Chapter 6 Dynamic Op Amp Limitations

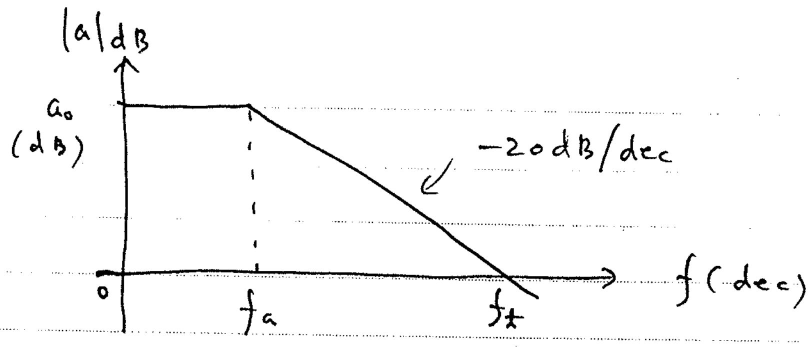
- Unity-gain frequency, f_t
- Gain-bandwidth product, GBP
- Closed-loop bandwidth, f_A
- Full-power bandwidth, FPB
- Rise time, t_R
- Slew rate, SR
- Settling time, t_s
- Current-feedback amplifier (CFA) → very high speed applications
- Most op amps are internally compensated for stability ⇒ dominant pole compensation

6.1 Open-Loop Response

$$a(jf) = \frac{a_0}{1 + jf/f_a}$$: dominant pole compensation

a_0 : open-loop dc gain
f_a : open-loop −3 dB freq. OR open-loop bandwidth

$$|a(jf)| = \frac{a_0}{\sqrt{1 + (f/f_a)^2}}, \quad \angle a(jf) = -\tan^{-1}\frac{f}{f_a}$$



f_t : unity-gain freq. OR transition freq.

at $f = f_t$, $1 = a_o / \sqrt{1 + (f_t/f_a)^2}$

Since $f_t \gg f_a$, $f_t = a_o f_a$.

For 741, $a_o = 200,000$, $f_a = 5$ $\Rightarrow$ $f_t = 1\,\text{MHz}$

$$\begin{cases} a(jf)\big|_{f \ll f_a} \to a_o \angle 0^\circ \\ a(jf)\big|_{f = f_a} = a_o/\sqrt{2} \angle -45^\circ \\ a(jf)\big|_{f \gg f_a} \to \dfrac{f_t}{f} \angle -90^\circ \end{cases}$$

For $f \gg f_a$, $GBP = |a(jf)| \times f = f_t$

$\Rightarrow$ Dominant pole compensation $\Rightarrow$ constant-GBP op amp

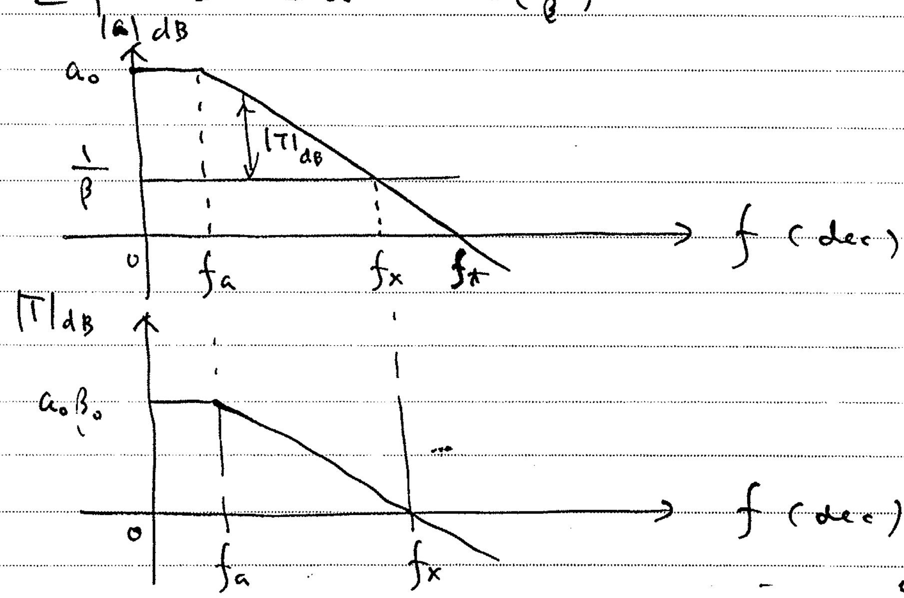
$$|a(jf_o)| = \frac{f_t}{f_o} = a_o \frac{f_a}{f_o}$$

- Most op amps : GBW = 500 kHz ~ 20 MHz
- f_t is a stable parameter
  (a & a_o are not stable)

* Loop Gain, $T = a\beta = a/(1/\beta)$

$$\begin{cases} |T|_{dB} = 20\log_{10}|T| = 20\log_{10}|a| - 20\log_{10}\left|\frac{1}{\beta}\right| \\ \qquad\qquad = |a|_{dB} - |1/\beta|_{dB} \\ \angle T = \angle a - \angle\left(\frac{1}{\beta}\right) \end{cases}$$

Fig6.3)



f_x = crossover freq.

