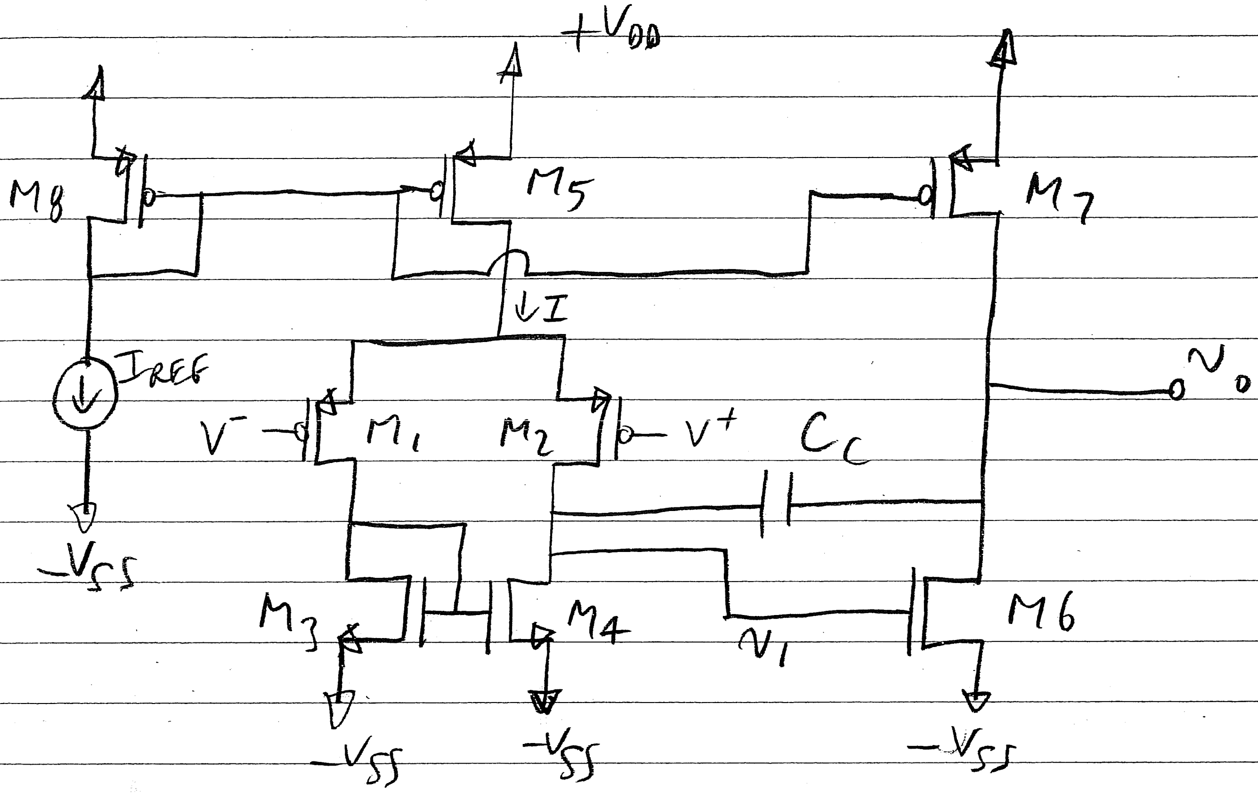
TS1

TWO-STAGE CMOS OPAMP



FOR 0 SYSTEMATIC dc OFFSET

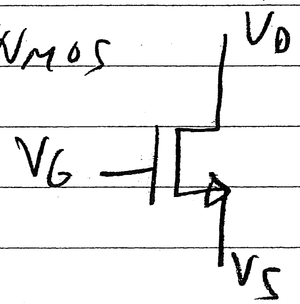
(FROM BEFOR)

$$\frac{(W/L)_6}{(W/L)_4} = 2\,\frac{(W/L)_7}{(W/L)_5}$$

(TS2)

