Basic Opamp Design and Compensation

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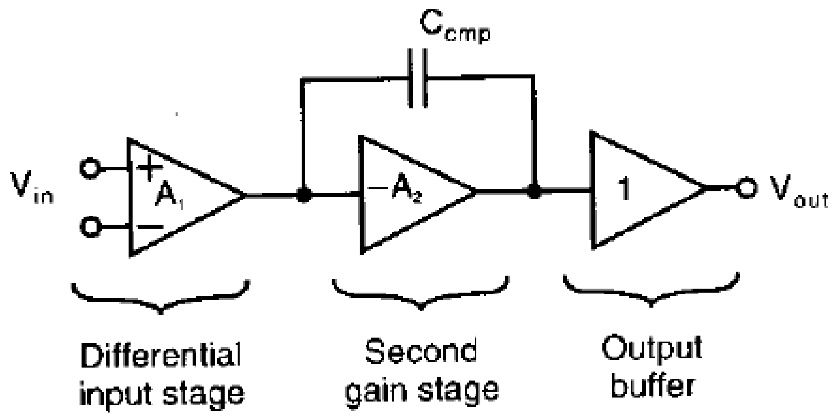
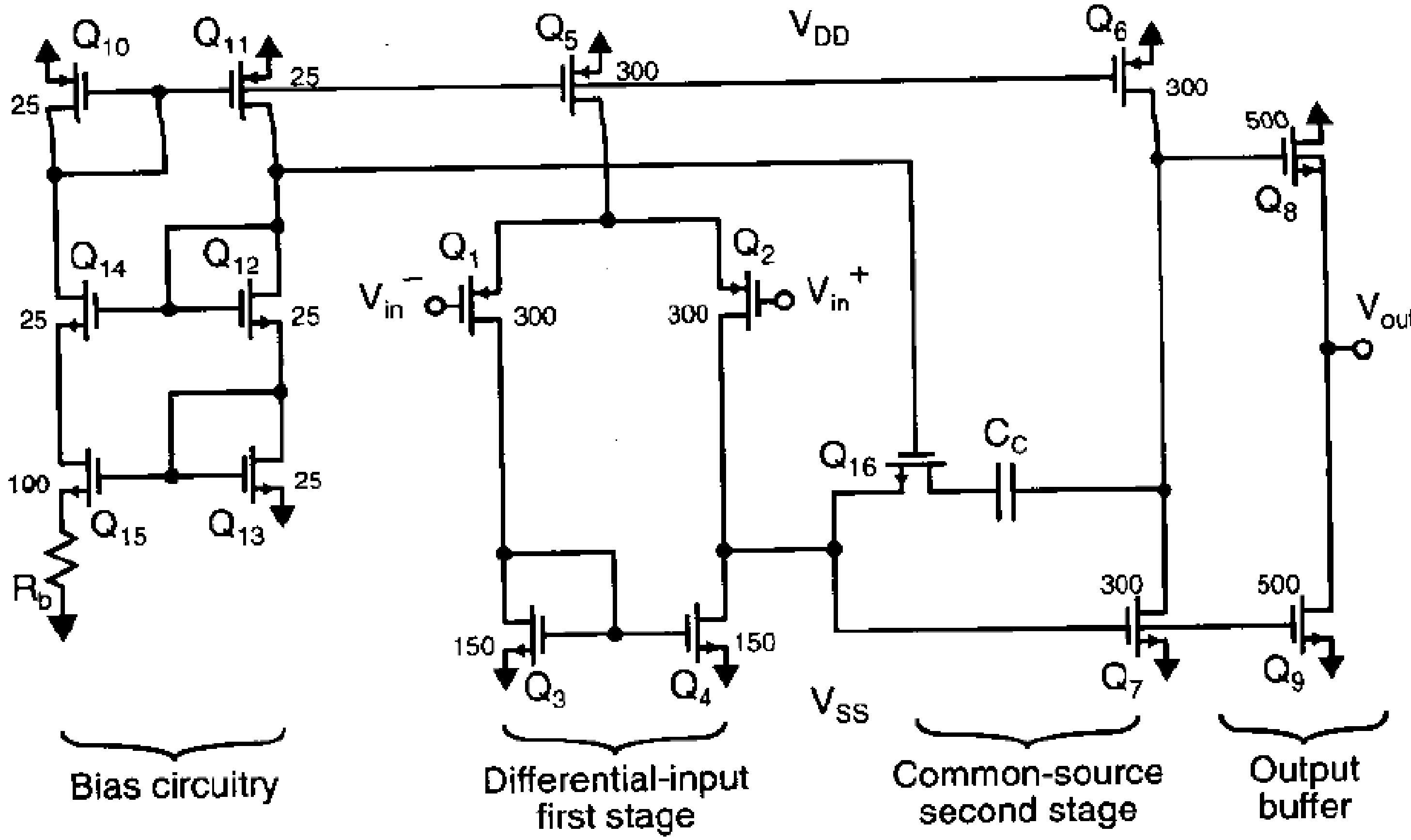
Two-Stage opamp





