HW 4

21 April 2020 06:25 PM

① a) Inverting amplifier

$$\frac{V_{in} - V_i^-}{R_1} = \frac{V_i^- - V_{out}}{R_2}$$

$$\Rightarrow \boxed{\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}} \qquad V_i^- = 0$$

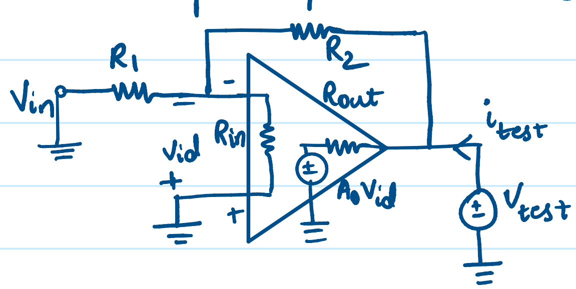
Non-Inverting amplifier

$$\frac{V_{out} - V_i^-}{R_2} = \frac{V_i^-}{R_1} \qquad \Big|\, V_i^- = V_i^+ = V_{in}$$

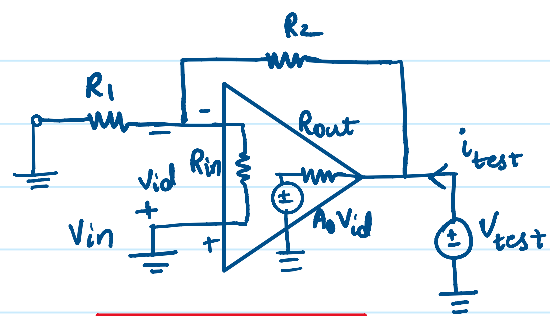
$$\frac{V_{out}}{R_2} = V_{in}\left(\frac{1}{R_2} + \frac{1}{R_1}\right)$$

$$\boxed{\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}}$$

Closed loop Output resistance

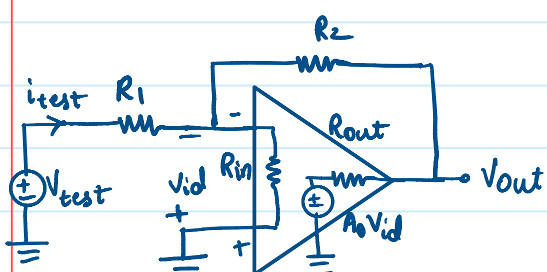


$$\boxed{R_{out\text{-}CL} = \frac{V_{test}}{i_{test}} = R_{out} \,||\, (R_1 + R_2) \approx R_{out}}$$



$$\boxed{R_{out\text{-}CL} = R_{out}}$$

Closed loop input resistance



$$i_{test} = \frac{V_{test} - V_i^-}{R_1} \qquad V_i^- = 0$$

$$\Rightarrow \boxed{R_{in\text{-}CL} = R_1}$$

No current flows through the '+' terminal of an ideal Op-amp

$i_{test} = 0$

$$\Rightarrow \boxed{R_{in\text{-}CL} = \infty}$$

Problem 1 (Contd.)

21 April 2020 07:22 PM

(b) Inverting Op-amp

1. Gain

$$\frac{V_{in} + V_{id}}{R_1} = -\frac{V_{id} - V_o}{R_2} \qquad V_{id} = \frac{V_o}{A_o}$$

$$\frac{\left(V_{in} + \frac{V_o}{A_o}\right)}{R_1} = \frac{\left(-\frac{V_o}{A_o} - V_o\right)}{R_2} \quad \Rightarrow \quad \frac{V_{in}}{R_1} = -V_o\left[\frac{1}{R_2} + \frac{1}{A_o R_2} + \frac{1}{A_o R_1}\right]$$

$$\frac{V_o}{V_1} = -\frac{1}{R_1} \cdot \frac{1}{\frac{1}{R_2}\left[1 + \frac{1}{A_o} + \frac{R_2}{A_o R_1}\right]}$$