RECALL FOR ACTIVE REGION

NMOS

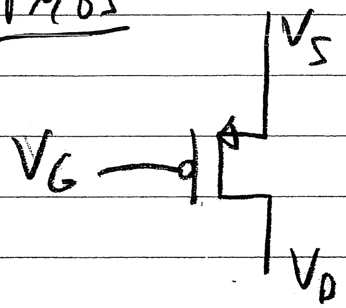


$$V_{DS} \geq V_{GS} - V_{tN}$$

$$V_D \geq V_G - V_{tN}$$

$$V_G \leq V_D + V_{tN}$$

PMOS



$$V_{SD} \geq V_{SG} - |V_{tp}|$$

$$-V_D \geq -V_G - |V_{tp}|$$

$$V_G \geq V_D - |V_{tp}|$$

INPUT COMMON-MODE RANGE

TIE V^+ TO V^- + CONNECT TO V_{ICM}

MIN V_{ICM} => KEEP M1 + M2 ACTIVE

$$V_{ICM} \geq -V_{SS} + V_{tN} + V_{OV3} - |V_{tp}| \qquad (1)$$

MAX V_{ICM} => KEEP M5 ACTIVE

$$V_{ICM} + |V_{tp}| + |V_{OV1}| \leq V_{DD} - |V_{OV5}| \qquad (2)$$

COMBINING 1 & 2 WE HAVE

$$-V_{SS} + V_{tN} + V_{OV3} - |V_{tP}| \leq V_{ICM} \leq V_{DD} - |V_{tP}| - |V_{OV1}| - |V_{OV5}|$$

IF $V_{tN} \approx |V_{tP}|$

$$-V_{SS} + V_{OV3} \leq V_{ICM} \leq V_{DD} - |V_{tP}| - |V_{OV1}| - |V_{OV5}|$$

CAN BE CLOSER TO $-V_{SS}$ THAN V_{DD}

OUTPUT VOLTAGE SWING

$$-V_{SS} + V_{OV6} \leq v_o \leq V_{DD} - |V_{OV7}|$$

WITHIN ONE V_{OV} OF EACH POWER SUPPLY.

(TS4)

VOLTAGE GAIN

$$\tilde{v}_{id} \equiv v^+ - v^-$$

$$A_1 \equiv \frac{v_1}{v_{id}} = -g_{m1}(r_{o2} \| r_{o4})$$

WHERE $g_{m1} = \frac{2I_D}{V_{OV_1}} = \frac{2\left(\frac{I}{2}\right)}{V_{OV_1}} = \frac{I}{V_{OV_1}}$

$$r_{o2} = \frac{|V_{A2}|}{\left(I/2\right)} \qquad r_{o4} = \frac{V_{A4}}{\left(I/2\right)}$$

$$A_1 = \frac{-\left(\frac{2}{V_{OV_1}}\right)}{\left(\frac{1}{|V_{A2}|}\right) + \left(\frac{1}{V_{A4}}\right)}$$

FOR A GIVEN I ⇒ TO INCREASE A_1

DECREASE V_{OV_1} & INCREASE $|V_{A2}|$ & V_{A4}
(LARGER W/L) (LONGER L)

TS5

$$A_2 \equiv \frac{v_o}{v_1} = -g_{m6}\,(r_{o6} \,||\, r_{o7})$$

WHERE $\quad g_{m6} = \dfrac{2 I_{D6}}{V_{OV6}}$

$$r_{o6} = \frac{V_{A6}}{I_{D6}} \qquad r_{o7} = \frac{|V_{A7}|}{I_{D6}} \qquad \text{SINCE } I_{D7} = I_{D6}$$

$$A_2 = \frac{-\dfrac{2}{V_{OV6}}}{\left(\dfrac{1}{V_{A6}}\right) + \left(\dfrac{1}{|V_{A7}|}\right)}$$

TO INCREASE $A_2 \Rightarrow$ DECREASE V_{OV6}
(LARGE W/L)

INCREASE V_{A6}, V_{A7}
(LONGER L)

