P3360 / AEP 3630

Lecture 10

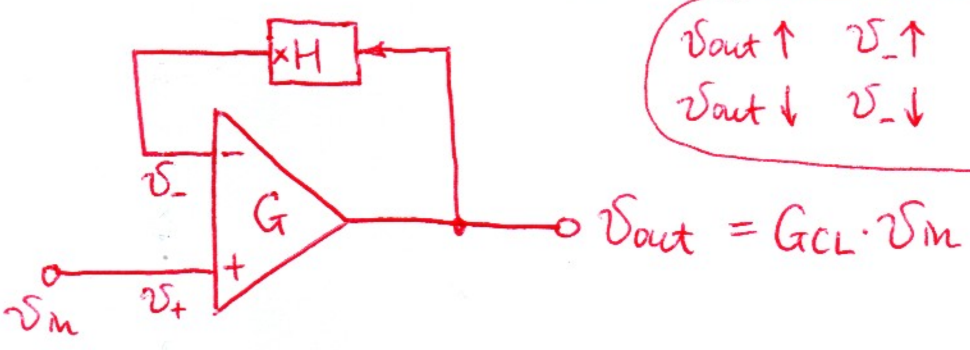
Negative Feedback

Good amp :

- $R_{in} \gg R_s$ (large input impedance)
- $R_{out} \ll R_L$ (small output imp.)
- $G(\omega) = \text{const}$ (in freq. range of interest)

"Bare" op-amp problems :

- small active range (10's μV)
- large G variations (temp. drifts)
- $G \propto \frac{1}{\omega}$ for $\omega_c \gtrsim 10\,Hz$
- Rout is fairly large ($R_{out} \sim 80\Omega$)



$v_{out}\uparrow$ $v_-\uparrow$ $v_{out}\downarrow$
$v_{out}\downarrow$ $v_-\downarrow$ $v_{out}\uparrow$ } fluct. in v_{out} with v_{in} fixed are reduced

do after defns.

$G = G_{OL}$ = open-loop gain ("bare" op-amp gain)

H = transfer fcn of feedback loop (e.g. voltage divider)

G_{CL} = closed loop gain

HG = loop gain

$$v_{out} = G(v_+ - v_-) = G(v_{in} - H v_{out}) \Rightarrow$$

$$v_{out}(1+GH) = G v_{in}$$

$$\boxed{G_{CL} \equiv \frac{v_{out}}{v_{in}} = \frac{G}{1+GH}}$$

$|H| < 1$ (passive network)

E.g. choose $|GH| \gg 1$ $\quad G \sim 2\times10^5$, $H \sim \frac{1}{100}$

$\Rightarrow GH \sim 2\times10^3$

$\boxed{G_{CL} = \frac{1}{H}}$ for $|GH| \gg 1$ (indep. of G!)

- throw away some (most) gain to make a stable circuit, indep. of op-amp fluctuations

Advantages of negative F.B.

① G_{CL} is insensitive to G (G_{OL}) variations

$$\frac{dG_{CL}}{dG} = \frac{d}{dG}\left(\frac{G}{1+GH}\right) = \frac{(1+GH) - H(G)}{(1+GH)^2} = \frac{1}{(1+GH)^2} \ll 1$$

e.g. 741 $\quad G_{typ} \sim 2\times10^5 \quad G_{min} \sim 2\times10^4$

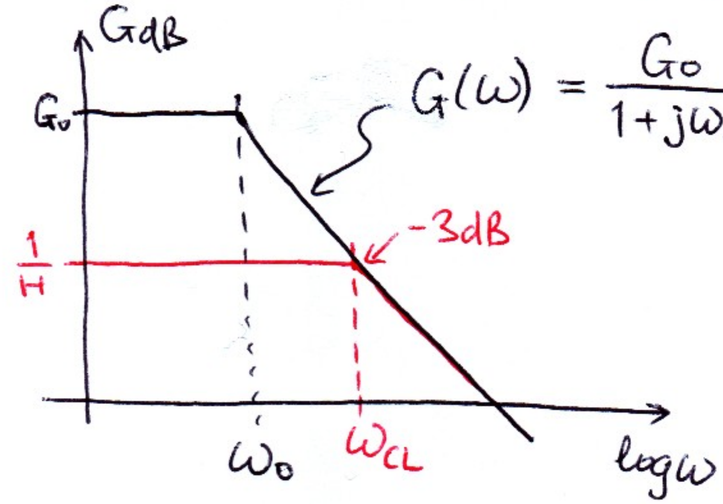
H	G	G_{CL} (close to $\frac{1}{H}$)	
$1/100$	2×10^5	99.95	$\Delta G_{CL} \lesssim 0.5\%$ for
"	2×10^4	99.5	ΔG variation by $\times 10$
"	2×10^3	95.24	