$$A_{CL} = -\frac{R_2}{R_1\left(1 + \frac{1}{A_o \beta}\right)} \qquad \beta = \frac{R_1}{R_1 + R_2}$$

$$\boxed{A_{CL} = -\frac{R_2}{R_1} \frac{A_o \beta}{1 + A_o \beta}}$$

2. Output resistance

$$R_{out\text{-}CL} = \frac{V_{test}}{i_{test}} \Rightarrow i_{test} = i_o + i_f$$

$$i_o = \frac{V_{test} - A_o V_{id}}{R_{out}} \quad \& \quad i_f = \frac{V_{test}}{R_1 + R_2}$$

$$V_{id} = -V_i^- \quad \& \quad V_i^- = \beta V_{test}$$

$$i_{test} = \frac{V_{test} + A_o \beta V_{test}}{R_{out}} + \frac{V_{test}}{R_1 + R_2}$$

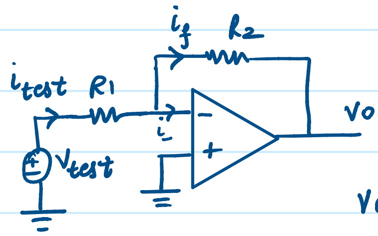
$$\frac{V_{test}}{i_{test}} = \left(\frac{R_{out}}{1 + A_o \beta}\right) \| (R_1 + R_2)$$

$$\boxed{R_{out\text{-}CL} \approx \left(\frac{R_{out}}{1 + A_o \beta}\right)}$$

Problem 1 (Contd.)

02 May 2020 06:56 PM

3. Input Resistance



$$\frac{V_{test}}{i_{test}} = \frac{i_{test} R_1 + v_i^-}{i_{test}} \quad \text{—— (1)}$$

$$V_o = A_0 v_{id}$$

$$V_o = -A_0 v_i^-$$

$$i_{test} = i_- + i_f = \frac{v_i^-}{R_{in}} + \frac{v_i^- + A_0 v_i^-}{R_2}$$

$$\frac{i_{test}}{v_i^-} = \frac{1}{R_{in}} + \frac{1+A_0}{R_2}$$

from (1), $\boxed{R_{in\text{-}CL} = R_1 + \left(R_{in} \parallel \frac{R_2}{1+A_0}\right)}$

Non-inverting amplifier

1. Gain

$$V_o = A_0 (v_i^+ - v_i^-)$$

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

$$V_o = A_0 (V_{in} - \beta V_o)$$

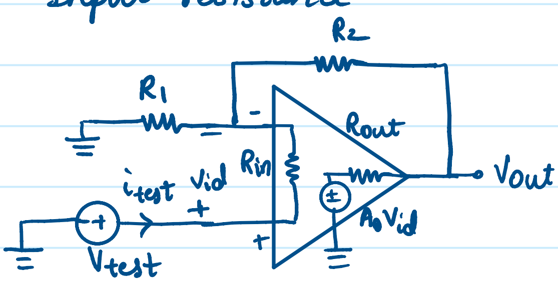
$$V_o (1 + A_0\beta) = A_0 V_{in}$$

$$A_{CL} = \frac{V_o}{V_{in}} = \frac{A_0}{1+A_0\beta}$$

2. Output resistance same as inverting case

$$R_{out\text{-}CL} = \frac{R_{out}}{1+A_0\beta} \parallel (R_1+R_2)$$

3. Input resistance



Problem 1 (Contd.)