$$A_v = A_1 A_2$$

$$A_v = g_{m1}\,(r_{o2} \,||\, r_{o4})\, g_{m6}\,(r_{o6} \,||\, r_{o7})$$

OUTPUT RESISTANCE

$$R_o = r_{o6} \parallel r_{o7}$$

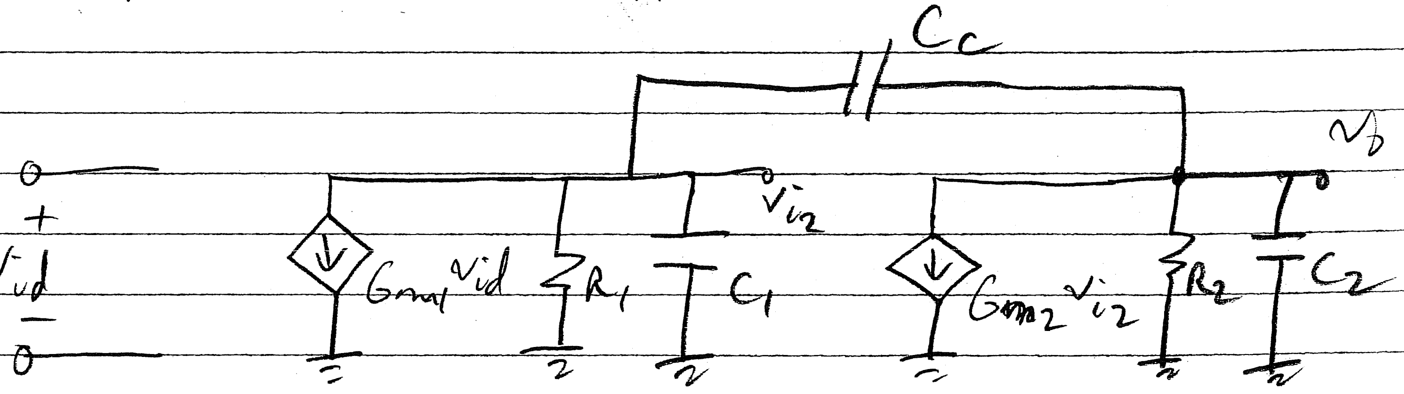
IF IN FEEDBACK WITH $\beta = 1$

THEN
$$R_{of} = \frac{R_o}{1 + A_v\beta} \simeq \frac{r_{o6} \parallel r_{o7}}{g_{m1}(r_{o1} \parallel r_{o2})\, g_{m6}(r_{o6} \parallel r_{o7})}$$

