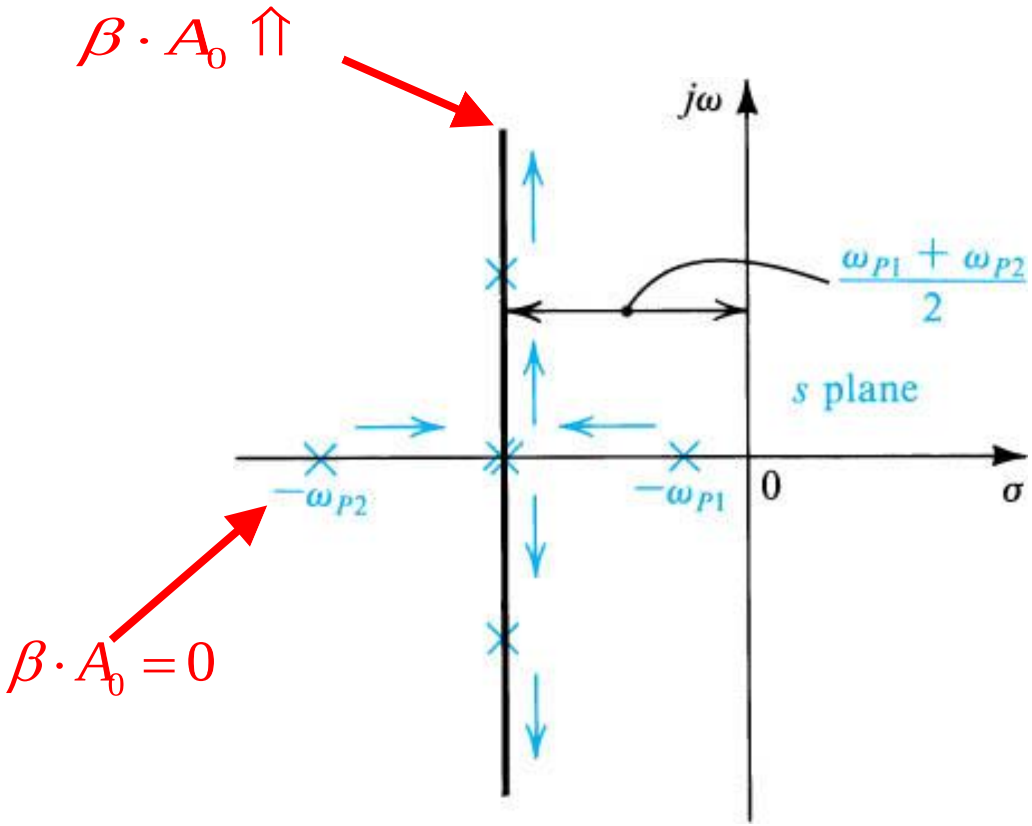
, which leads to

$$\mathrm{s}^2 + s(\omega_{p1} + \omega_{p2}) + (1+\beta \cdot A_0)\,\omega_{p1}\,\omega_{p2} = 0$$

The closed-loop poles are

$$\mathrm{s} = -\frac{1}{2}(\omega_{p1} + \omega_{p2}) \pm \frac{1}{2}\sqrt{(\omega_{p1} + \omega_{p2})^2 - 4(1+\beta \cdot A_0)\omega_{p1}\omega_{p2}}$$

•Root-Locus Diagram



Root-locus diagram for a feedback amplifier whose open-loop transfer function has two real poles.

Characteristic Equation of a second-order network:

$$s^2 + s\cdot\frac{\omega_0}{Q} + \omega_0^2 = 0 \Rightarrow s = -\frac{\omega_0}{2Q} \pm \frac{\sqrt{(\omega_0 / Q)^2 - 4\omega_0{}^2}}{2}$$

ω_o pole frequency, Q : pole Q factor.

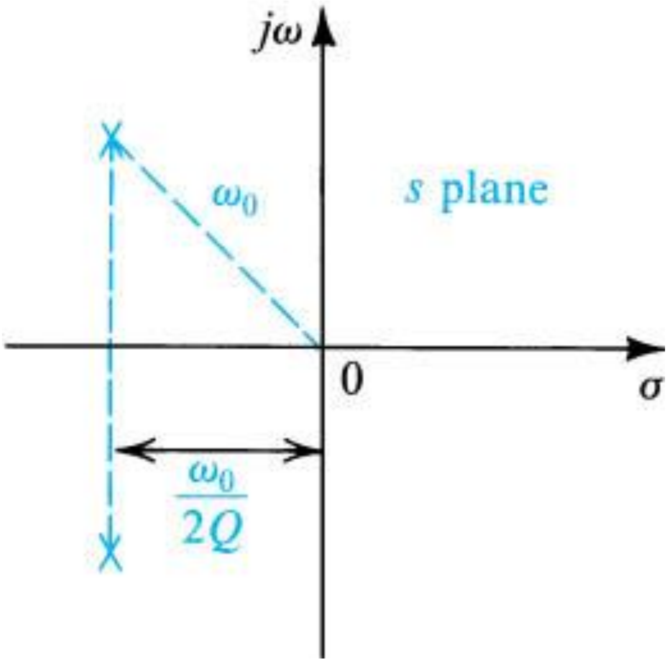
$Q<0.5 \Rightarrow$ real poles

$Q>0.5 \Rightarrow$ complex poles

$Q \rightarrow \infty \Rightarrow$ poles on jw-axis

$$Q = \frac{\sqrt{(1+\beta\cdot A_0)\omega_{p1}\omega_{p2}}}{\omega_{p1}+\omega_{p2}}$$