opamp Gain

$$A_{V1} = -g_{m_1}\left(r_{ds2} \| r_{ds4}\right)$$

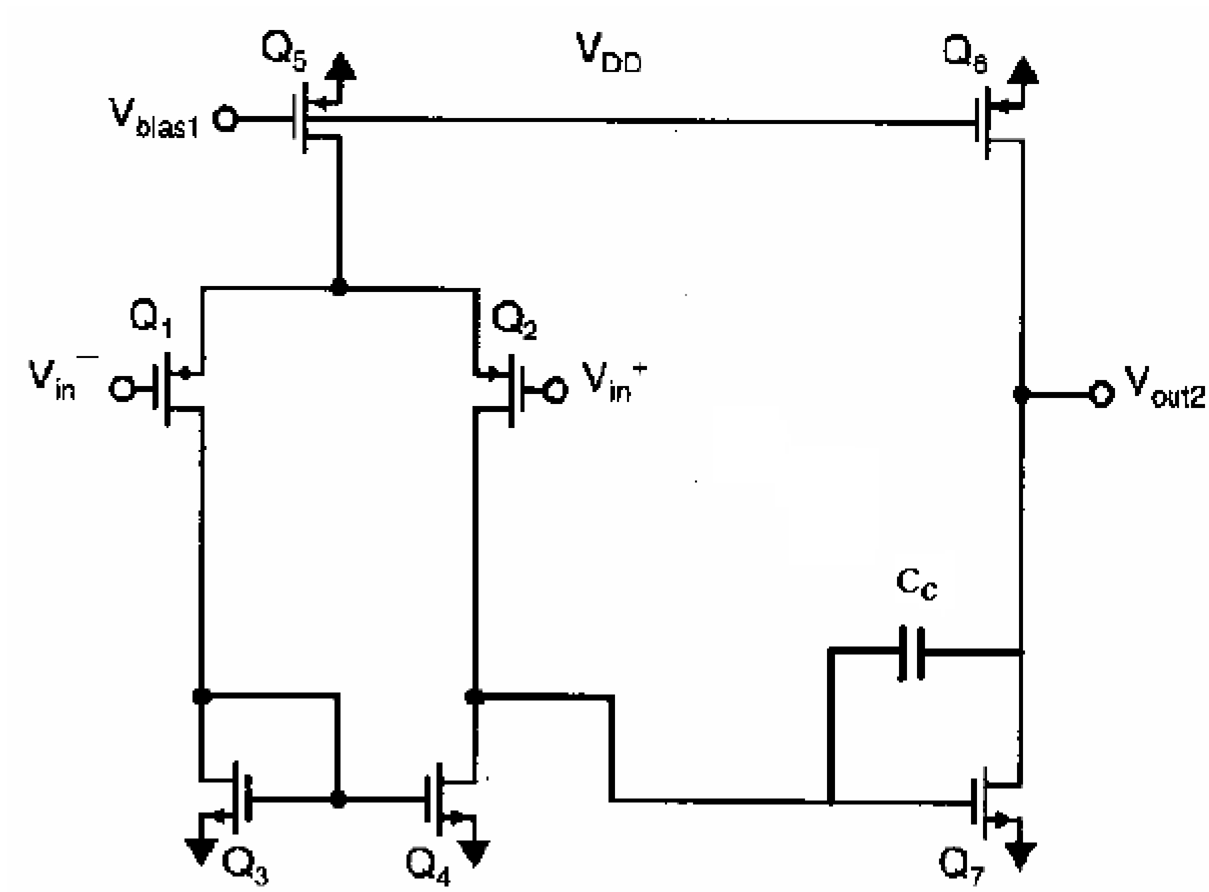
$$A_{v2} = -g_{m7}(r_{ds6} \| r_{ds7})$$

$$A_{v3} \cong \frac{g_{m8}}{G_L + g_{m8} + g_{ds8} + g_{ds9}}$$

$$A_0 = A_{V1} \times A_{V2} \times A_{V3}$$

Slew Rate

$$SR = \left|\frac{dV_o}{dt}\right|_{max} = \frac{I_{D5}}{C_C}$$



Guidelines for Biasing of the Two-Stage opamp

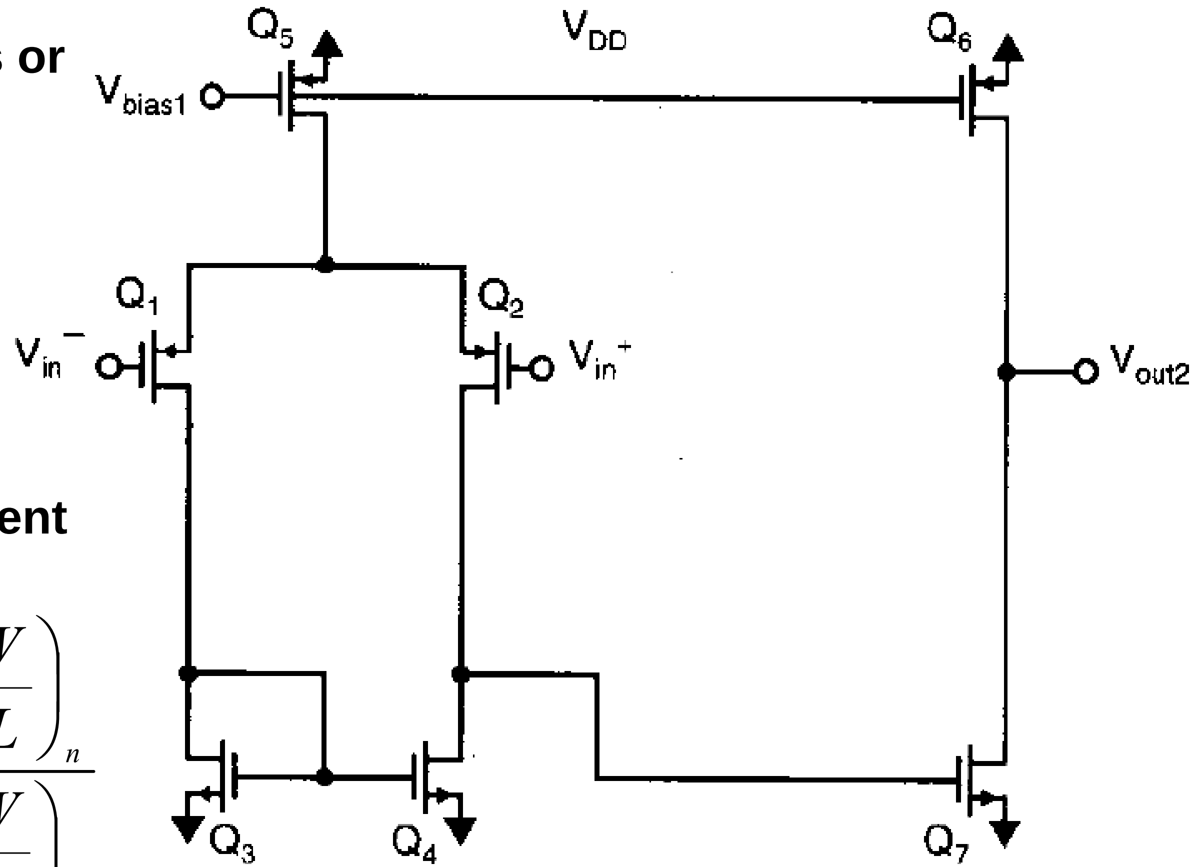
1. **100 mV < $V_{DS(SAT)}$ < 200mV**
2. **$V_{DS} > 2V_{DS(SAT)}$**

3. (both Mi and Mj are npmos or pmos)

$$\frac{I_{D_i}}{I_{D_j}} = \frac{\left(\frac{W}{L}\right)_i}{\left(\frac{W}{L}\right)_j}$$

