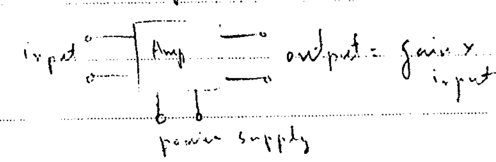
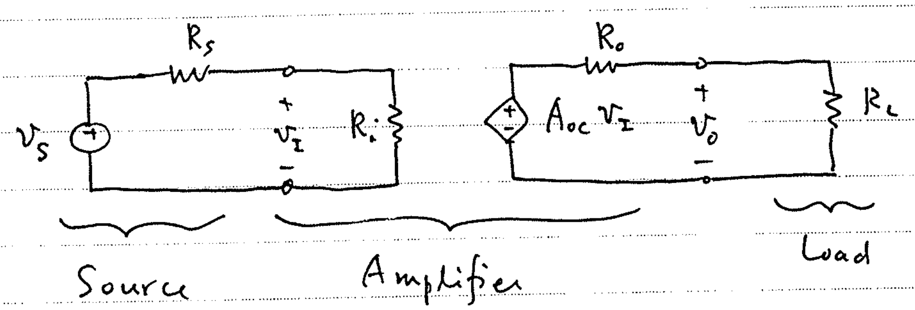
Chapter 1 Operational Amplifier Fundamentals

1.1 Amplifier Fundamentals (linear Amplifier)



* Voltage Amplifier

Thevenin



VCVS

R_i : input resistance
R_o : output "
v_I : input
v_O : output
A_{oc} : Voltage gain (unloaded or open-circuit)

$$v_o = \frac{R_L}{R_o + R_L} A_{oc} v_I \quad , \quad v_I = \frac{R_i}{R_s + R_i} v_s$$

dc 가능
overload [illegible]

$$\frac{v_o}{v_s} = \underbrace{\frac{R_i}{R_s + R_i}}_{\text{loading}} A_{oc} \underbrace{\frac{R_L}{R_o + R_L}}_{\text{loading}} \quad : \text{source-to-load gain}$$

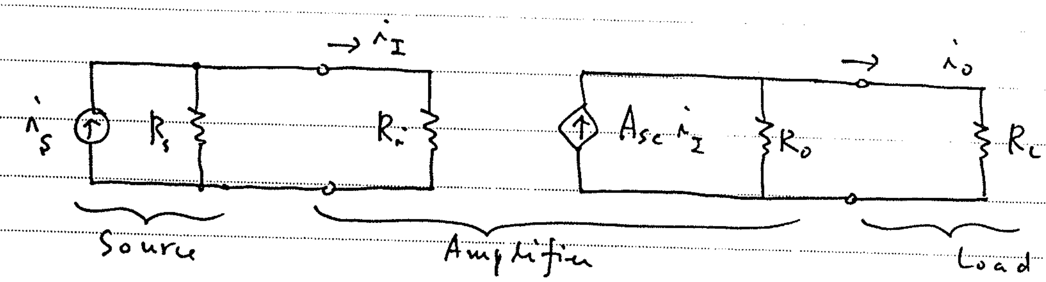
$$\therefore \left|\frac{v_o}{v_s}\right| \le |A_{oc}|$$

(loading effect 때문)

$$\begin{cases} R_i = \infty \text{ and } R_o = 0 \Rightarrow \text{no loading (ideal amplifier)} \\ R_i \gg R_s \text{ and } R_o \ll R_L \Rightarrow \text{minimal loading} \end{cases}$$

* Current Amplifier

Norton



$\boxed{\text{CCCS}}$

A_{sc} : (unloaded or short-circuit) current gain

$$\frac{i_o}{i_s} = \underbrace{\frac{R_s}{R_s + R_i}}_{\text{loading}} A_{sc} \underbrace{\frac{R_o}{R_o + R_L}}_{\text{loading}} \quad : \text{ source-to-load gain}$$

$$\begin{cases} R_i = 0 \text{ and } R_o = \infty & \Rightarrow \text{ no loading} \\ R_i \ll R_s \text{ and } R_o \gg R_L & \Rightarrow \text{ minimal loading} \end{cases}$$