② Larger input range

$$(v_{in})_{active} = \frac{V_{sat+} - V_{sat-}}{G_{CL}} \approx H\left(V_{sat+} - V_{sat-}\right)$$

e.g. $H \sim \frac{1}{100}$, $\pm15V$ rails $\Rightarrow (v_{in})_{active} \simeq \frac{28V}{100} = 0.28\,V$

③ Flat freq. response of gain (G_{CL})



$$G(\omega) = \frac{G_0}{1 + j\omega/\omega_0}$$ "bare" op-amp gain

$$G_{CL} = \frac{1}{H}\frac{GH}{1+GH} = \frac{1}{H}\frac{1}{1+\frac{1}{GH}}$$

ω_{CL} = corner freq. when $\left|\frac{1}{GH}\right| \sim 1$

if $\omega \gg \omega_0$, $G \sim \frac{G_0}{j\omega/\omega_0}$, $\Rightarrow$

$$\boxed{\omega_{CL} \simeq \omega_0 G_0 H}$$

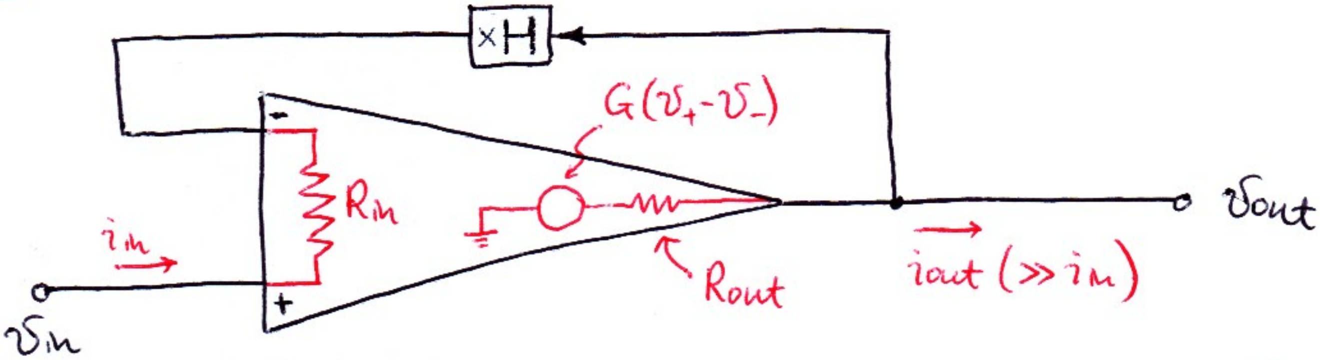
$\omega_{CL} \cdot G_{CL} = \omega_0 G_0 = \text{const}$

"gain-bandwidth product" rule

E.g. 741 $\quad G_0 \sim 2\times10^5$, $f_0 \sim 10\,\text{Hz}$ $\quad\Rightarrow\quad G_0 \cdot f_0 = 2\times10^6\,\text{Hz}$

Let $G_{CL} = \frac{1}{H} = 100$, $\Rightarrow$ $f_{CL} = 20\,\text{kHz}$

④ Increased input impedance



$$i_{in} R_{in} = v_+ - v_- = v_{in} - H v_{out} = v_{in} - H\frac{G}{1+GH}v_{in} = \frac{v_{in}}{1+GH}$$

$$\boxed{R_{in,CL} \equiv \frac{v_{in}}{i_{in}} = R_{in}(1+GH)}$$

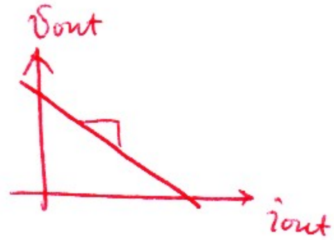
E.g. 741, $G \sim 2\times10^5$, $R_{in} \sim 1\,\text{M}\Omega$

$H \sim \frac{1}{100}$, $\Rightarrow$ $R_{in,CL} \sim 2\,\text{G}\Omega$

5 decreased output impedance

$$v_{out} = G(v_{in} - H v_{out}) - i_{out} \cdot R_{out}$$

$$v_{out} = \underbrace{\frac{G}{1+GH} v_{in}}_{\text{same as before}} - \underbrace{i_{out} \frac{R_{out}}{1+GH}}_{\text{due to loading}}$$



$$\boxed{R_{out,CL} = \frac{R_{out}}{1+GH}}$$

e.g. $G \sim 2 \times 10^5$, $H \sim \frac{1}{100}$, $R_{out} \sim 80\Omega$

$R_{out,CL} \simeq 0.04\Omega$

(ideal volt. source)

Rules for analyzing negative F.B circuits

1) current rule : inputs of op-amp draw no current
2) voltage rule : $v_{diff} = v_+ - v_- \sim 0$ (very small unless saturates)
   $v_+ \approx v_-$