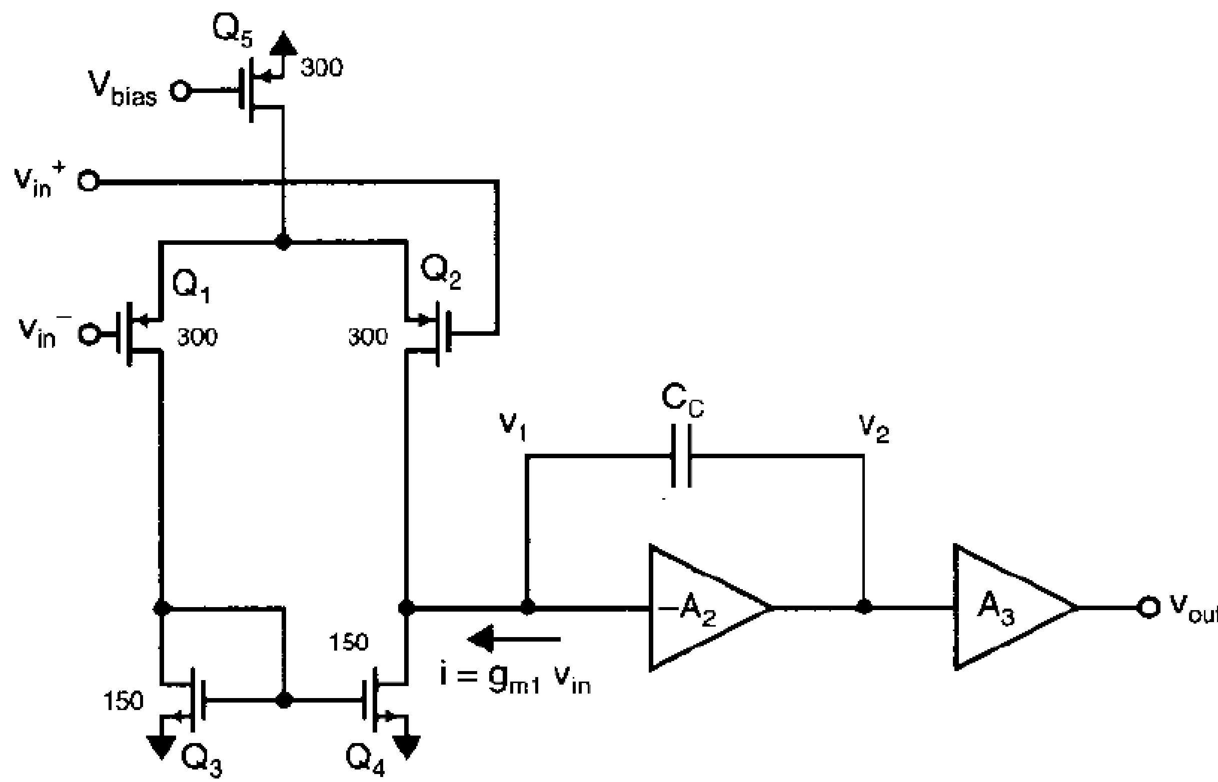
4.(Transistors are from different types)

$$\frac{I_{D_n}}{I_{D_p}} = \frac{\mu_n}{\mu_p}\frac{\left(\frac{W}{L}\right)_n}{\left(\frac{W}{L}\right)_p} \cong 3\frac{\left(\frac{W}{L}\right)_n}{\left(\frac{W}{L}\right)_p}$$



Frequency Response (first-order model)

$$A(s) = \frac{A_0}{1 + \frac{s}{\omega_{p1}}}$$



$$\omega_{p1} \cong \frac{1}{\left(r_{ds2} \| r_{ds4}\right) C_C \left(1 + A_2\right)}$$

$$\cong \frac{1}{\left(r_{ds2} \| r_{ds4}\right) C_C A_2}$$

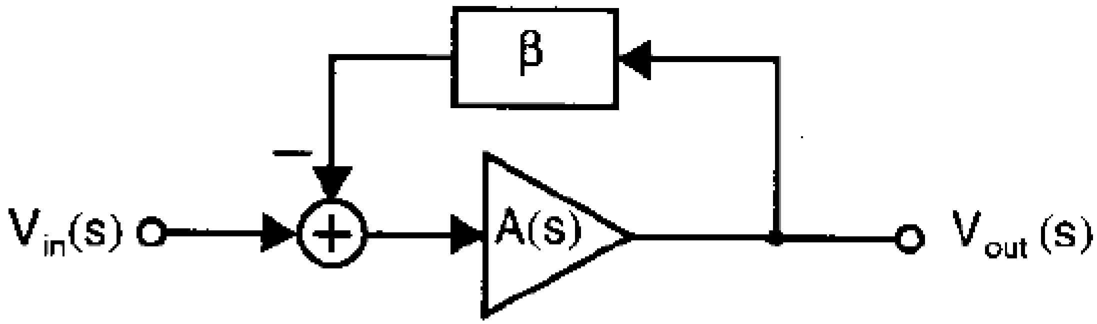
$$A_0 = g_{m_i} \left(r_{ds2} \| r_{ds4}\right) A_2$$

It is proven that:

$$UGBW = \omega_{ta} = A_0 \omega_{p1} = \frac{g_{m_i}}{C_C}$$

Since a first order transfer function is assumed for the Opamp, therefore it does not have stability problem.

Using opamp in closed-loop configurations



$$A(s) = \frac{A_0}{(1 + s/\omega_{p1})}$$

$$A_{CL}(s) = \frac{A(s)}{1 + \beta A(s)}$$

$$A_{CL}(s) \approx \frac{\omega_{ta}}{\beta\omega_{ta} + s} = \frac{1}{\beta}\frac{1}{(1 + s/\beta\omega_{ta})}$$

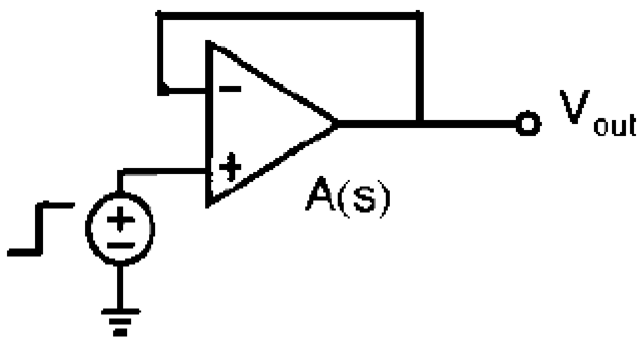
Hence for the closed-loop amplifier, we have:

$$A_{CL}(0) = \frac{1}{\beta}$$

$$\omega_{-3dB} = \beta\omega_{ta}$$

Using opamp in closed-loop configurations (Eample#1)