* Transconductance Amplifier $\Leftrightarrow$ $\boxed{\text{VCCS}}$

  $v_I \rightarrow i_o$: $i_o = A_G\, v_I$

* Transresistance Amplifier $\Leftrightarrow$ $\boxed{\text{CCVS}}$

  $i_I \rightarrow v_o$: $v_o = A_z\, i_I$

Table 1.1 (p. 5)

p4. Example 1.1 숙제

1.2 The Operational Amplifier : high-gain voltage amplifier (dc amp.)

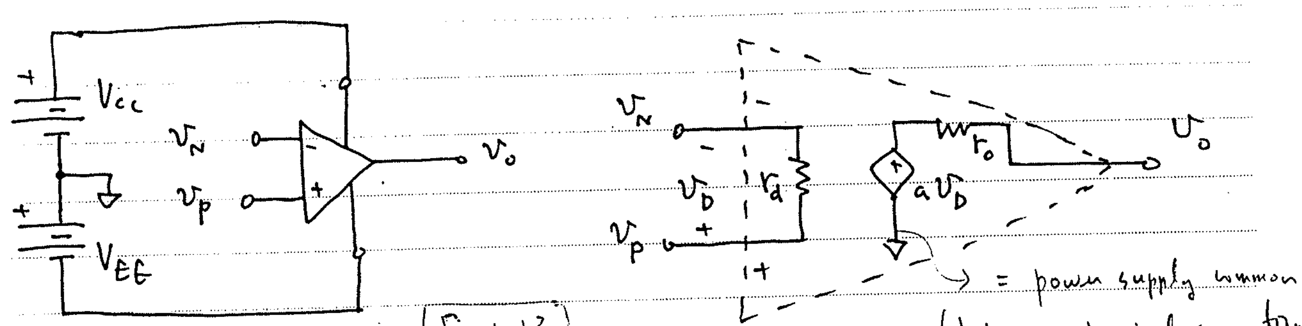


Fig 1.13

- v_N : inverting input
- v_P : noninverting input
- V_{CC} and V_{EE} : supply voltage
- r_d : differential input resistance
- a : voltage gain (unloaded)
- r_o : output resistance

(r_d, a, r_o : open-loop parameters)

$v_D = v_P - v_N$: differential input voltage

$v_O = a v_D = a(v_P - v_N)$: open-circuit output voltage

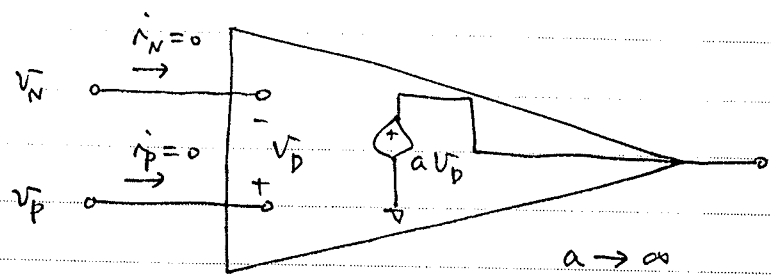
- input : double-ended or differential
- output : single-ended

Op amp: differential amplifier, dc amplifier

* Ideal Op Amp.

$a \to \infty$, $r_d = \infty$

$r_o = 0$, $i_P = i_N = 0$

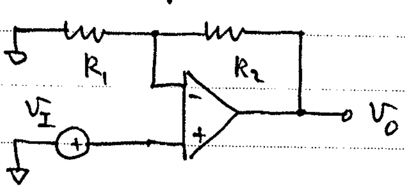


$$\lim_{a\to\infty} v_O = \lim_{a\to\infty} a v_D \quad (= \text{some constant})$$

$$(\text{as } a \to \infty,\ v_D \to 0)$$

1.3 Basic Op Amp Considerations [op amp / op amp circuit]

* Noninverting Amplifier

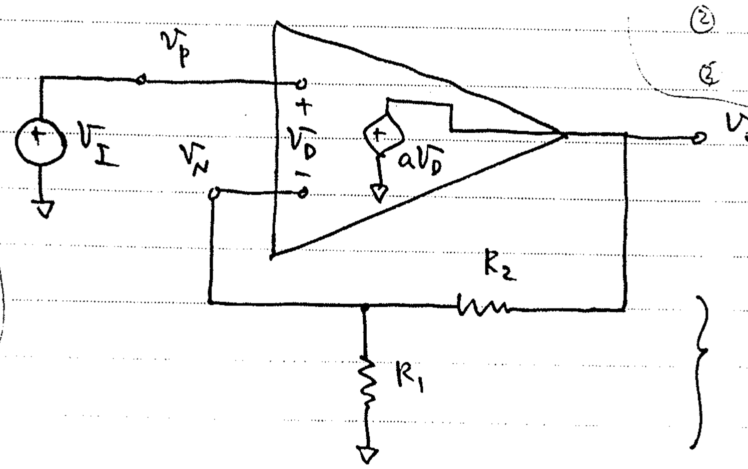


* Ideal Op amp circuit with negative feedback for linear amplification.

① $v_N = v_P$ - - -

② $i_N = i_P = 0$

③ output saturation.