$$R_{of} \simeq \frac{1}{g_{m6}\, g_{m1}(r_{o1} \parallel r_{o2})}$$

FREQ RESPONSE

CAN MODEL OPAMP AS



$G_{m1} = g_{m1}$ $\qquad$ $G_{m2} = g_{m6}$

$R_1 = r_{o2} \| r_{o4}$ $\qquad$ $R_2 = r_{o6} \| r_{o7}$

$C_1 = C_{gd2} + C_{db2} + C_{gd4} + C_{db4} + C_{gs6}$

$C_2 = C_{db6} + C_{db7} + C_{gd7} + C_L$

C_C ADDED COMPENSATION CAPACITOR THAT INCLUDES C_{gd6}

FROM BEFORE WE FOUND

$$f_{p1} \cong \frac{1}{2\pi R_1 G_{m2} R_2 C_C}$$ DOMINANT POLE

$$f_{p2} \cong \frac{G_{m2}}{2\pi C_2}$$ NON-DOMINANT POLE

$$f_Z \approx \frac{G_{m2}}{2\pi C_C}$$ ZERO

& $$f_t \approx |A_v| f_{p1} = \frac{G_{m1}}{2\pi C_C}$$ UNITY GAIN FREQ

TO ENSURE REASONABLE STABILITY WITH $\beta = 1$

REQUIRE $f_t \leq f_{p2}$ & $f_t \leq f_Z$

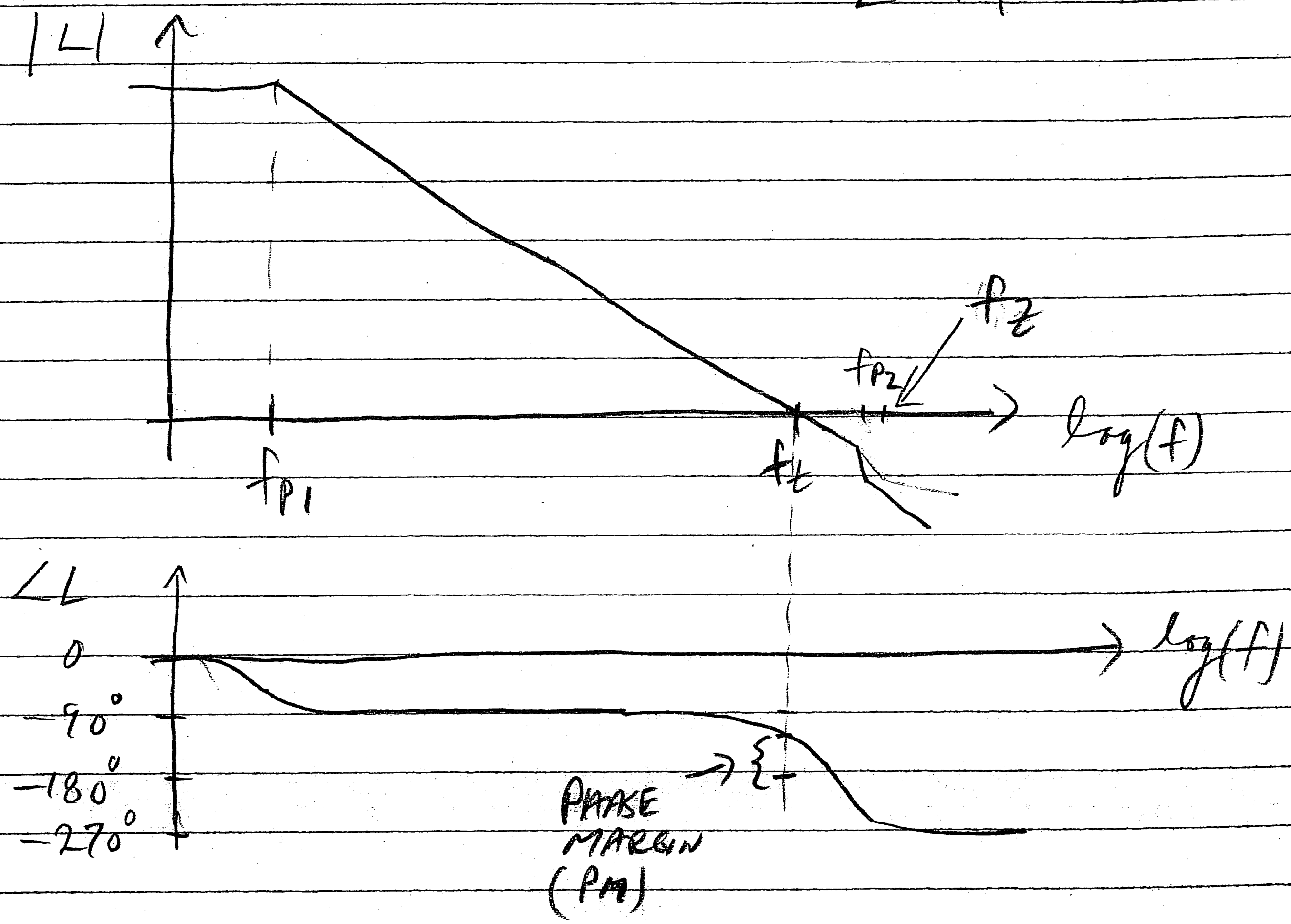
SO $$\frac{G_{m1}}{C_C} \leq \frac{G_{m2}}{C_2}$$ (f_{p2} REQUIREMENT)

AND $G_{m1} \leq G_{m2}$ (f_Z REQUIREMENT)

TS9

PHASE MARGIN (ASSUME $\beta = 1$)

$L = A\beta = A$



f_{P2} LEFT HALF PLANE POLE ⇒ $-90°$ (PHASE LAG)

f_Z RIGHT HALF PLANE ZERO ⇒ $-90°$ (PHASE LAG)

$$\phi_{P_2} = -\tan^{-1}\left(\frac{f_t}{f_{P_2}}\right)$$ ← AT f_t DUE TO f_{P2}

$$\phi_Z = -\tan^{-1}\left(\frac{f_t}{f_Z}\right)$$ ← AT f_t DUE TO f_Z

TS10

SO PHASE AT $f_t \Rightarrow \phi_{TOTAL}$

$$\phi_{TOTAL} = -90^\circ - \tan^{-1}\left(\frac{f_t}{f_{P2}}\right) - \tan^{-1}\left(\frac{f_t}{f_z}\right)$$

PHASE MARGIN $PM = \phi_{TOTAL} - (-180^\circ)$

$$= 180 + \phi_{TOTAL}$$

$$PM = 90 - \tan^{-1}\left(\frac{f_t}{f_{P2}}\right) - \tan^{-1}\left(\frac{f_t}{f_z}\right)$$