$V_{step}U(t)$

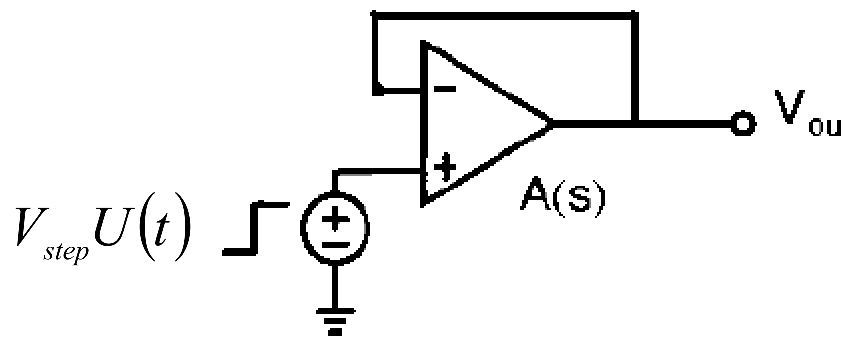


After performing an accurate analysis, we have:

$$V_o(s) = \frac{\frac{A_0}{1+A_0}}{1+\frac{s}{(1+A_0)\omega_{p1}}} \times \frac{1}{s} \times V_{step} \cong \frac{1-\frac{1}{A_0}}{1+\frac{s}{\omega_{ta}}} \times \frac{1}{s} \times V_{step}$$

$$v_o(t) \cong \left(1-\frac{1}{A_0}\right) V_{step}\left(1-e^{\frac{-t}{\tau}}\right), \quad \tau = \frac{1}{\omega_{ta}}$$

Using opamp in closed-loop configurations (Eample#1)



$$v_o(t) \cong \left(1 - \frac{1}{A_0}\right) V_{step} \left(1 - e^{\frac{-t}{\tau}}\right), \quad \tau = \frac{1}{\omega_{ta}}$$

$$\left(\frac{dv_o}{dt}\right)_{\max} = \left.\frac{dv_o}{dt}\right|_{t=0} = V_{step}\omega_{ta}$$

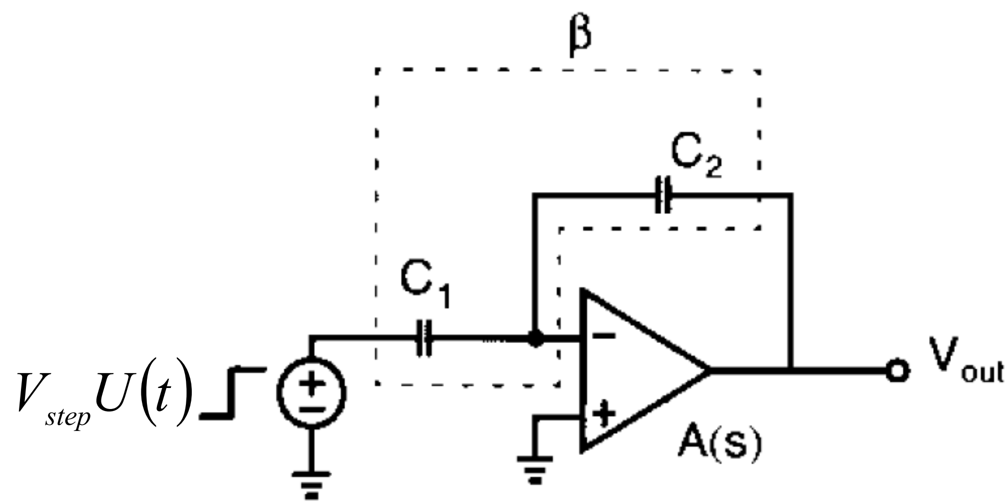
if $V_{step}\omega_{ta} \leq SR \Rightarrow$

The circuit has only the linear settling - time.

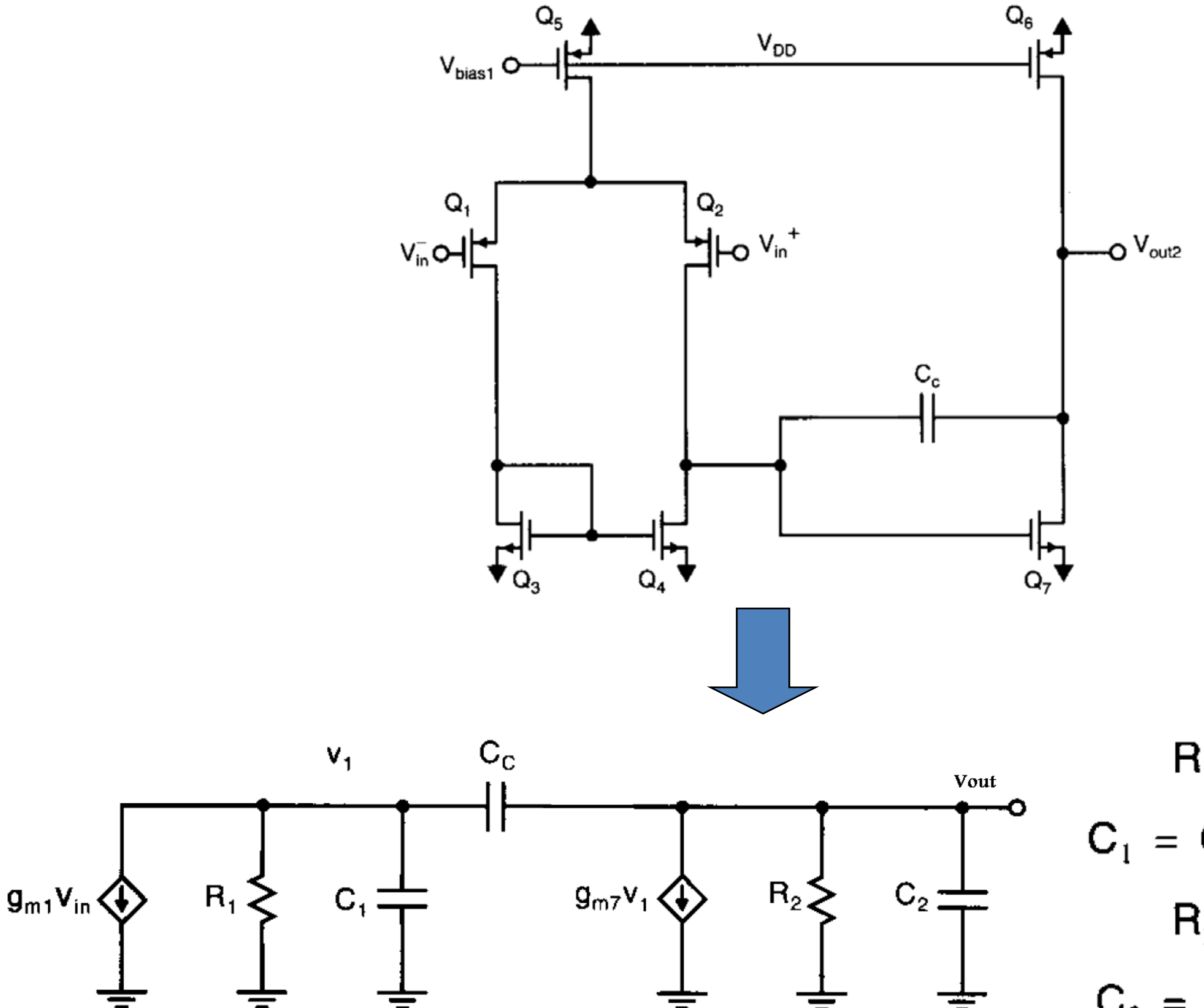
if $V_{step}\omega_{ta} \geq SR \Rightarrow$

The circuit has both the linear and non - linear settling - times.