$|T(jf_x)|_{dB} = 0$ OR $|T(jf_x)| = 1$

For $f \ll f_x$, $|T| \gg 1 \Rightarrow$ negative feedback is effective. nearly ideal

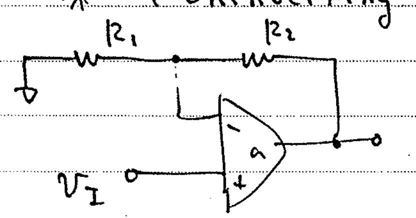
6.2 Closed-Loop Response

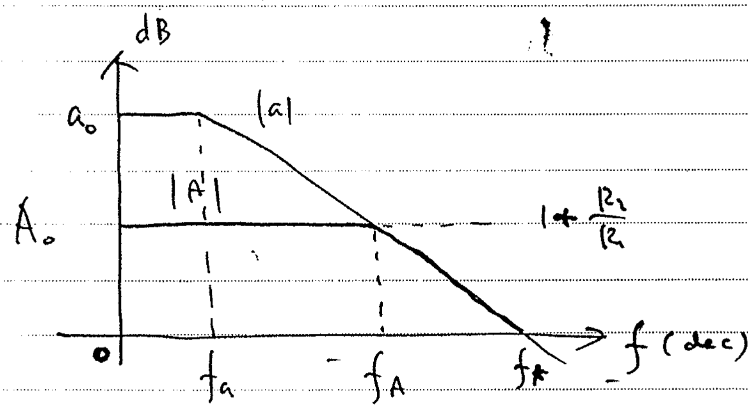
$$A(jf) = A_{ideal} \cdot \frac{1}{1 + 1/T(jf)}$$

$$\varepsilon_m = \left| \frac{1}{1 + 1/T(jf)} \right| - 1 \quad : \text{magnitude error}$$

$$\varepsilon_\phi = -\angle\left[1 + 1/T(jf)\right] \quad : \text{phase error}$$

* Noninverting Amplifier





$$A(jf) = \left(1 + \frac{R_2}{R_1}\right) \frac{1}{1 + (1 + R_2/R_1)(1 + jf/f_a)/a_0}$$

$$= \frac{A_0}{1 + jf/f_A}$$

where $A_0 = \left(1 + \frac{R_2}{R_1}\right) \dfrac{1}{1 + (1 + R_2/R_1)/a_0}$

$$f_A = f_a\left(1 + a_0 \frac{R_1}{R_1 + R_2}\right)$$

For $a_o \gg 1 + R_2/R_1$,

$$A(jf) = A_o \frac{1}{1 + jf/f_A}$$

where $A_o \doteq 1 + \frac{R_2}{R_1}$, $f_A \doteq \beta f_t$

$$\beta = \frac{R_1}{R_1 + R_2} = \text{feedback factor}$$

$$f_t = a_o f_a = \text{unity-gain freq.}$$

$\Rightarrow$ { f_A : -3 dB freq. OR closed-loop bandwidth
A_o : closed-loop dc gain

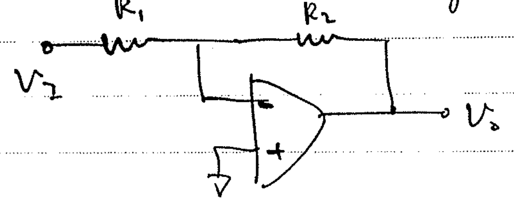
◎ Example 6.1

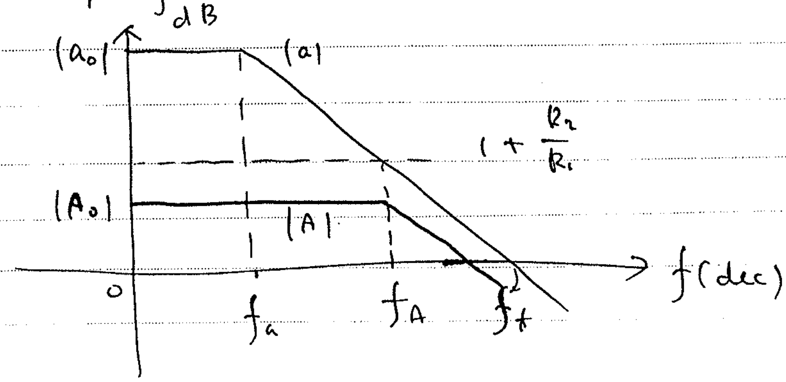
* Gain-Bandwidth Tradeoff "figure of merit" of an op amp