$$\omega_o = \sqrt{(1+\beta\cdot A_0)\omega_{p1}\omega_{p2}}$$

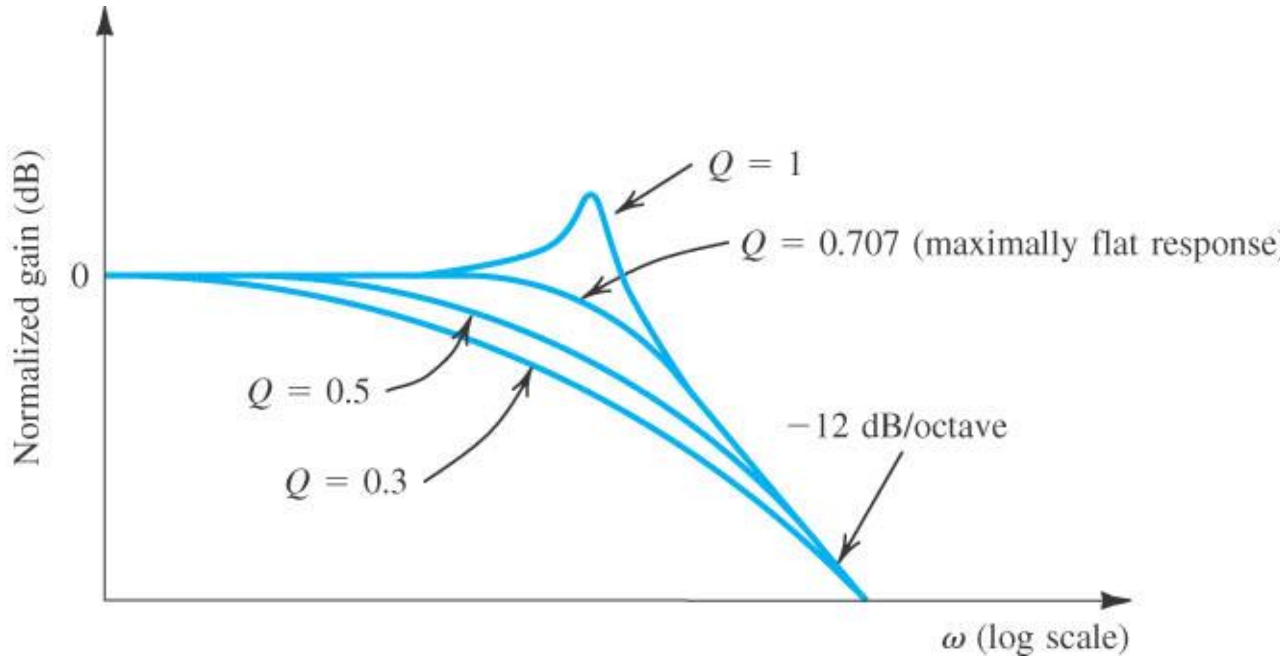


Definition of ω_0 and Q of a pair of complex-conjugate poles.

$$s^2 + s(\omega_{p1}+\omega_{p2}) + (1+\beta\cdot A_0)\,\omega_{p1}\,\omega_{p2} = 0 \Rightarrow Q = \frac{\sqrt{(1+\beta\cdot A_0)\omega_{p1}\omega_{p2}}}{\omega_{p1}+\omega_{p2}}$$

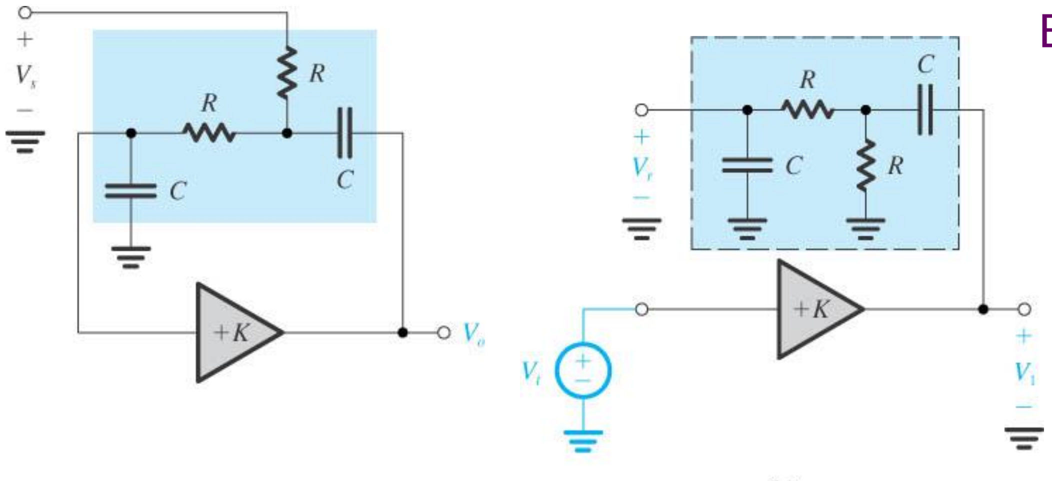
Q<=0.707→ no peak
Q = 0.707 (poles at 45º angles)→maximally flat

$$H(s) = \frac{\omega_0^2}{s^2 + s \cdot \frac{\omega_0}{Q} + \omega_0^2}$$

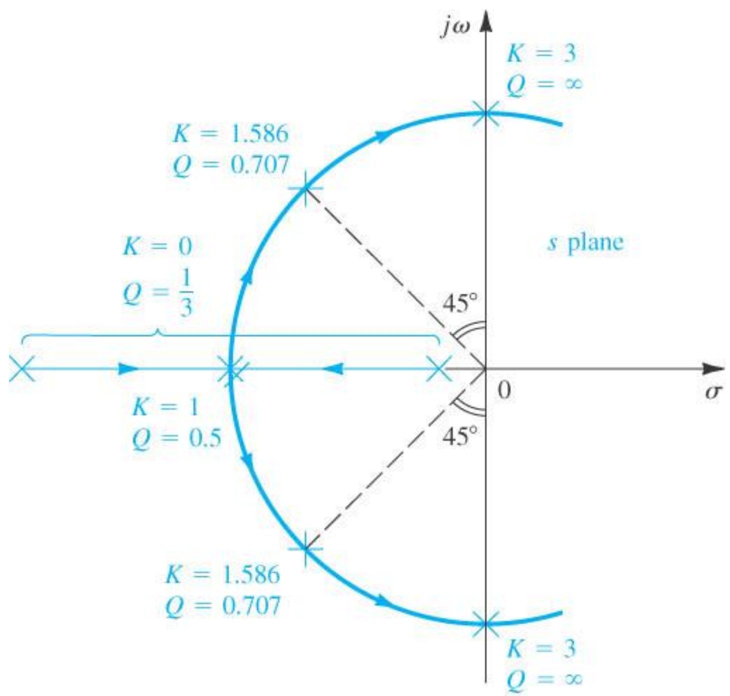


Normalized gain of a two-pole feedback amplifier for various values of *Q*. Note that *Q* is determined by the loop gain according to Eq. (10.70).