Using opamp in closed-loop configurations (Eample#2)



Frequency Response (second-order model)



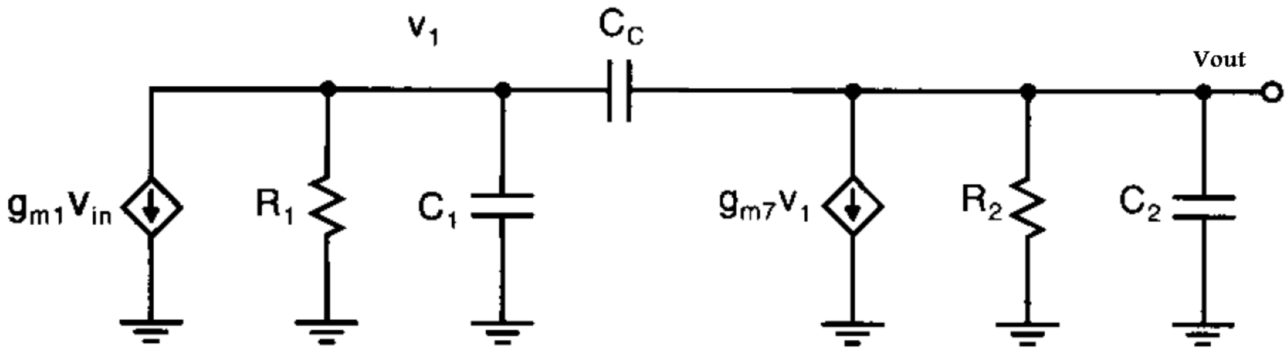
$$R_1 = r_{ds4} \parallel r_{ds2}$$

$$C_1 = C_{db2} + C_{db4} + C_{gs7}$$

$$R_2 = r_{ds6} \parallel r_{ds7}$$

$$C_2 = C_{db7} + C_{db6} + C_{L2}$$

Frequency Response (second-order model)



$$\frac{V_{out}}{V_{in}} = \frac{g_{m1} g_{m7} R_1 R_2 \left(1 - \frac{sC_C}{g_{m7}}\right)}{1 + sa + s^2 b}$$

$$a = (C_2 + C_C)R_2 + (C_1 + C_C)R_1 + g_{m7}R_1R_2C_C$$

$$b = R_1R_2(C_1C_2 + C_1C_C + C_2C_C)$$

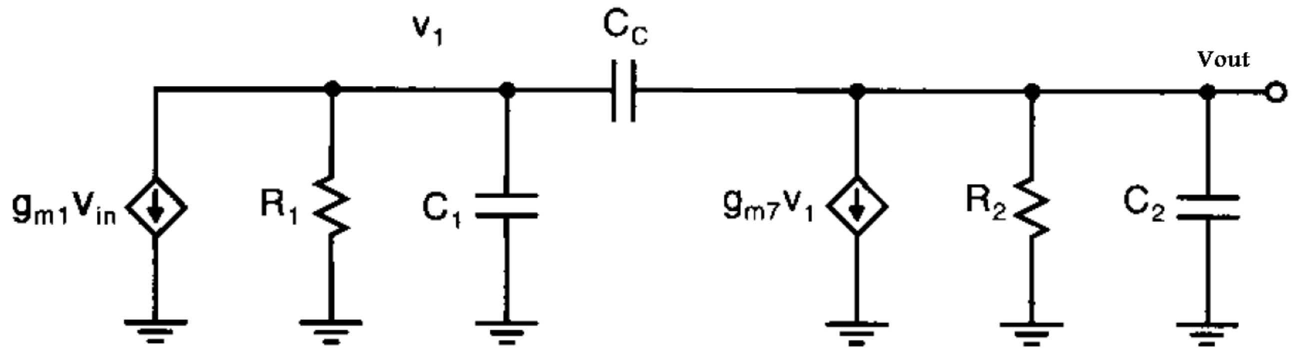
$$D(s) = \left(1 + \frac{s}{\omega_{p1}}\right)\left(1 + \frac{s}{\omega_{p2}}\right) \cong 1 + \frac{s}{\omega_{p1}} + \frac{s^2}{\omega_{p1}\omega_{p2}}$$

$$\omega_{p1} \cong \frac{1}{R_1[C_1 + C_C(1 + g_{m7}R_2)] + R_2(C_2 + C_C)} \cong \frac{1}{R_1C_C(1 + g_{m7}R_2)} \cong \boxed{\frac{1}{g_{m7}R_1R_2C_C}}$$

$$\omega_{p2} \cong \frac{g_{m7}C_C}{C_1C_2 + C_2C_C + C_1C_C} \cong \boxed{\frac{g_{m7}}{C_1 + C_2}}$$

$$\boxed{\omega_z = \frac{-g_{m7}}{C_C}}$$

Frequency Response (second-order model)



$$\omega_{p1} = \frac{1}{g_{m7} R_1 R_2 C_C}, \quad \omega_{p2} = \frac{g_{m7}}{C_1 + C_2}, \quad \omega_z = \frac{-g_{m7}}{C_C}$$

- As g_{m7} increases, the separation between the first and second poles increase.
- Increasing C_C moves the dominant pole to a lower frequency without affecting the second pole.
- Hence, the use of a Miller capacitance for compensation is often called "pole-splitting compensation".
- The pole-splitting makes the opamp more stable.