$$GBP = A_o f_A = f_t$$

◎ Example 6.2

* Inverting Amplifier





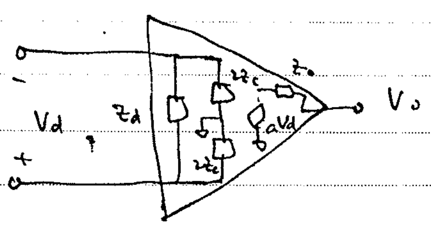
$$A(jf) = A_o \frac{1}{1 + jf/f_A}$$

$$\left.\begin{array}{l} A_o \simeq -\dfrac{R_2}{R_1}, \quad f_A \simeq \beta f_t \\ \beta = \dfrac{R_1}{R_1 + R_2} \end{array}\right\} \text{ when } a_o \gg 1 + \frac{R_2}{R_1}$$

$$GBP = |A_o| \cdot f_A = \frac{R_2}{R_1} \times f_t \frac{R_1}{R_1 + R_2}$$

$$= \frac{R_2}{R_1 + R_2} f_t$$

6.3 Input and Output Impedances



$$\left\{\begin{array}{ll} Z_d & : \text{ differential input impedance} \\ Z_c & : \text{ common-mode input impedance} \\ Z_o & : \text{ output impedance} \end{array}\right.$$

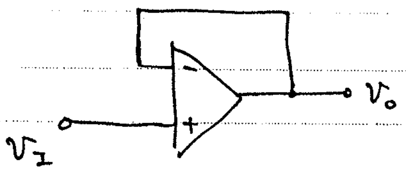
BJT : r_d & r_c ~ MΩ or GΩ , $r_c \gg r_d$

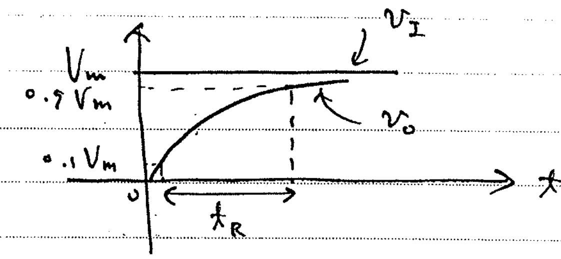
FET : $r_d \doteq r_c$ ~ > 100 GΩ

At high freq, $\left\{\begin{array}{lll} Z_d & \text{becomes} & \text{capacitive} \\ Z_o & \text{"} & \text{inductive} \end{array}\right.$

6.4 Transient Response

* Rise Time, t_R





$$A(jf) = \frac{1}{1 + jf/f_t}$$

$$v_I(t) = V_m u(t) \Rightarrow v_O(t) = V_m\left(1 - e^{-t/\tau}\right)$$

$$\tau = \frac{1}{2\pi f_t}$$

$$t_R = \tau(\ln 0.9 - \ln 0.1)$$

$$= \frac{0.35}{f_t}$$

Ex) 741 $\Rightarrow$ $t_R \simeq 350$ ns

* Slew-Rate

For the step response above,

$$\left.\frac{dv_O}{dt}\right|_{max} = \left.\frac{dv_O}{dt}\right|_{t=0} = \frac{V_m}{\tau}$$

In order to get the same τ, we need $\frac{dv_O}{dt}$ ↑ as V_m ↑

However, $\frac{dv_o}{dt}$ saturates to a constant value called SR.

$$V_{om(crit)} = \frac{SR}{2\pi f_t}$$

↳ critical output-step magnitude at the onset of SR limiting.

* Full-Power Bandwidth

For a sinusoidal input, $v_o(t) = V_{om} \sin 2\pi f t$.

$$\frac{dv_o(t)}{dt} = 2\pi f V_{om} \cos 2\pi f t \Rightarrow \left.\frac{dv_o}{dt}\right|_{max} = 2\pi f V_{om}$$

Before SR limiting, $2\pi f V_{om} \le SR$ or

$$f V_{om} \le \frac{SR}{2\pi}$$

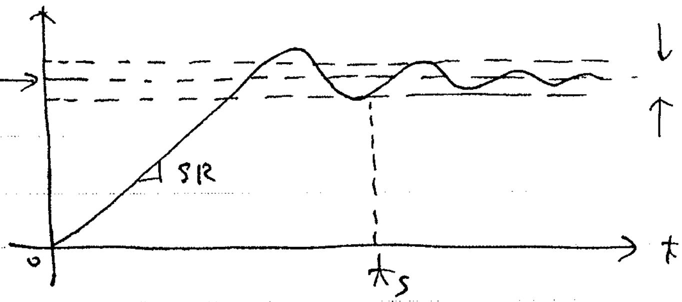
⇓

f↑ 이면 V_{om} 은 작게 } trade off
V_{om}↑ 이면 f 는 작게

$$FPB = \frac{SR}{2\pi V_{sat}}$$: full-power bandwidth

($f < FPB \Rightarrow v_o(t)$가 $\pm V_{sat}$ 이더라도 SR limiting에 의한 제약이 없음.)

* Settling Time , t_s



6.5

H/w : 6.10 (c) ,