} feedback network

$r_d = \infty$

$r_o = 0$

$$v_P = v_I$$

$$v_N = \frac{R_1}{R_1 + R_2} v_O = \frac{1}{1 + R_2/R_1} v_O$$

$$v_o = a(v_P - v_N) = a\left(v_I - \frac{1}{1 + R_2/R_1} v_o\right)$$

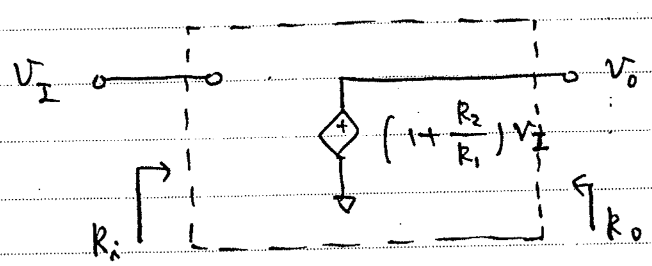
$$A = \frac{v_o}{v_I} = \left(1 + \frac{R_2}{R_1}\right) \frac{1}{1 + (1 + R_2/R_1)/a}$$

$$\begin{cases} a = \text{open-loop gain} \\ A = \text{closed-loop gain} \end{cases}$$

$\boxed{\text{Example 1.2}}$ 숙제

$$A_{ideal} = \lim_{a \to \infty} A = 1 + \frac{R_2}{R_1}$$

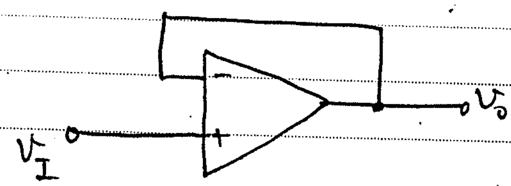
$\Rightarrow$ "Accurate and Stable gain by external components only."

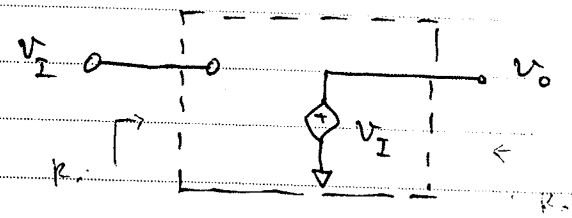


$$\begin{cases} R_i = \infty & : \text{closed-loop input resistance} \\ R_o = 0 & : \quad '' \quad '' \quad \text{output} \quad '' \end{cases}$$

$\Rightarrow$ We need $a \to \infty$ to get good performances of op amp circuit.

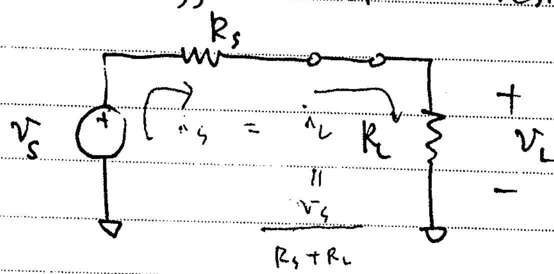
* Voltage Follower (Unity-gain Amplifier)





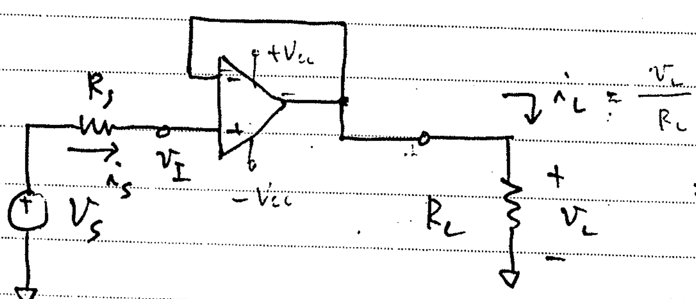
$R_i = \infty$, $R_o = 0$, $A = 1$

⇒ Buffer or resistance transformer



⇒ loading effect

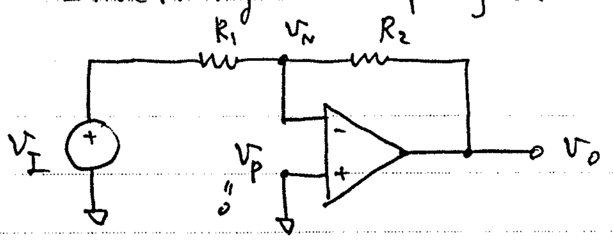
$$v_L = \frac{R_L}{R_s + R_L} v_s$$

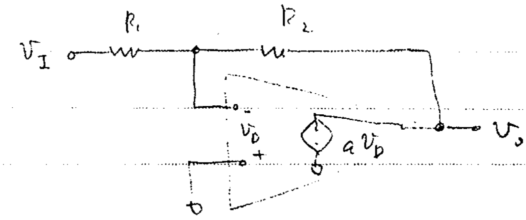


⇒ No loading effect

- $v_L = v_I = v_s$
- $i_s = 0$
- i_L is supplied by power supply of op-amp circuit.