Example1

Consider a two-stage opamp with the following characteristics:

$$g_{m1} = 1\frac{mA}{V}, g_{m7} = 3\frac{mA}{V}$$

$$R_1 = 10\ k, R_2 = 15\ k$$

$$C_1 = 0.1\ pF, C_2 = 0.3\ pF, C_C = 2\ pF$$

a) Calculate A_0 , ω_{p1}, ω_{p2}, ω_z, and A(s).

$$A_0 = g_{m1}g_{m7}R_1R_2 = 450 \rightarrow A_0\Big|_{dB} = 53\ dB$$

$$\omega_{ta} = \frac{g_{m1}}{C_C} = \frac{1m}{2p} = 0.5\ G\ \frac{Rad}{s} = 2\pi \times 80\ MHz$$

$$\omega_{ta} = A_0 \times \omega_{p1} \rightarrow \omega_{p1} = 2\pi \times 177\ kHz$$

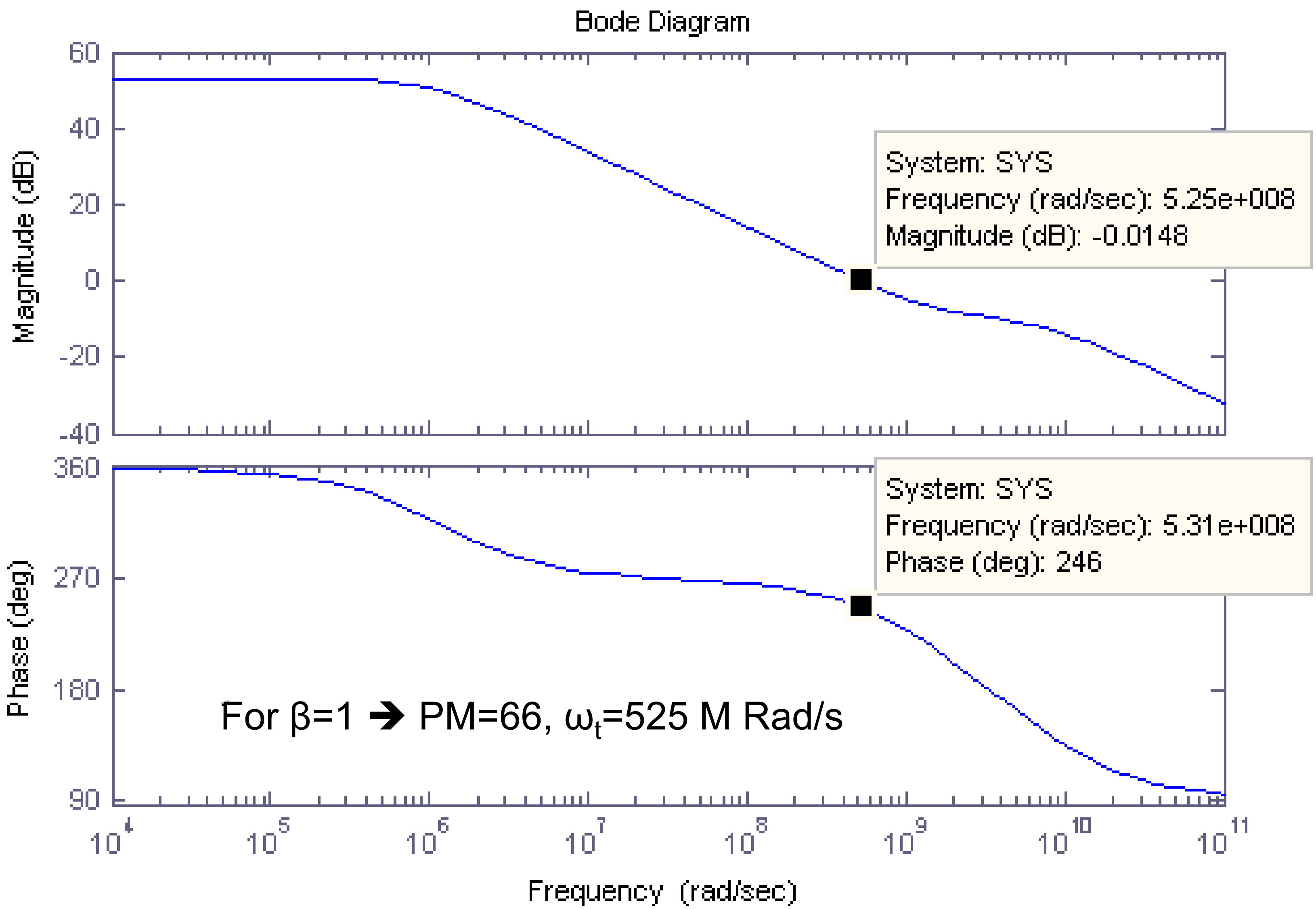
$$\omega_{p2} = \frac{g_{m7}}{C_1 + C_2} = 2\pi \times 1.19\ GHz$$

$$\omega_z = -\frac{g_{m7}}{C_C} = -2\pi \times 239\ MHz$$

$$A(s) = 450\frac{\left(1 - \frac{s}{1.5\times10^9}\right)}{\left(1 + \frac{s}{1.1\times10^6}\right)\left(1 + \frac{s}{7.5\times10^9}\right)}$$

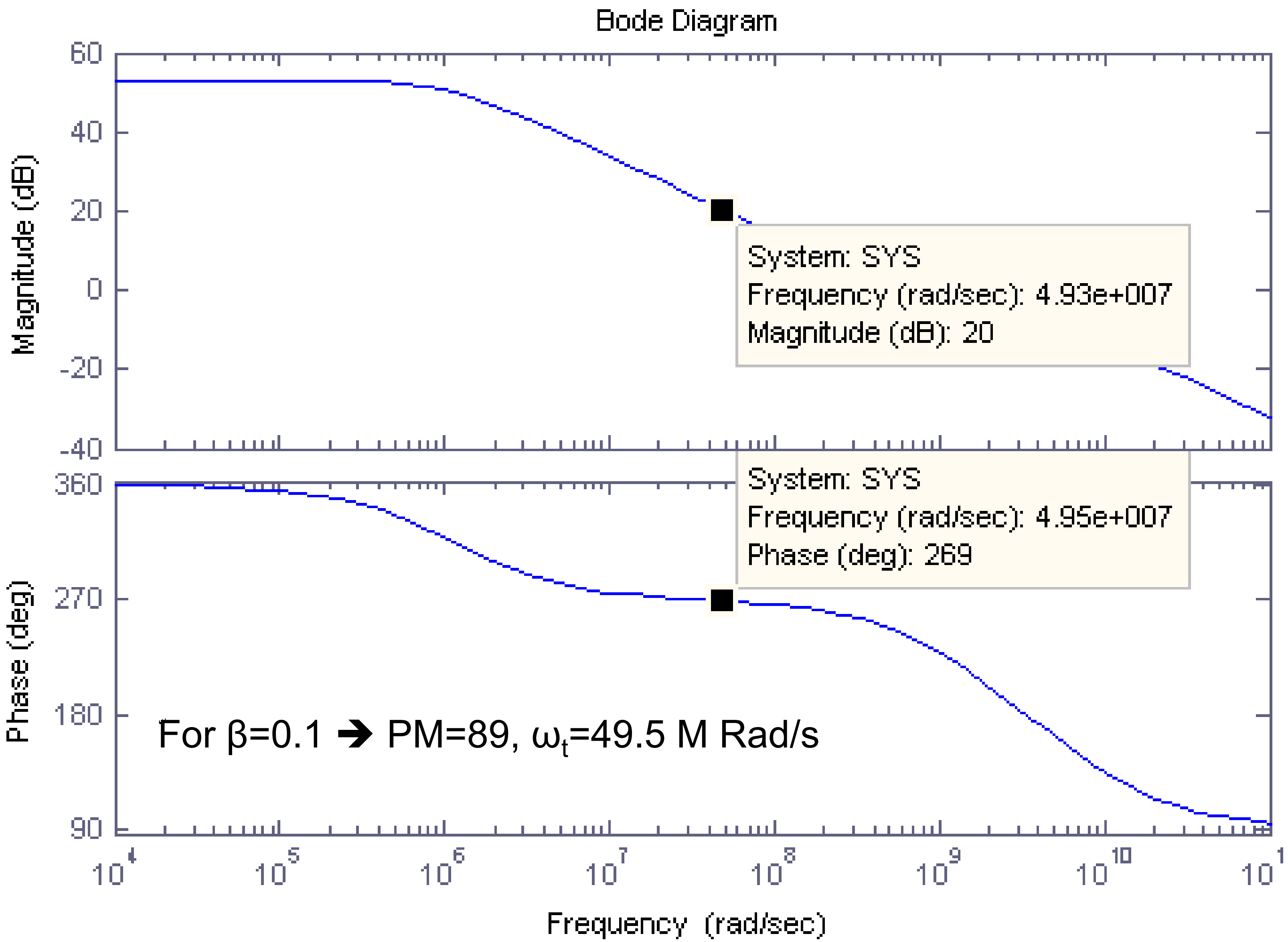
b) Plot the Bode diagram of A(s).