Example 10.11: Positive-feedback loop



(a) (b)



(c)

By Negative-feedback loop method

$$L(s)=\frac{-V_r}{V_t}=-K\frac{s/RC}{s^2+s(3/RC)+(1/RC)^2}$$

Characteristic equation $\Rightarrow$ 1+L(s)=0

$$\Rightarrow s^2+s(\frac{3-K}{RC})+(\frac{1}{RC})^2=0$$

$$\Rightarrow \omega_o=\frac{1}{RC} \text{ and } Q=\frac{1}{3-K}$$

$$s_1,s_2=-\frac{\omega_0}{2Q}\pm\frac{\sqrt{(\omega_0/Q)^2-4\omega_0^{\,2}}}{2}$$

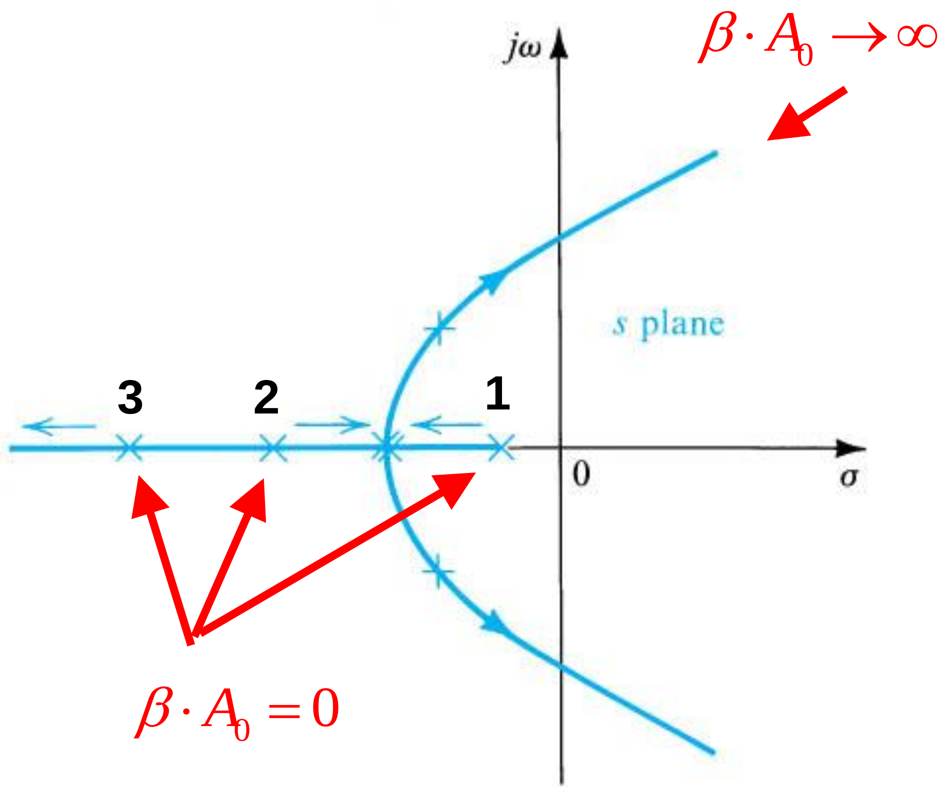
Properly choose Q

→ filter or oscillator

By Positive-feedback loop method

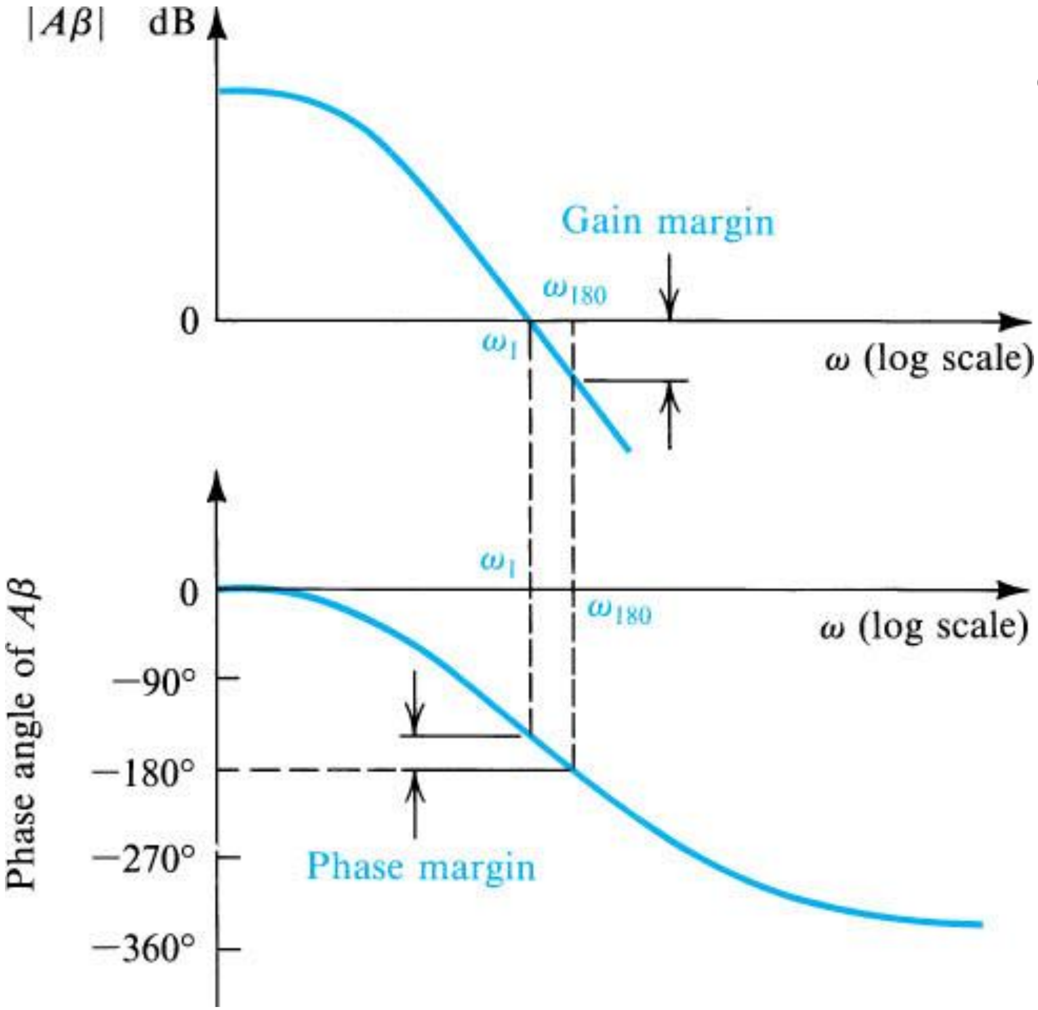
$$L(s)=\frac{V_r}{V_t}\Rightarrow \text{1-L(s)=0}$$