* Inverting Amplifier



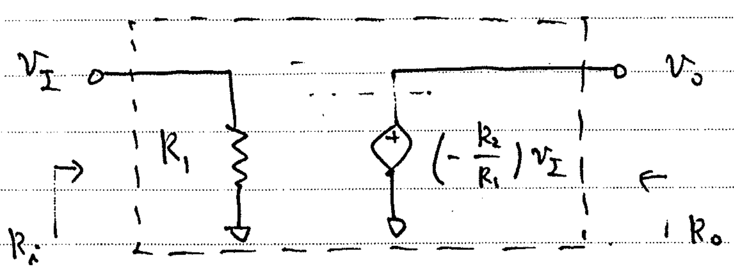


$$v_N = \frac{R_2}{R_1 + R_2} v_I + \frac{R_1}{R_1 + R_2} v_o \quad \text{(superposition)}$$

$$v_o = a(v_P - v_N) = a\left(-\frac{1}{1 + R_1/R_2} v_I - \frac{1}{1 + R_2/R_1} v_o\right)$$

$$A = \frac{v_o}{v_I} = -\frac{R_2}{R_1} \frac{1}{1 + (1 + R_2/R_1)/a}$$

$$A_{ideal} = \lim_{a \to \infty} A = -\frac{R_2}{R_1}$$



$$R_i = R_1 , \qquad R_o = 0$$

- $v_P = 0 \Rightarrow \lim_{a \to \infty} v_N = 0$ (otherwise $v_o \to \infty$) : virtual ground

- Loading effect at input ($\because R_i = R_1$)

$\boxed{\text{Fig 1. 12}}$

1.4 Ideal Op Amp Circuit Analysis

$$\left[\begin{array}{lll} \text{Input voltage constraint} & : & v_P = v_N \\ \text{Input current constraint} & : & i_P = i_N = 0 \end{array}\right.$$

$\Uparrow$

Negative feedback

$\boxed{\text{3가지 회로는 다시 해석}}$

$\left(\lim_{a \to \infty} v_N = v_P \quad : \quad v_N \text{ follow } v_P \text{ by negative feedback} \right)$ → virtual short

* Summing Amplifier (Adder)

$\boxed{\text{Fig 1.15}}$ $\quad R_{ik} = R_k \quad , \quad R_o = 0$

$\boxed{\text{Example 1.5}}$ (Fig 1.16) 숙제

* Difference Amplifier (Subtractor)

(use superposition)

$\boxed{\text{Fig 1.17}}$ $\quad R_{i1} = R_1 \quad , \quad R_{i2} = R_3 + R_4$

$R_o = 0$

$v_o = \frac{R_2}{R_1}\left(\frac{1 + R_1/R_2}{1 + R_3/R_4} v_2 - v_1\right)$

$v_{o1} = -\frac{R_2}{R_1} v_1$

$v_{o2} = \left(1 + \frac{R_2}{R_1}\right)\frac{R_4}{R_3 + R_4} v_2$

$$\frac{R_3}{R_4} = \frac{R_1}{R_2} \Rightarrow \text{Balanced bridge}$$

$$v_o = \frac{R_2}{R_1}(v_2 - v_1)$$

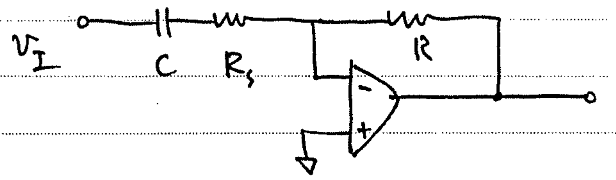
(Example 1.6) 숙제

* Differentiator

$\boxed{\text{Fig 1.18}}$ $\Rightarrow$ may oscillate (unstable)

$$\begin{cases} v_o(t) = -RC\frac{dv_I(t)}{dt} \\ V_o(s) = -RCsV_I(s) \end{cases}, \quad s = j\omega$$

- Stabilized differentiator over a limited frequency range.