c) What is the phase margin if we use the opamp in a closed-loop configuration with feedback coefficient of β=1?



For $\beta=1$ ➔ PM=66, ω_t=525 M Rad/s

d) What is the phase margin for β=0.1?



For $\beta=0.1$ ➔ PM=89, $\omega_t=49.5$ M Rad/s

For $\beta=1$ ➔ PM=66, $\omega_t=525$ M Rad/s

For $\beta=0.1$ ➔ PM=89, $\omega_t=49.5$ M Rad/s

It is considered that for greater values of β, the stability of the closed-loop system decreases.

It is considered that for greater values of β, the bandwidth of the closed-loop system increases.

Example2

Consider a two-stage opamp with the following characteristics:

$$g_{m1} = 1\frac{mA}{V}, g_{m7} = 3\frac{mA}{V}$$

$$R_1 = 10\ k, R_2 = 15\ k$$

$$C_1 = 0.1\ pF, C_2 = 0.3\ pF, C_C = 1\ pF$$

a) Calculate A_0 , ω_{p1}, ω_{p2}, ω_z, and A(s).

$$A_0 = g_{m1}g_{m7}R_1R_2 = 450 \rightarrow A_0\Big|_{dB} = 53\ dB$$

$$\omega_{ta} = \frac{g_{m1}}{C_C} = \frac{1m}{1p} = 1\ G\ \frac{Rad}{s} = 2\pi \times 160\ MHz$$

$$\omega_{ta} = A_0 \times \omega_{p1} \rightarrow \omega_{p1} = 2\pi \times 354\ kHz$$

$$\omega_{p2} = \frac{g_{m7}}{C_1 + C_2} = 2\pi \times 1.19\ GHz$$

$$A(s) = 450\frac{\left(1 - \frac{s}{3\times 10^9}\right)}{\left(1 + \frac{s}{2.2\times 10^6}\right)\left(1 + \frac{s}{7.5\times 10^9}\right)}$$

$$\omega_z = -\frac{g_{m7}}{C_C} = -2\pi \times 478\ MHz$$

b) What is the phase margin for feedback coefficient of β=1?
c) What is the phase margin for feedback coefficient of β=0.1?

For $\beta=1$ ➔ PM=63, ω_t=1.04 G Rad/s

For $\beta=0.1$ ➔ PM=89, ω_t=99 M Rad/s

It is considered that if C_C is decreased, the bandwidth of the system is increased while the stability problem is worsened.

Comparison between the Example1 and Example2

Example1: (C_C=2 pF)

For β=1 ➔ PM=66, ω_t=525 M Rad/s

For β=0.1 ➔ PM=89, ω_t=49.5 M Rad/s

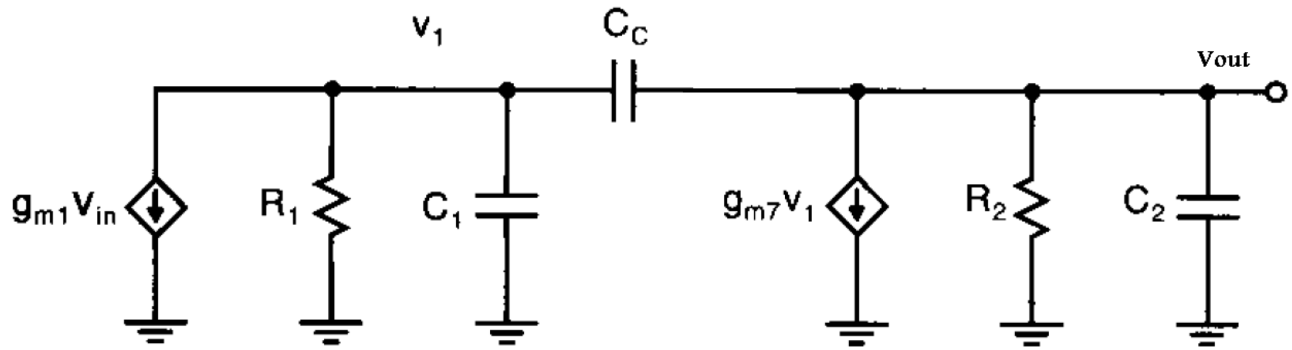
Example2: (C_C=1 pF)

For β=1 ➔ PM=63, ω_t=1.04 G Rad/s

For β=0.1 ➔ PM=89, ω_t=99 M Rad/s

The compensation of the opamp of Example2 is performed better than that of the Example1 because it leads to a higher bandwidth and enough phase margin.