10.8.5 Amplifier with a Three or More Poles



Root-locus diagram for an amplifier with three poles. The arrows indicate the pole movement as $A_0\beta$ is increased.

10.9 Stability Study Using Bode Plots



Bode plot for the loop gain $A\beta$ illustrating the definitions of the gain and phase margins.

ω_1 : unity-gain frequency

at $\omega = \omega_{180}$**,** $\phi(j\omega_{180}) = 180^{\circ}$

$$A(j\omega_1)\beta = 1 \cdot e^{-j\theta}$$

where $\theta = 180^{\circ} -$ **phase margin**

or phase margin $\equiv 180^{\circ} - \theta$

At ω_1 the closed-loop gain is

$$A_f(j\omega_1) = \frac{A(j\omega_1)}{1 + A(j\omega_1)\cdot\beta} = \frac{\frac{1}{\beta}\times e^{-j\theta}}{1 + e^{-j\theta}}$$

$\Rightarrow$ for a phase margin $= 45^{\circ}$, $\theta = 135^{\circ}$

$$\Rightarrow \left|A_f(j\omega_1)\right| = \frac{1/\beta}{\left|1 + e^{-j\theta}\right|} = 1.3\frac{1}{\beta}$$

10.9.3 An Alternative Approach for Investigating Stability:

$$A = \frac{10^5}{(1 + j\frac{f}{10^5})(1 + j\frac{f}{10^6})(1 + j\frac{f}{10^7})}$$

Its phase can be expressed as

$$\phi = -[tan^{-1}(\frac{f}{10^5}) + tan^{-1}(\frac{f}{10^6}) + tan^{-1}(\frac{f}{10^7})]$$

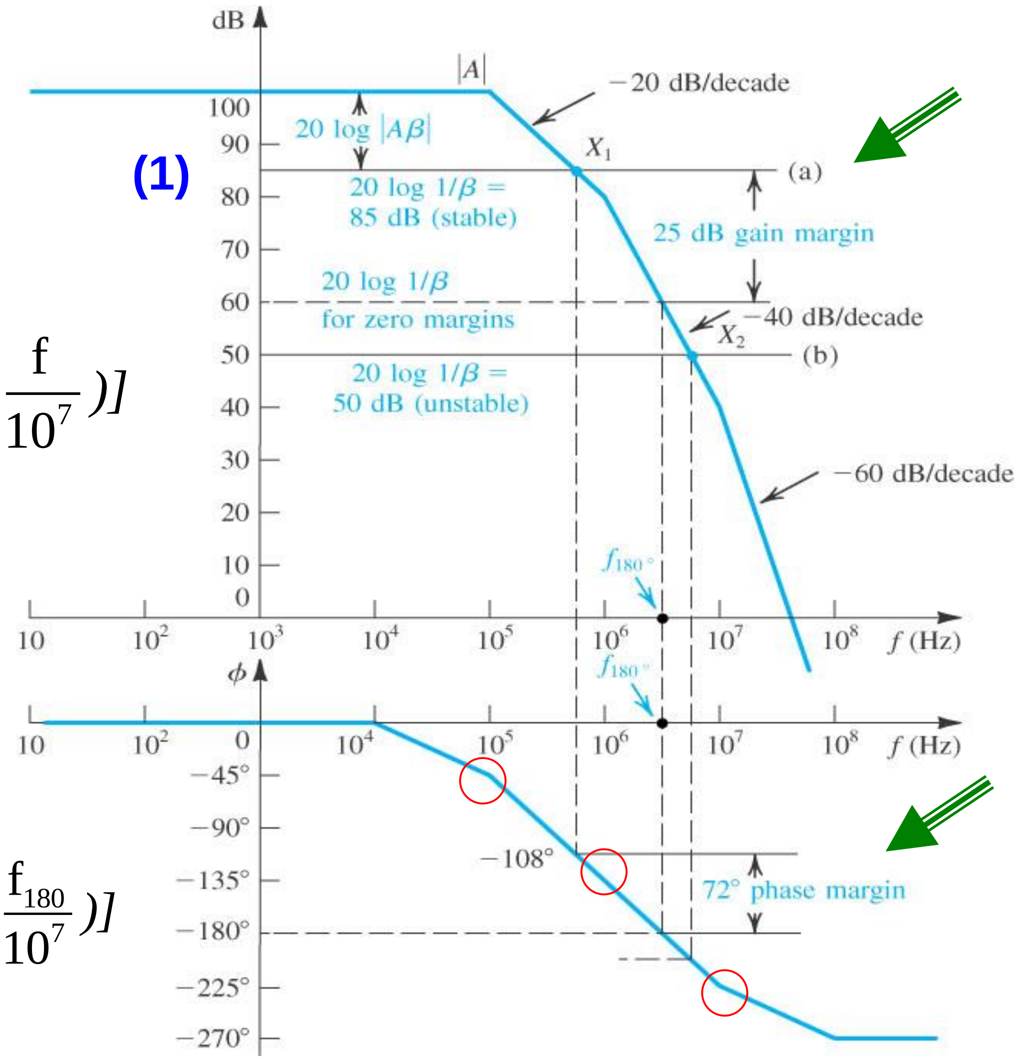
By the right figure

$$f_{180} = 3.2 \times 10^6\, Hz,\ \ A(f_{180}) = 58.2 dB$$

$$180^0 = -[tan^{-1}(\frac{f_{180}}{10^5}) + tan^{-1}(\frac{f_{180}}{10^6}) + tan^{-1}(\frac{f_{180}}{10^7})]$$

$$f_{180,\ \text{exact}} = 3.34 \times 10^6\, Hz$$

(1)