: 발진 예방

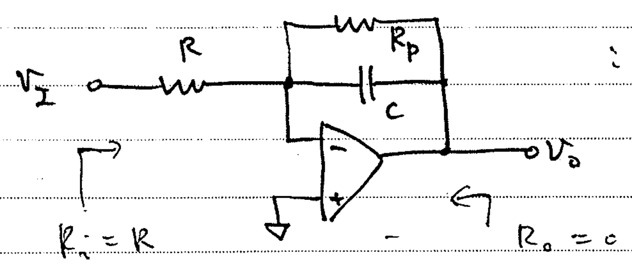
* Integrator

$$v_O(t) = -\frac{1}{RC}\int_0^t v_I(\xi)\,d\xi + v_O(0)$$

$\boxed{\text{Fig 1.19}}$ $R_i = R$, $R_o = 0$

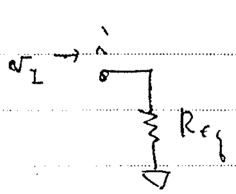
→ may saturate (even with $v_I = 0$)

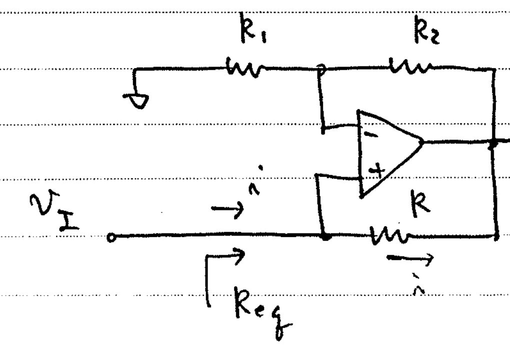
- Lossy integrator over a limited freq. range.



: 포화 예방

* Negative-Resistance Converter (NIC)





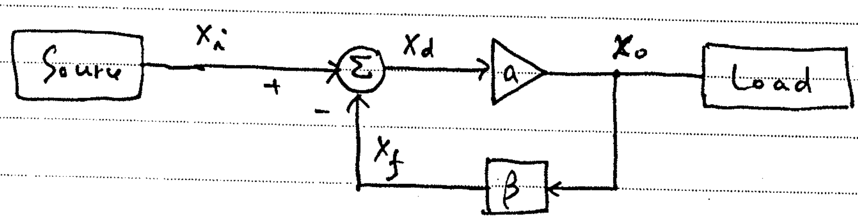
$$v_O = \left(1 + \frac{R_2}{R_1}\right) v_I$$

$$i = \frac{v_I - v_O}{R} = -\frac{R_2}{R_1 R} v_I$$

$$R_{eq} = \frac{v_I}{i} = -\frac{R_1}{R_2} R \quad : \text{negative resistance}$$

- Current flows into the source (v_I)
- Neutralize unwanted resistance
- Control pole location

1.5 Negative feedback : degenerative ($\neq$ regenerative)



- Amplifier or error amplifier : $x_o = a x_d$
- feedback network : $x_f = \beta x_o$
- Summing network : $x_d = x_i - x_f$

$$\left\{ \begin{array}{ll} a : & \text{open-loop gain, forward gain} \\ \beta : & \text{feedback factor} \\ x_d : & \text{error signal} \\ x_i : & \text{input "} \\ x_o : & \text{output "} \end{array} \right.$$

$$A = \text{closed-loop gain} = \frac{x_o}{x_i} = \frac{a}{1 + a\beta}$$

$x_o = a x_d$
$= a(x_i - x_f)$
$= a(x_i - \beta x_o)$
$(1 + a\beta) x_o = a x_i$

$a\beta > 0 \Leftrightarrow$ negative feedback $\Leftrightarrow A < a$

$1 + a\beta$: amount of feedback

$T = a\beta$ = return ratio or loop gain

$$A = \frac{1}{\beta}\,\frac{T}{1+T}$$

$$A_{ideal} = \lim_{T\to\infty} A = \frac{1}{\beta}$$

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

$$\text{Error function} = \frac{1}{1 + 1/T} = 1 - \frac{1}{1+T} = 1 - \varepsilon$$

$$A = A_{ideal}\,(1 - \varepsilon)$$

$$\varepsilon = \frac{1}{1+T}$$: fractional deviation of A from A_{ideal}

$$\text{Gain error (\%)} = 100 \times \frac{A - A_{ideal}}{A_{ideal}} \cong -\frac{100}{T}$$

for $T \gg 1$

Example 1.7 [illegible]

$$\begin{cases} x_d = \dfrac{x_o}{a} = \dfrac{A x_i}{a} = \dfrac{A}{a} x_i = \dfrac{1}{1+T} x_i \Rightarrow x_d \to 0 \text{ as } T \to \infty \\ x_f = \beta x_o = \beta A x_i = \dfrac{1}{1 + \frac{1}{T}} x_i \Rightarrow x_f \to x_i \text{ as } T \to \infty \end{cases}$$

$\Rightarrow$ Op amp [illegible] $v_p = v_n$, $i_p \to 0$ [illegible]