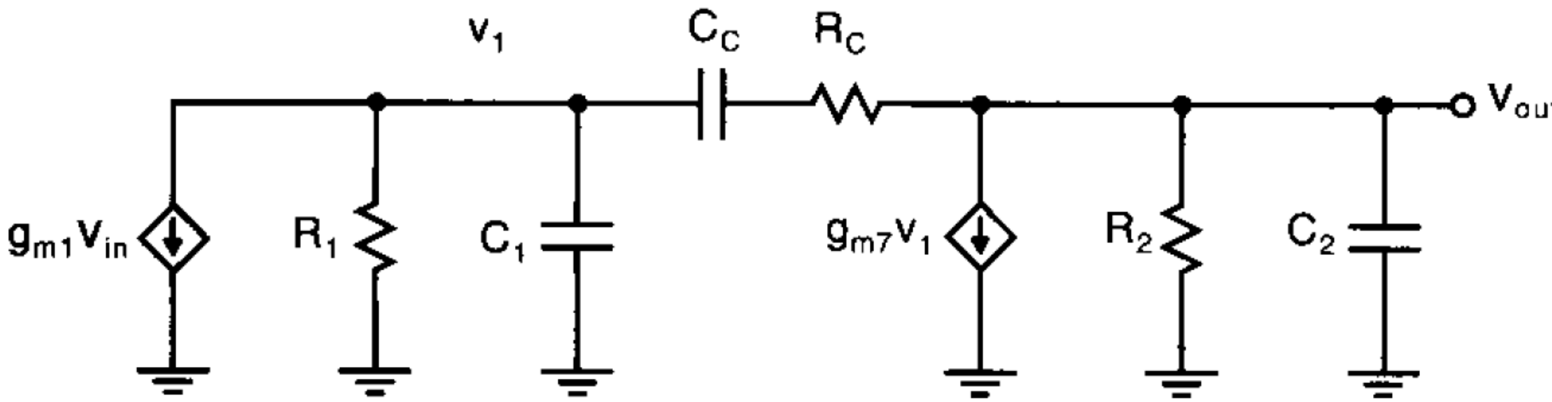
Frequency Response (second-order model)



$$\omega_{p1} = \frac{1}{g_{m7}R_1R_2C_C}, \quad \omega_{p2} = \frac{g_{m7}}{C_1 + C_2}, \quad \omega_z = \frac{-g_{m7}}{C_C}$$

•A problem arises due to the right-half-plane zero, ω_z . It introduces negative phase shift (phase lag).
•The right-half-plane zero makes the stability more difficult.
•Fortunately by using the resistor, R_C, in series with C_C, this problem is mitigated.

Right-Half-Plane Zero Problem

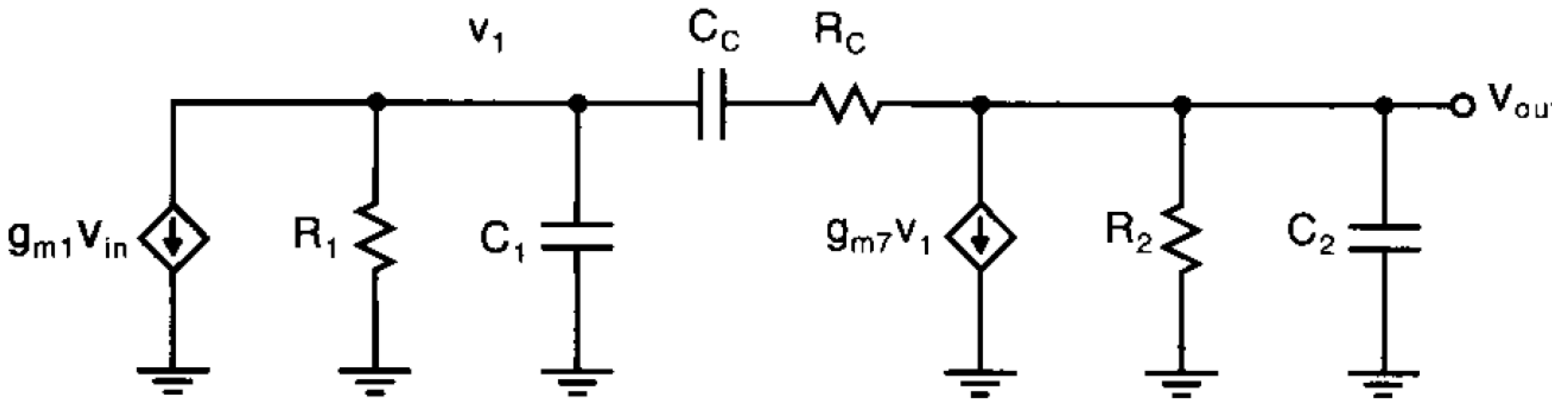


$$\omega_{p1} \cong \frac{1}{g_{m7} R_1 R_2 C_C}, \quad \omega_{p2} \cong \frac{g_{m7}}{C_1 + C_2}, \quad \omega_{p3}, \quad \omega_z = \frac{-1}{C_C\left(\frac{1}{g_{m7}} - R_C\right)}$$

There are three approaches to solve the right-half-plane zero problem as follows:

1. zero cancellation
2. pole-zero cancellation
3. lead compensation

Zero cancellation, Pole-zero cancellation



$$\omega_{p1} \cong \frac{1}{g_{m7} R_1 R_2 C_C}, \quad \omega_{p2} \cong \frac{g_{m7}}{C_1 + C_2}, \quad \omega_{p3}, \quad \omega_z = \frac{-1}{C_C\left(\frac{1}{g_{m7}} - R_C\right)}$$

In order to eliminate the right-half0plane zero, we should choose the value of R_C as follows:

$$R_C = 1/g_{m7}$$

Pole-zero cancellation is performed if $\omega_{p2}=\omega_z$. After a few manipulation, the condition for pole-zero cancellation is obtained as follows:

$$R_C = \frac{1}{g_{m7}}\left(1 + \frac{C_1 + C_2}{C_C}\right)$$

Lead compensation

$$\omega_{p1} \cong \frac{1}{g_{m7} R_1 R_2 C_C}, \quad \omega_{p2} \cong \frac{g_{m7}}{C_1 + C_2}, \quad \omega_{p3}, \quad \omega_z = \frac{-1}{C_C\left(\frac{1}{g_{m7}} - R_C\right)}$$

The pole-zero cancellation method is not reliable because C_2 is often not known a priori. David Johns recommends the lead compensation method as follows:

$$\omega_z = 1.7\omega_t$$

By using $\omega_t \cong \omega_{ta} = \frac{g_{m1}}{C_C}$ and $\omega_z = 1.7\omega_t$, the value of R_C is given as follows:

$$R_C = \frac{1}{1.7 g_{m1}} + \frac{1}{g_{m7}} \cong \frac{1}{1.7 g_{m1}}$$