Stability analysis using Bode plot of |A|.

$$20\log|A(j\omega)| - 20\log\left(\frac{1}{\beta}\right) = 20\log|A\beta|$$

(a) $20\log\left(\frac{1}{\beta}\right) = 85dB \Rightarrow \beta = 5.623\times10^{-5}$

$\Rightarrow phase = -108^o \Rightarrow \text{Phase Margin} = 72^o$

$\Rightarrow \text{Gain Margin} \cong 25dB$

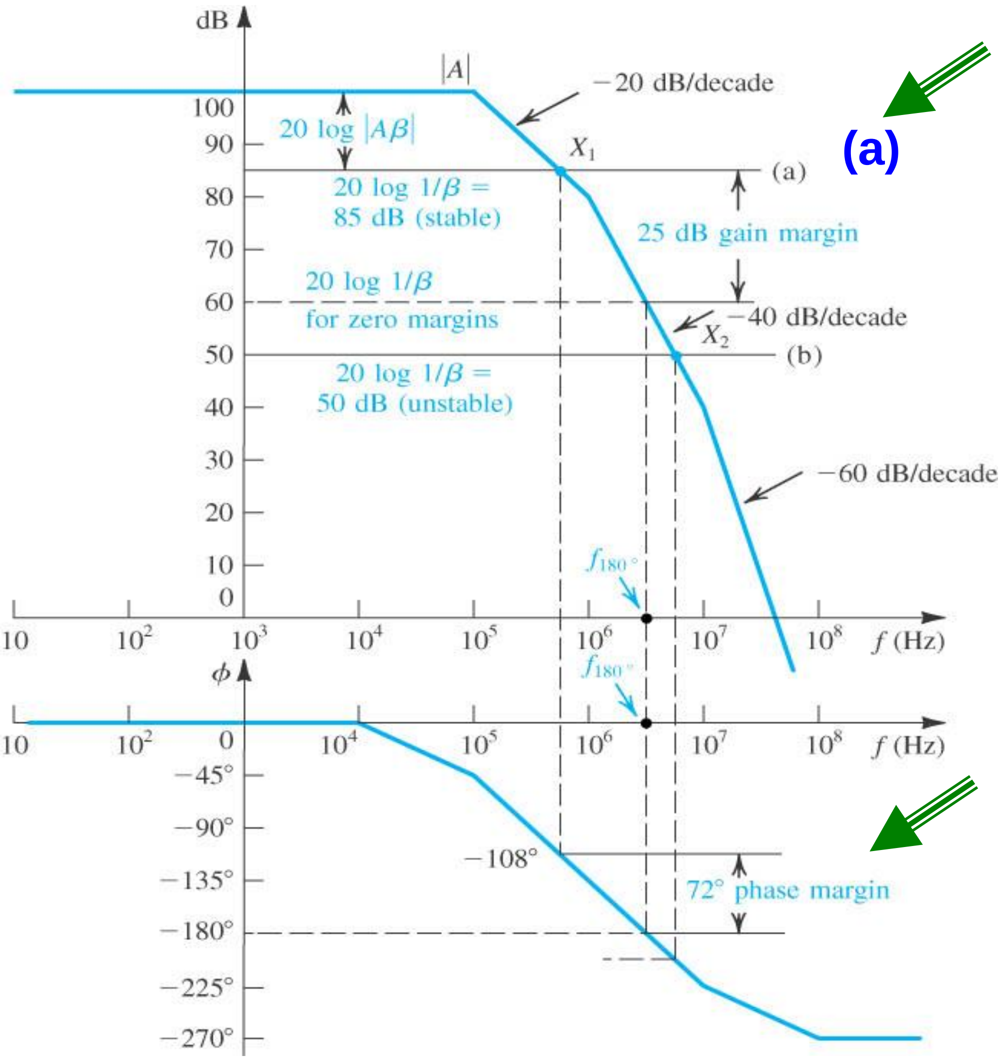
$f_t : 100dB - 85dB = 20\log\left(\frac{f_t}{10^5}\right)$

$\Rightarrow f_t \approx 5.6\times10^5\,\text{Hz}$

$(|A\beta| = 1 \Rightarrow \text{ exactly } f_t = 4.936\times10^5)$

$\Rightarrow 100dB \Rightarrow A_o = 10^5$

$$A_f = \frac{A_o}{1+A_o\beta} = 15099 \Rightarrow 83.6dB$$



Stability analysis using Bode plot of |A|.

$$20\log|A(j\omega)| - 20\log(\frac{1}{\beta}) = 20\log|A\beta|$$

(2) $20\log(\frac{1}{\beta}) = 50dB \Rightarrow \textit{unstable}$ ($\because$ phase margin $<0^{o}$)