SO RIGHT HALF PLANE ZERO CAUSES WORSE PHASE MARGIN

(NOTE A LEFT HALF PLANE ZERO WOULD HELP IMPROVE PHASE MARGIN)

LHP & RHP ZERO

TS10A

CONSIDER NUMERATOR

ROOT

$$\left(1 + \frac{s}{\omega_z}\right) \Rightarrow s = -\omega_z$$

IF $\omega_z > 0$ LHP ZERO

$$\angle\left(1 + \frac{j\omega}{\omega_z}\right) = \angle \tan^{-1}\left(\frac{\omega}{\omega_z}\right)$$

IF $\omega = \omega_z \Rightarrow$ PHASE $= 45^\circ$

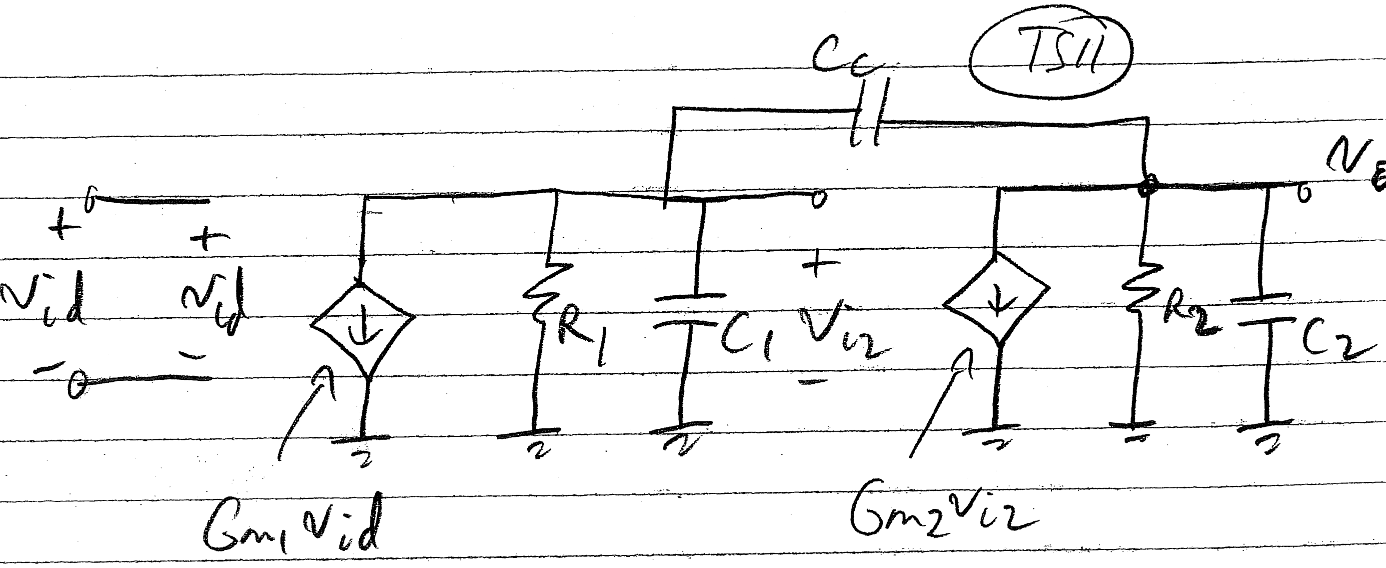
$(\tan^{-1}(1))$

IF $\omega_z < 0$ RHP ZERO

$$\angle\left(1 + \frac{j\omega}{\omega_z}\right) = \angle \tan^{-1}\left(\frac{\omega}{\omega_z}\right)$$