* Gain Desensitivity

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

$$\frac{dA}{da} = \frac{1}{(1+a\beta)^2}, \quad 1 + a\beta = \frac{a}{A}$$

$$\frac{dA}{A} = \frac{1}{1+T}\,\frac{da}{a}$$

$$\Rightarrow \quad 100\,\frac{\Delta A}{A} \simeq \frac{1}{1+T}\left(100\,\frac{\Delta a}{a}\right)$$

$1+T$: desensitivity factor

Similarly,

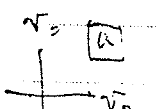
$$100\,\frac{\Delta A}{A} \simeq -100\,\frac{\Delta\beta}{\beta}$$

Example 1.8 숙제 - - -

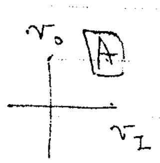
* Nonlinear Distortion Reduction

For a linear amplifier, $x_o = a x_d$ or $x_o = A x_i$

In general, $a = \dfrac{dx_o}{dx_d}$ or $A = \dfrac{dx_o}{dx_i}$



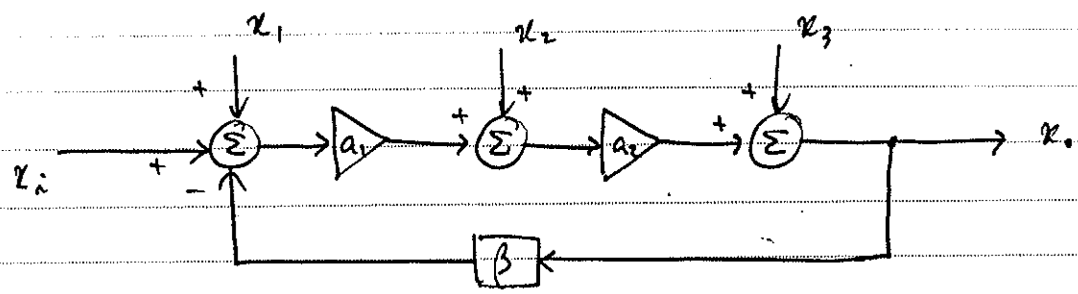
VTC : voltage transfer curve (Fig 1.23)



$\Big\langle$ a : nonlinear and saturation
A : linear and "

Fig. 1.24 [illegible]

* Effect of Feedback on Disturbances and Noise



Examples :

- x_1 : input noise or input offset error
- x_2 : power-supply hum
- x_3 : output noise or load changes

$$x_o = x_3 + a_2\left[x_2 + a_1\left(x_i - \beta x_o + x_1\right)\right]$$

$$\Rightarrow \quad x_o = \frac{a_1 a_2}{1 + a_1 a_2 \beta}\left(x_i + x_1 + \underbrace{\frac{x_2}{a_1} + \frac{x_3}{a_1 a_2}}_{\text{noise reduction}}\right)$$

For $a_1 a_2 \beta \gg 1$,

$$x_o = \frac{1}{\beta}\left(x_i + x_1 + \frac{x_2}{a_1} + \frac{x_3}{a_1 a_2}\right)$$

$$\left(\text{noise gain} = \frac{1}{\beta}\right)$$

↳ gain for input noise x_1

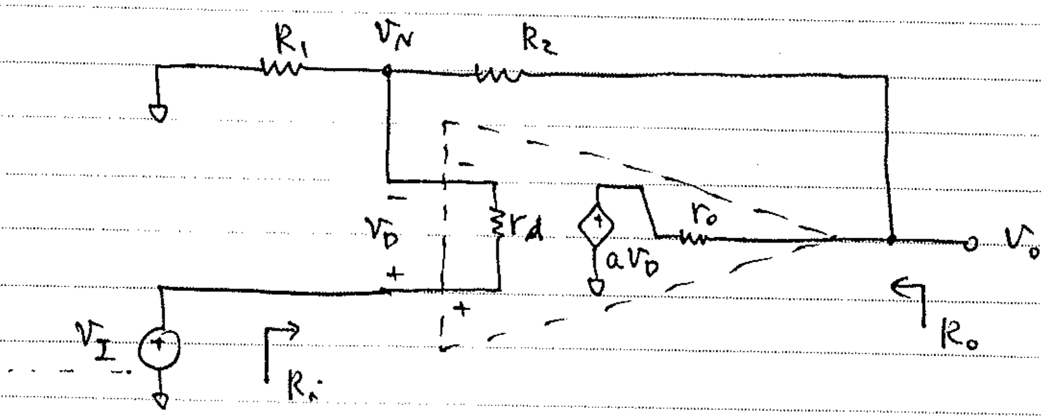
※ x_1은 줄지 않으므로, 초단에서 잡음 처리를 줄이는 것이 중요.