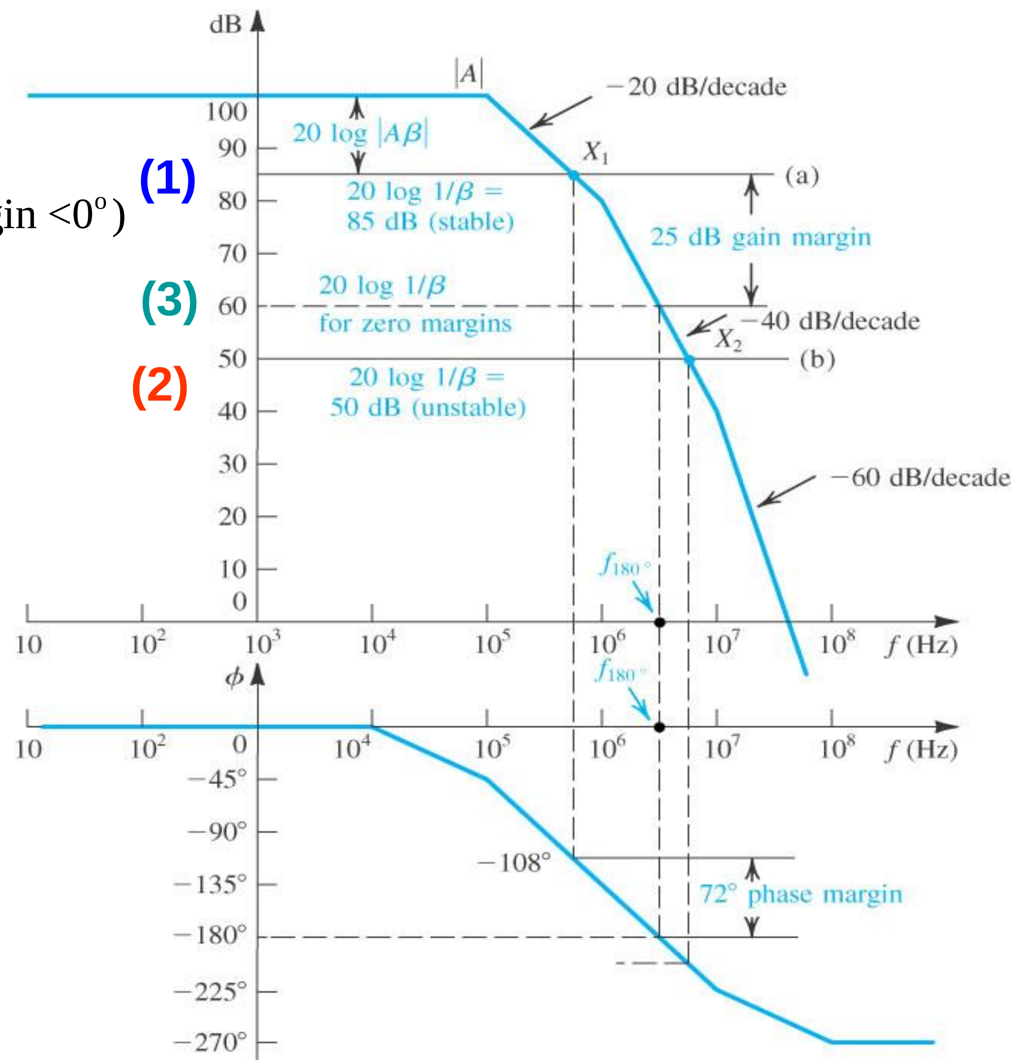
$\beta = 0.00316$

(3) what is the minimum $20\log(\frac{1}{\beta}) \Rightarrow \textit{stable}$

$$20\log(\frac{1}{\beta})_{\min} = 60dB \Rightarrow \beta = 0.001$$

(4) 180^{o}-phase point always ocurs on the -40dB/decade segment in Bode plot.

$\Rightarrow$ The closed-loop amplifier is stable if 20dB($1/\beta$) line intersects the 20log|A| curve at a point on the -20dB/decade segment.

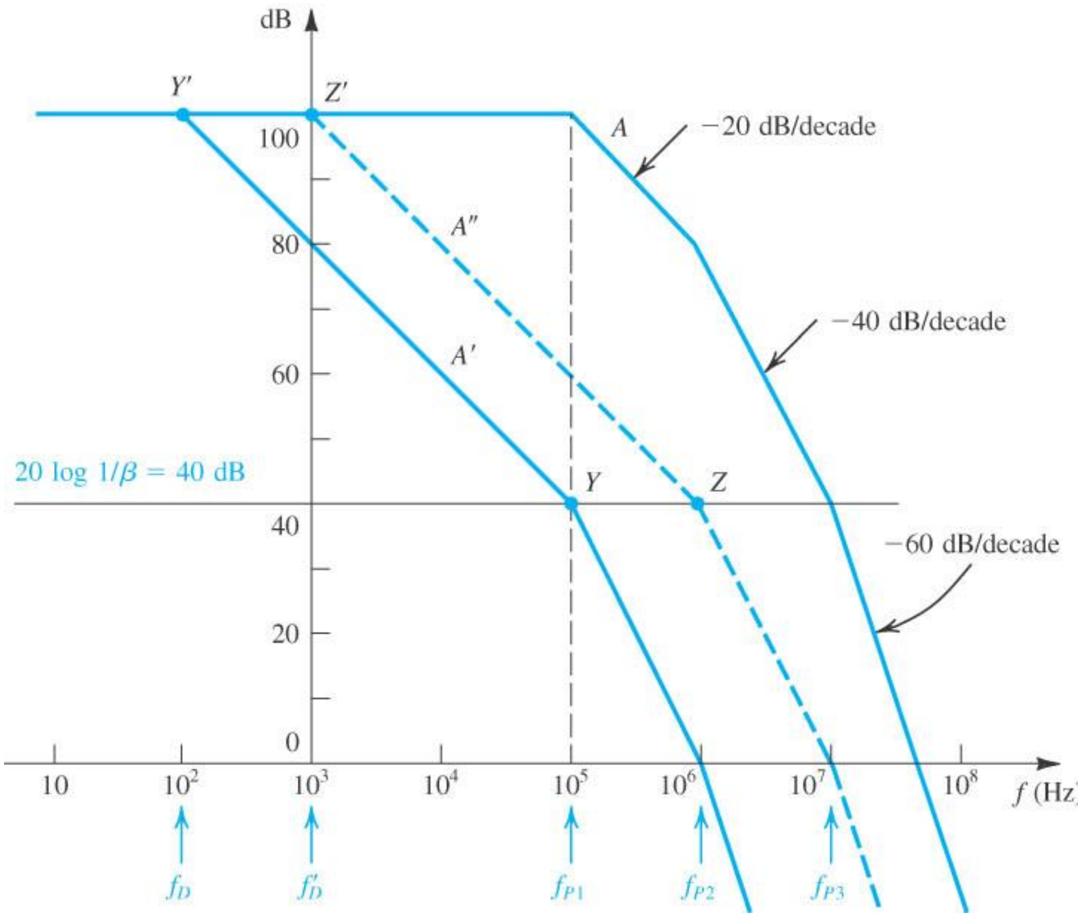


10.10 Frequency Compensation
10.10.1 The Theory

→To modify the open-loop transfer function A(s) of an amplifier having three or more poles so that the closed-loop amplifier is stable!

→A': Introducing a new pole in the function A(s) at a sufficiently low frequency, f_D. (but mid-band gain is lost too much) (β=0.01, closed-loop gain~40dB)

→A": Eliminate the pole or shift the pole



Frequency compensation for $\beta = 10^{-2}$. The response labeled A' is obtained by introducing an additional pole at f_D. The A'' response is obtained by moving the original low-frequency pole to f'_D.