IF $\omega = -\omega_z \Rightarrow$ PHASE $= -45^\circ$

$(\tan^{-1}(-1))$



ZERO OCCURS WHERE $\frac{v_o}{v_{id}} = 0$

SO TO FIND ZERO CAN ASSUME $v_o = 0$

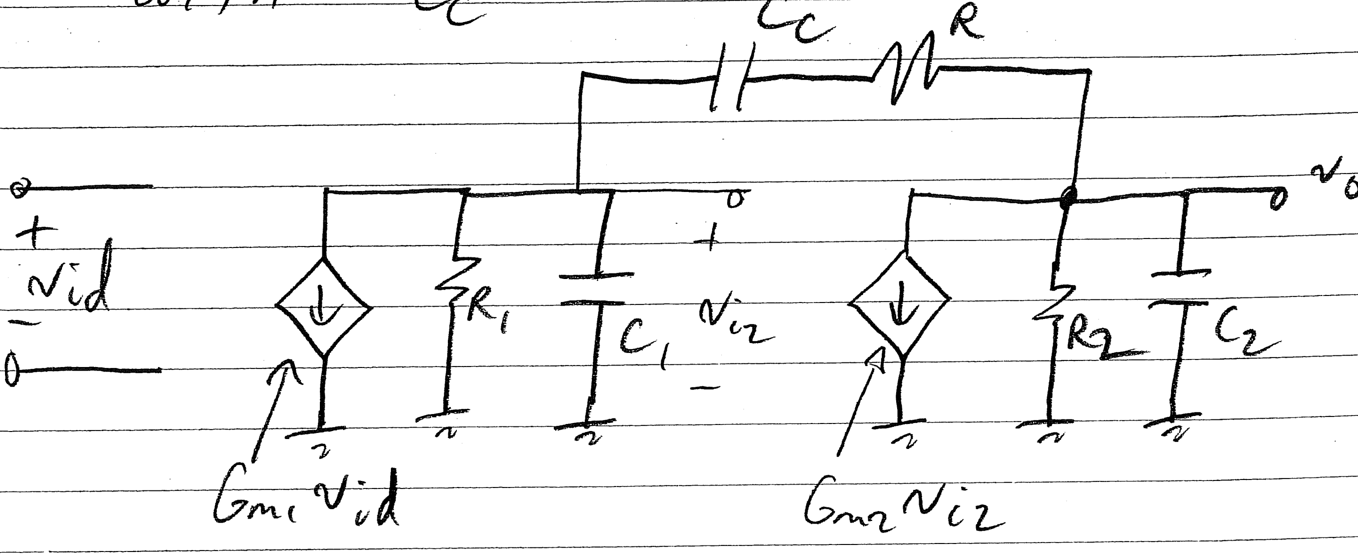
AND WRITE

$$\frac{v_{i2}}{\frac{1}{sC_c}} = G_{m2} v_{i2} \Rightarrow s = \frac{1}{C_c\left(\frac{1}{G_{m2}}\right)}$$

RHP $\quad \omega_z = \frac{1}{C_c\left(\frac{1}{G_{m2}}\right)}$

$$f_z = \frac{1}{2\pi C_c\left(\frac{1}{G_{m2}}\right)}$$

INTRODUCE R IN SERIES WITH C_C



NOW $\dfrac{v_{i2}}{R + \frac{1}{sC_C}} = G_{m2} v_{i2}$

$$\Rightarrow s = \frac{1}{C_C\left(\frac{1}{G_{m2}} - R\right)} \Rightarrow \omega_z = \frac{1}{C_C\left(\frac{1}{G_{m2}} - R\right)}$$

IF $R = \dfrac{1}{G_{m2}}$ $\omega_z \to \infty$

MUCH BETTER PHASE MARGIN

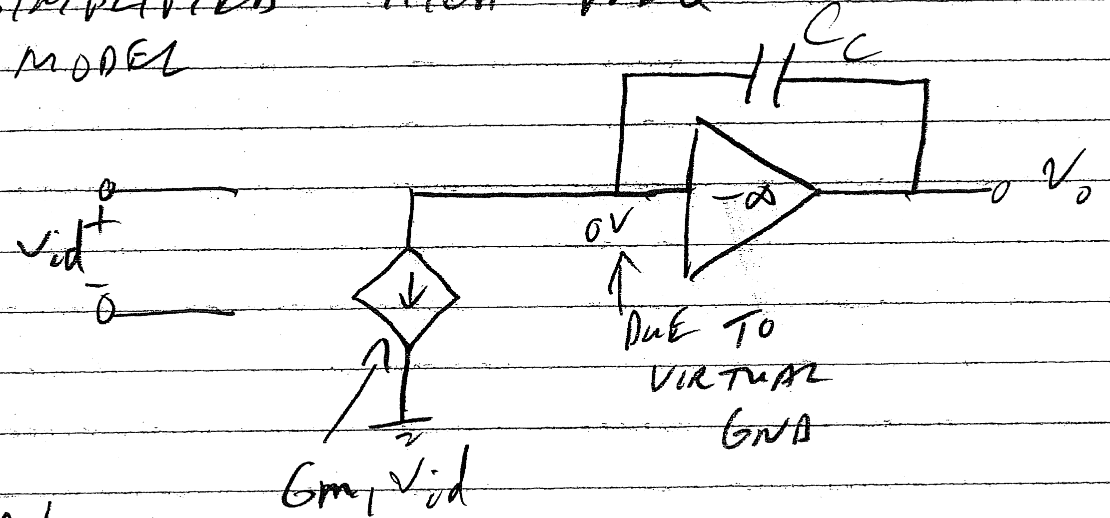
IF $R > \dfrac{1}{G_{m2}}$ ZERO IN LEFT HALF PLANE