1.6 Feedback in Op Amp Circuits

input (summing)	output (sampling)
series ($R_i \uparrow$)	series ($R_o \uparrow$)
shunt ($R_i \downarrow$)	shunt ($R_o \downarrow$)

$\boxed{\text{Fig } 1.26}$

* Noninverting Configuration



topology : series - shunt

$$\frac{v_I - v_N}{r_d} - \frac{v_N}{R_1} + \frac{v_o - v_N}{R_2} = 0 \quad : \text{KCL at } N$$

$$\frac{v_N - v_o}{R_2} + \frac{a(v_I - v_N) - v_o}{r_o} = 0 \quad : \text{KCL at } o$$

$$\Rightarrow A = \frac{v_o}{v_I} = \frac{(1 + R_2/R_1)\,a + r_o/r_d}{1 + a + R_2/R_1 + (R_2 + r_o)/r_d + r_o/R_1}$$

$$\simeq \left(1 + \frac{R_2}{R_1}\right) \frac{1}{1 + 1/T}$$

with $\beta = \dfrac{R_1}{R_1 + R_2}$

Finding R_i : fig 1.28 (a)

$$R_i = r_d\left(1 + \frac{a}{1 + (R_2 + r_o)/R_1}\right) + R_1 \,//\, (R_2 + r_o)$$

for large a and $r_o \ll R_2$,

$$R_i \simeq r_d(1 + a\beta) = r_d(1 + T)$$

Finding R_o : fig 1.28 (b)

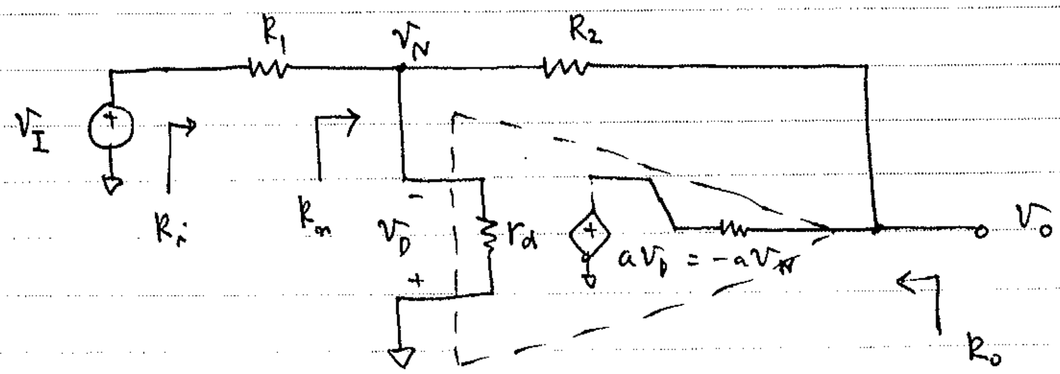
$$R_o = \frac{r_o}{1 + (a + r_o/R_1 + r_o/r_d)/(1 + R_2/R_1 + R_2/r_d)}$$

for r_d in $M\Omega$, R_1 & R_2 in $k\Omega$

r_o in Ω

$$R_o \simeq \frac{r_o}{1 + T}$$

* Inverting Configuration



$$A = -\frac{aR_2 - r_o}{(1+a)R_1 + (R_2 + r_o)(1 + R_1/r_d)}$$

for $r_o \ll R_2$ and $R_1/r_d \ll 1$,

$$A \simeq -\frac{R_2}{R_1}\frac{1}{1 + 1/T}$$

with $\beta = \dfrac{R_1}{R_1 + R_2}$

(Note that $A_{ideal} \neq \dfrac{1}{\beta}$)

Finding R_i : Fig 1.30

$$R_i = R_1 + R_n$$
$$= R_1 + \frac{R_2 + r_o}{1 + a + (R_2 + r_o)/r_d}$$
$$\simeq R_1$$

Finding R_o : Fig 1.29 → Fig 1.28(b)

$$R_o \simeq \frac{r_o}{1 + T}$$

$\boxed{\text{Example 1.10}}$

⇒ "Ideal op amp assumption is valid for most cases"

1.7 Loop Gain , $T = a\beta$

$$\begin{cases} A = A_{ideal} \times \dfrac{1}{1 + 1/T} \\ R \simeq r \times (1+T)^{\pm 1} \end{cases}$$

$A_{ideal} = \dfrac{1}{\beta}$: not always true

* Finding T Directly

① Suppress all input sources
② Break the loop
③ Inject a test signal v_T
④ Find the return signal $v_R = a\beta \times (-1) \times v_T$

$$\Rightarrow \quad T = -\left.\frac{v_R}{v_T}\right|_{x_I = 0}$$

See Fig 1.31 ⇒ Eq (1.73)

* Finding β

① Suppress all input sources
② Disconnect the op amp
③ Replace the op amp with r_d and r_o
④ Apply a test source v_T via r_o
⑤ Find v_D across r_d

$$\Rightarrow \quad \beta = -\left.\frac{v_D}{v_T}\right|_{x_I = 0}$$

See fig 1.33 ⇒ Eq (1.25)

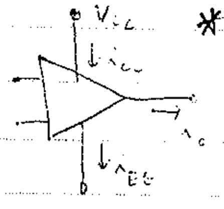
1.8 Op Amp Powering.