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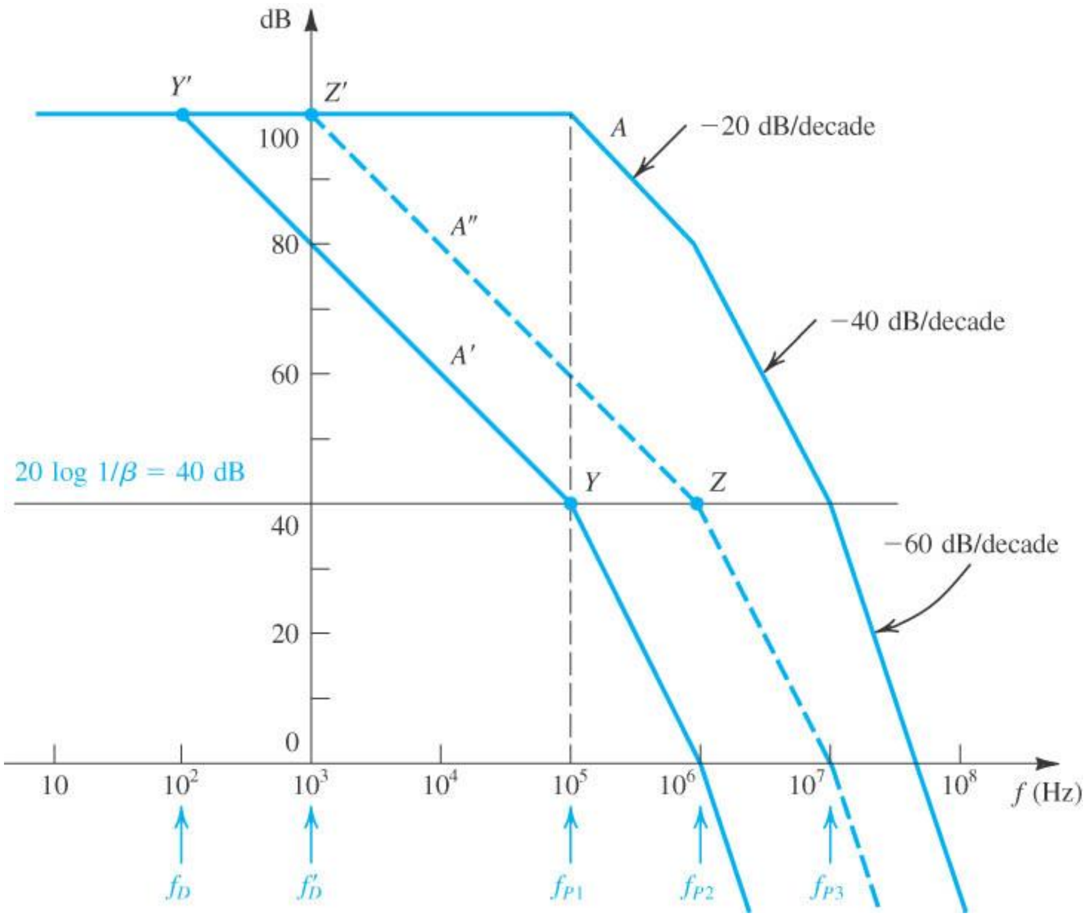

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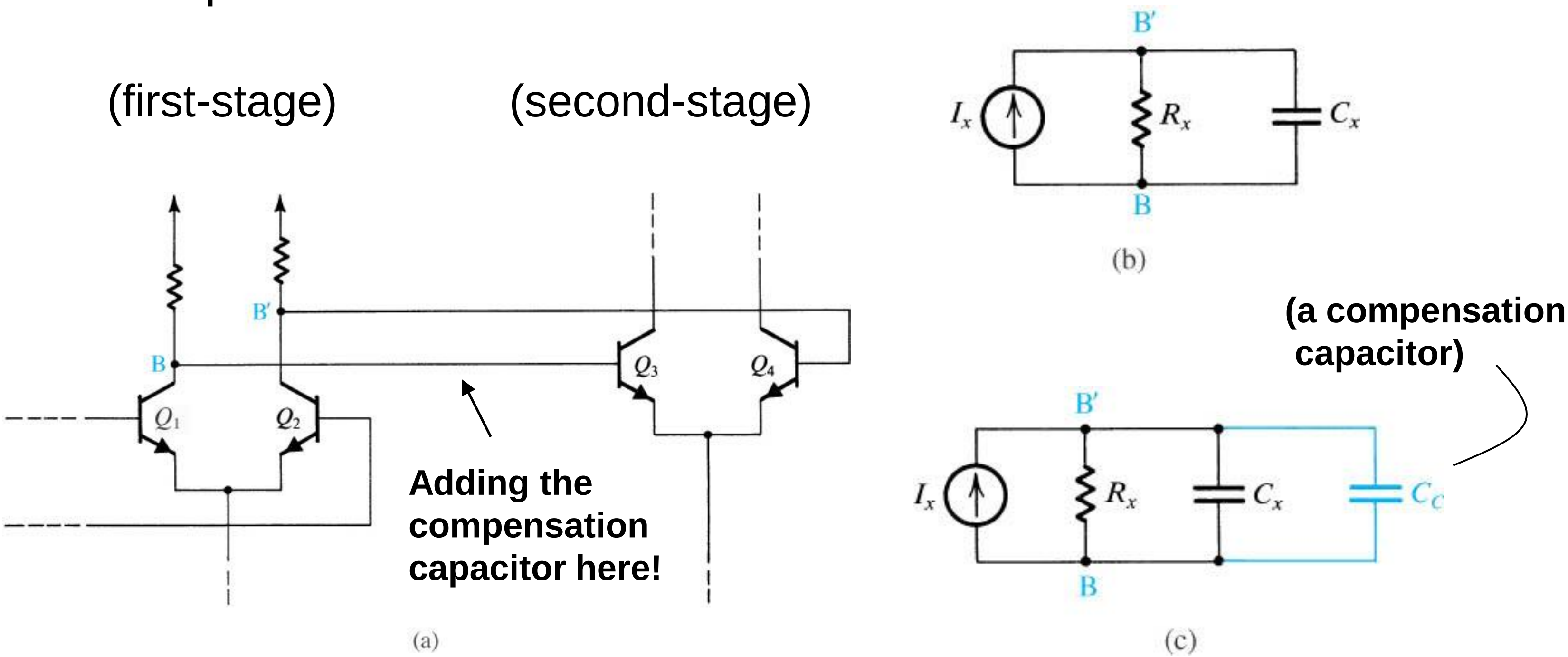
10.10.2 Implementation :