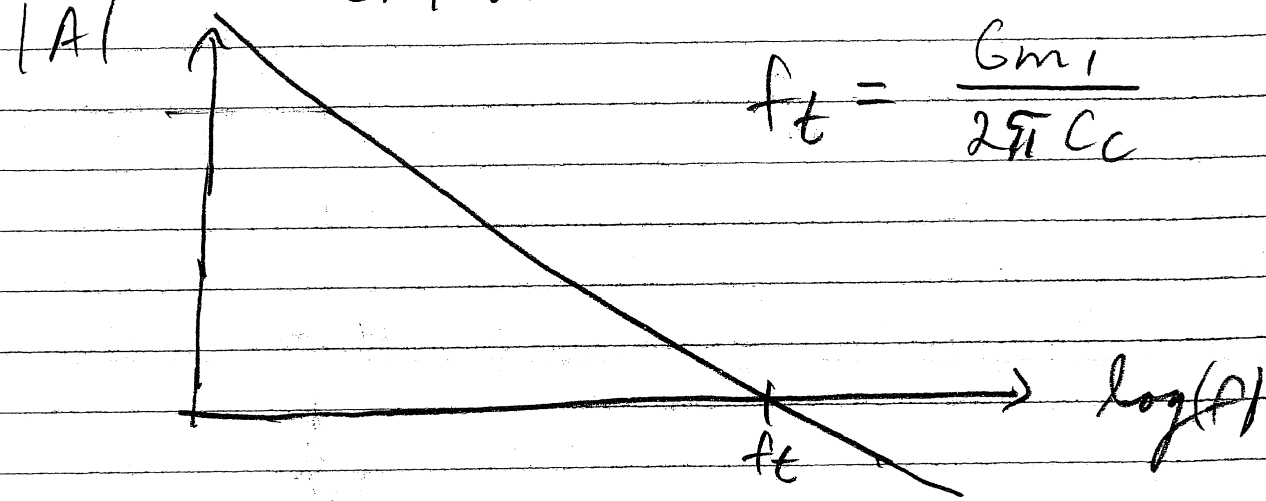
AND IMPROVES PHASE MARGIN

(LIMIT TO THIS AS THERE ARE OTHER POLES AS WELL)

TS13

SIMPLIFIED HIGH FREQ MODEL



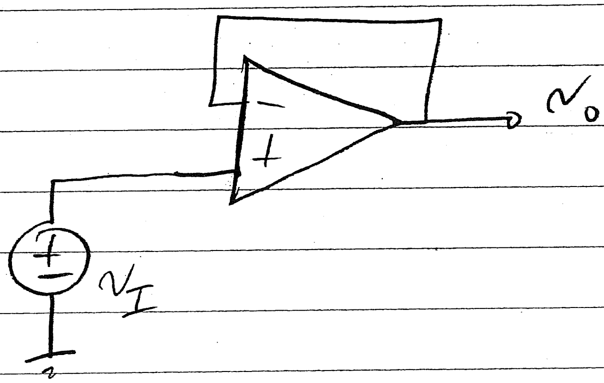


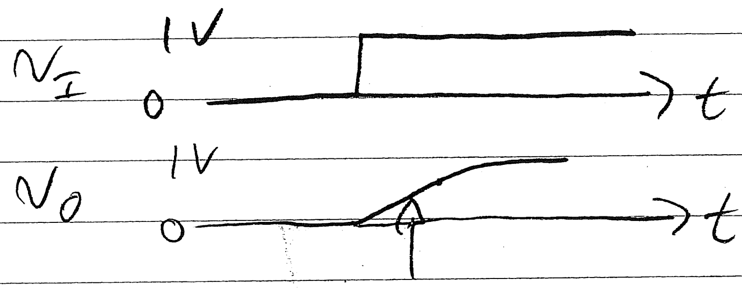
$$f_t = \frac{Gm_1}{2\pi C_c}$$

VALID FOR $f \gg f_{p1}$

(BUT NOT REALISTIC OUTPUT IMPEDANCE)