Fig 1.36. $\underset{}{\overset{\text{or Decoupling Capacitor}}{\text{Bypass capacitor}}}$: ac noise를 shunt out

{ 0.1 μF ceramic or low-inductance type
{ 10 μF polarized capacitor : Board level bypass

* 바이패스 경로, C는 IC에 가까이 배치

** 최근 제작사는 칩에 전원 부근 접지



V_{EE}

* Current flow and Power Dissipation

$\left\{ \begin{array}{l} i_o \\ i_{CC} \\ i_{EE} \end{array} \right\}$ See fig 1.37 $\boxed{i_{CC} = i_{EE} + i_o}$

$i_o = 0$ 일때 $i_{CC} = i_{EE} = I_Q \sim$ mA 정도 (일반 op amp)

{ op amp is sourcing ⇒ $i_{CC} = i_{EE} + i_o$
{ op amp is sinking ⇒ $i_{EE} = i_{CC} + i_o$

$$I_Q = i_{CC}\Big|_{i_o=0} = i_{EE}\Big|_{i_o=0}$$

↳ quiescent supply current ~ mA

micropower op amp : $I_Q \sim$ in μA

power dissipation due to i_o and I_Q
= internal power dissipation
↳ check againt max. rating in datasheet

⑨ $\boxed{\text{Example 1.14}}$: needs to be explained.

* Output Saturation

- See fig 1.39

$$\begin{cases} +V_{sat} = V_{OH} \simeq V_{CC} - 2 \quad [V] \\ -V_{sat} = V_{OL} \simeq V_{EE} + 2 \quad [V] \end{cases}$$

- rail-to-rail op amp

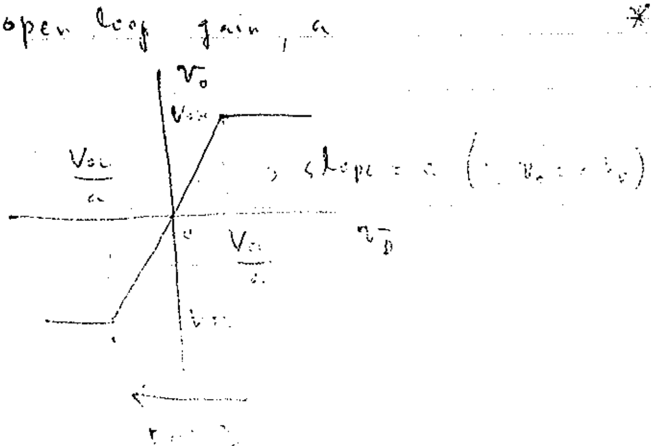
$$\begin{cases} V_{OH} = V_{CC} \\ V_{OL} = V_{EE} \end{cases}$$

- $V_{OL} < v_O < V_{OH} \Rightarrow$ op amp is in linear region

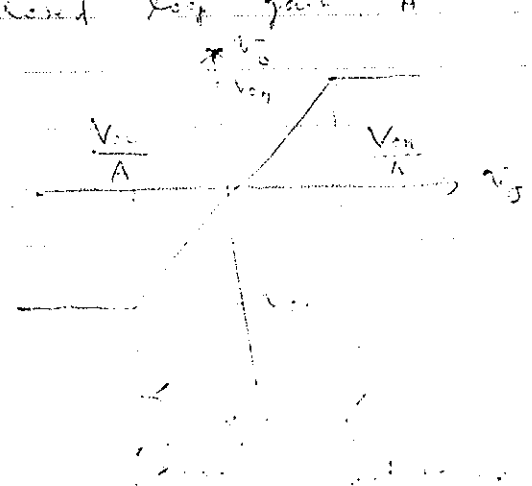
- clipping : Fig 1.40

* Input range (input swing), A, V_{OH}, V_{OL} $\Rightarrow$ output dynamic range 결정 (output swing)

* open loop gain, a



* closed loop gain A



Example 1.16 숙제

연습문제 : 숙제

요약 Ideal op amp with negative feedback for linear operation

① $v_p = v_N$

② $i_p = i_N = 0$

③ Saturation