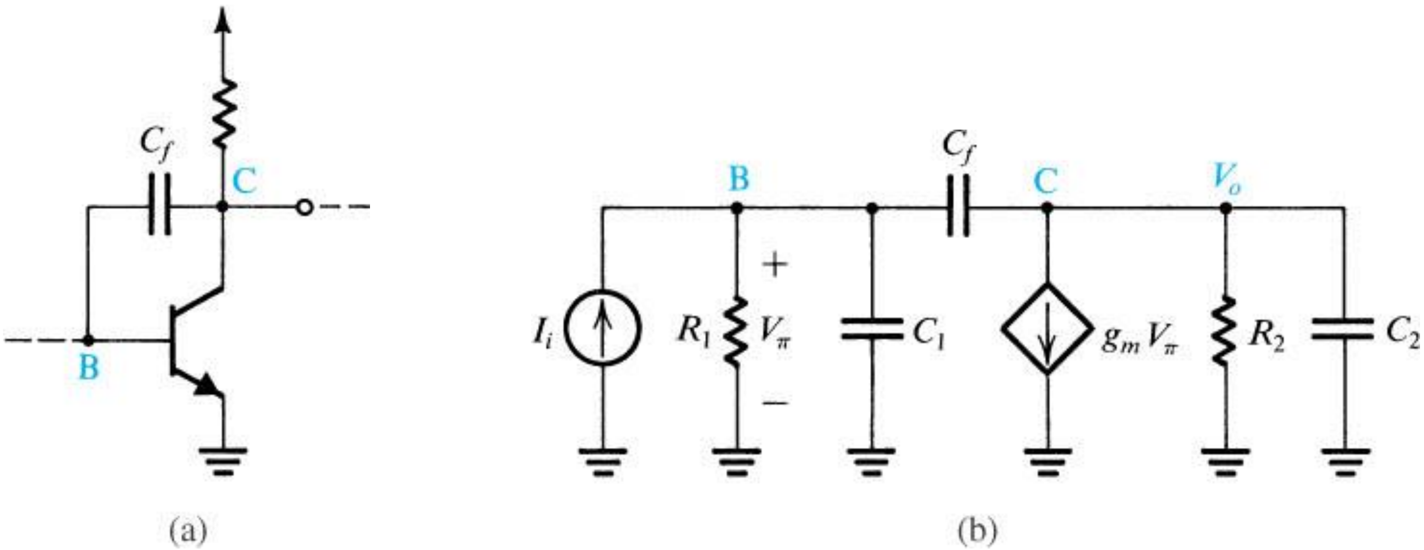


(a) Two cascaded gain stages of a multistage amplifier. **(b)** Equivalent circuit for the interface between the two stages in (a). **(c)** Same circuit as in (b) but with a compensating capacitor C_C added. Note that the analysis here applies equally well to MOS amplifiers.

$$f_{P1} = \frac{1}{2\pi C_x R_x} \Rightarrow f_D' = \frac{1}{2\pi (C_x + C_c) R_x}$$

How to have a large compensating capacitor C_C if it is needed

10.10.3 Miller Compensation and Pole Splitting



(a) A gain stage in a multistage amplifier with a compensating capacitor connected in the feedback path and **(b)** an equivalent circuit. Note that although a BJT is shown, the analysis applies equally well to the MOSFET case.

In the original case: $\mathbf{f_{p1}} = \dfrac{1}{2\pi \ C_1R_1}$ and $\mathbf{f_{p2}} = \dfrac{1}{2\pi \ C_2R_2}$

With frequency compensation, the transfer function becomes

$$\frac{\mathbf{V_o}}{\mathbf{I_i}} = \frac{(sC_f - g_m)R_1R_2}{1 + s[C_1R_1 + C_2R_2 + C_f(g_mR_1R_2 + R_1 + R_2)] + s^2\{[C_1C_2 + C_f(C_1 + C_2)]R_1R_2\}}$$

$$\approx \frac{(sC_f - g_m)R_1R_2}{1 + K_1 \cdot s + K_2 \cdot s^2}$$

On the other hand, the denominator polynomial D(s) can be written as

$$\mathbf{D(s)} = \left(\mathbf{1} + \frac{\mathbf{s}}{\omega'_{p1}}\right)\left(\mathbf{1} + \frac{\mathbf{s}}{\omega'_{p2}}\right) = 1 + s \cdot \left(\frac{1}{\omega'_{p1}} + \frac{1}{\omega'_{p2}}\right) + s^2 \cdot \frac{1}{\omega'_{p1} \ \omega'_{p2}}$$

$\Rightarrow$

$$\omega'_{p1} = \frac{1}{[C_1R_1 + C_2R_2 + C_f(g_mR_1R_2 + R_1 + R_2)]} \approx \frac{1}{(g_mR_2) \ C_fR_1}$$

$$\omega'_{p2} = \frac{1}{\omega'_{p1} \cdot \{[C_1C_2 + C_f(C_1 + C_2)]R_1R_2\}} \approx \frac{g_mC_f}{C_1C_2 + C_f(C_1 + C_2)}$$

Assume $\omega'_{p1} << \omega'_{p2}$

Pole Splitting

The dominant pole:

$$\omega'_{\mathrm{p1}} = \frac{1}{(g_m R_2) C_f \cdot R_1}$$

and the second pole :

$$\omega'_{\mathrm{p2}} = \frac{g_m C_f}{C_1 C_2 + C_f (C_1 + C_2)}$$

Important features:

a. as C_f is increased, ω'_{p1} is reduced, and ω'_{p2} is increased. (pole splitting)

b. by Miller effect, C_f is multipled by $(g_m R_2)$, it moves Z-point (Fig. 10.38) further to right; thus resulting in higher compensated open-loop gain.