SLEW-RATE

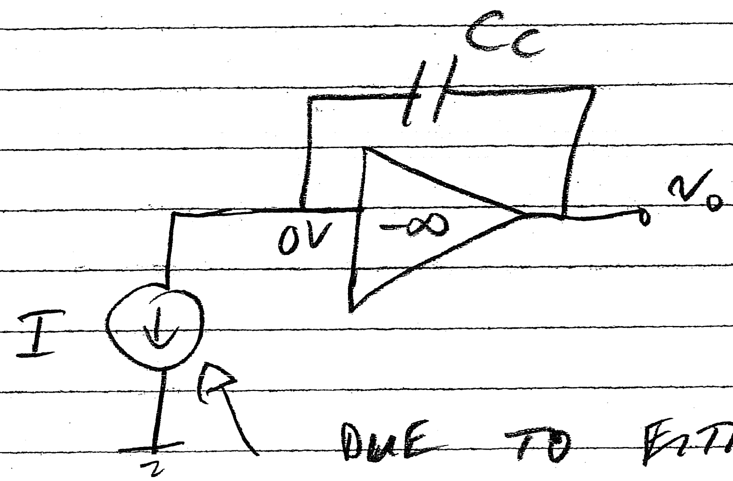




SLEW-RATE LIMITED $\quad$ MAX $\frac{dv_o}{dt}$

SLEW-RATE LIMIT OCCURS WHEN $\underline{\underline{I}}$ OF INPUT DIFF PAIR ALL GOES ONE SIDE OF DIFF PAIR AND CHARGE/DISCHARGES C_C

TS15



DUE TO EITHER $\begin{cases} i_{d4} = I \\ i_{d2} = 0 \end{cases}$

OR $\begin{cases} i_{d2} = I \\ i_{d4} = 0 \end{cases}$

$$q = CV \Rightarrow \frac{dq}{dt} = C\frac{dv}{dt} \Rightarrow I = C\frac{\Delta V}{\Delta t}$$

HERE

$$v_o(t) = \frac{I}{C_c}t$$

$$SR = \frac{I}{C_c}$$

RELATIONSHIP BETWEEN SR & f_t

$$G_{m1} = g_{m1} = \frac{2I_{D1}}{V_{OV1}} = \frac{2\left(\frac{I}{2}\right)}{V_{OV1}} = \frac{I}{V_{OV1}}$$

$$I = G_{m1} V_{OV1}$$

$$SR = \frac{G_{m1} V_{OV1}}{C_C} \quad \& \quad f_t = \frac{G_{m1}}{2\pi C_C}$$

$$\Rightarrow G_{m1} = 2\pi f_t C_C$$

$$SR = 2\pi f_t V_{OV1} \quad \& \quad \omega_t = 2\pi f_t$$

$$\boxed{SR = \omega_t V_{OV1}}$$

SO TO OBTAIN A HIGH SLEW-RATE

INCREASE V_{OV1} & ω_t

SHOULD CHOOSE PMOS INPUT STAGE

f_{P2} DUE TO NMOS $\Rightarrow$ INCREASES ω_t

V_{OV1} HIGHER FOR SAME I

TS17

FINALLY RECALL FROM CHAPTER 2

IF OUTPUT STEP SIZE IS $\hat{V}_0$

THEN WILL NOT SLEW-RATE LIMIT IF

$$\omega_t \hat{V}_0 \leq SR = \omega_t V_{ov_1}$$

IF STEP OUTPUT HAS

$\hat{V}_0 \leq V_{ov_1}$ THEN WILL NOT SLEW-RATE LIMIT.
& WILL ~~SETTLE~~ SETTLE AS EXPONENTIAL