02 May 2020 06:35 PM

$$\bar{V_i} = \beta V_o$$

$$\bar{V_i} = \beta(A_o V_{id}) = \beta A_o (V_{test} - \bar{V_i})$$

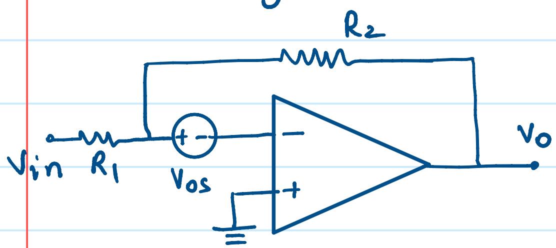
$$\bar{V_i}(1 + A_o\beta) = A_o\beta \, V_{test}$$

$$\bar{V_i} = \frac{A_o\beta}{1 + A_o\beta} V_{test}$$

$$R_{in-CL} = \frac{V_{test}}{i_{test}} = \frac{V_{test} \, R_{in}}{V_{test} - \left[\frac{A_o\beta}{1 + A_o\beta}\right] V_{test}} = R_{in}(1 + A_o\beta)$$

$$\boxed{R_{in-CL} = R_{in}(1 + A_o\beta)}$$

(c) Inverting Op-amp:



$$\frac{V_{in} - V_{os}}{R_1} = \frac{V_{os} - V_o}{R_2}$$

$$\frac{V_o}{R_2} = V_{os}\left[\frac{1}{R_2} + \frac{1}{R_1}\right] - \frac{V_{in}}{R_1}$$

$$\boxed{V_o = -\frac{R_2}{R_1} V_{in} + \left(1 + \frac{R_2}{R_1}\right) V_{os}}$$

$R_1 = 1K\Omega$, $R_2 = 10K\Omega$, $V_{os} = 0.1V$, $V_{in} = 0V$

$V_o = 1.1V$

Simulated value $V_o = 1.09998V$

Problem 1 (Contd.)

03 May 2020 12:06 AM

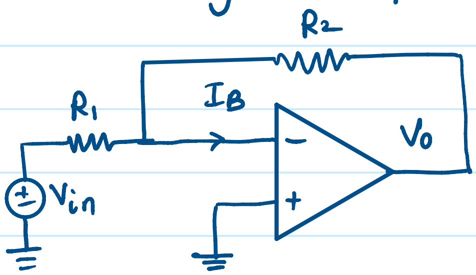
Non-inverting Op-amp

$$V_{os} + V_{in} = V_o \frac{R_1}{R_1+R_2} \Rightarrow V_o = \left(1+\frac{R_2}{R_1}\right)V_{in} + \left(1+\frac{R_2}{R_1}\right)V_{os}$$

$R_1 = 1k\Omega$, $R_2 = 10k\Omega$, $V_{os} = 0.1V$, $V_{in} = 0V$

Simulated value = 1.0999V

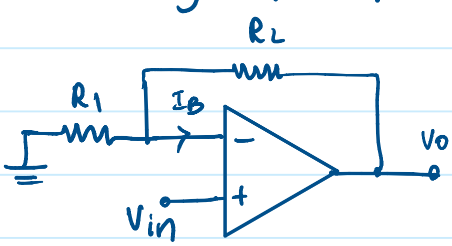
(d) Inverting Op-amp



$$\frac{V_{in}}{R_1} + \frac{V_o}{R_2} = I_B$$

$$\boxed{V_o = -\frac{R_2}{R_1}V_{in} + R_2 I_B}$$

Non-inverting Op-amp



$$\frac{V_o - V_i^-}{R_2} + \frac{0 - V_i^-}{R_1} = I_B$$

$$\frac{V_o - V_{in}}{R_2} = I_B + \frac{V_{in}}{R_1}$$

$$\boxed{V_o = \left(1+\frac{R_2}{R_1}\right)V_{in} + R_2 I_B}$$

Problem 2

03 May 2020 12:30 AM

(2) a) $V_i^+ = V_i^- = 0 \Rightarrow \frac{V_{out} - 0}{i_{in}} = R \| C$

$$= \frac{\frac{R}{sC}}{R + \frac{1}{sC}} = \frac{R}{1+sRC}$$

$$\Rightarrow \frac{V_{out}}{i_{in}} = \frac{R}{1+sRC}$$

(b) Taking inverse laplace transform

$$V_{out}(t) = \frac{R}{RC} e^{-t/RC} \cdot i(t) \qquad \Big| \; i(t) = i_{max} \text{ @ } t = t_{on}$$

$$V_{out}(t_{on}) = \frac{i_{max}}{C} e^{-t_{on}/RC}$$

Bonus:

$i_{max} = 10\mu A$ $\quad 0.1\%$ error $\quad t_{settle} = 7RC$

$\Rightarrow t_{on} = 7RC$

$V_{out} \leq 2.5V \Rightarrow \frac{i_{max}}{C} \leq 2.5V \Rightarrow C \geq \frac{10\mu}{2.5} \Rightarrow C \geq 4\mu F$

Select $C = 5\mu F$, $t_{on} = 1ms$

$$R = \frac{1m}{7 \times 5\mu} = 28.57\,\Omega$$

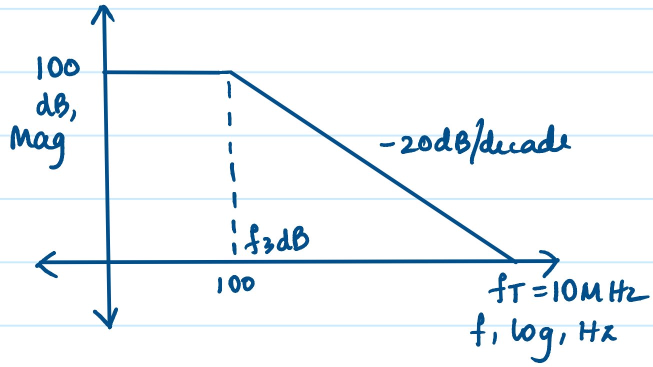
Problem 3

03 May 2020 01:01 AM

3 $A_0 = 100dB \quad f_T = 10MHz \quad , R_1 = R_2 = R_3 = R_4 = 10K\Omega$

$$V_{out} = -\frac{R_4}{R_3} V_{im} + \left(1 + \frac{R_4}{R_3}\right)\left(\frac{R_1}{R_1+R_2}\right) V_{ip} \quad \text{——} \ (1)$$

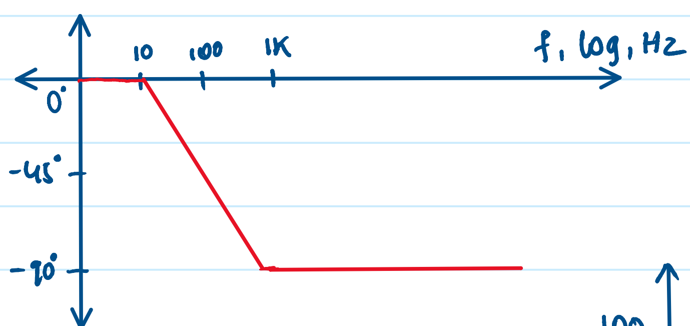
a

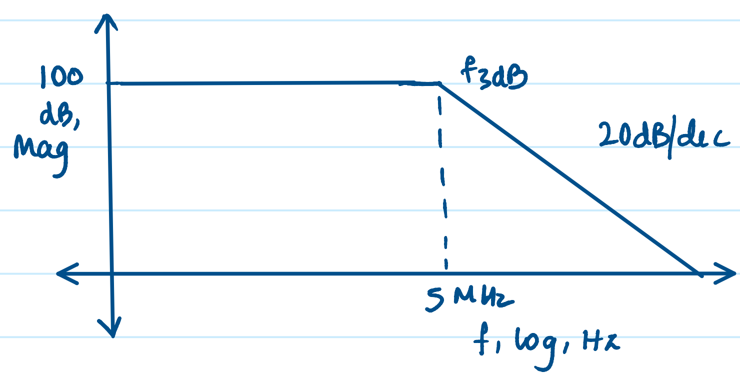


$A_0 = 10^{100/20} = 10^5 \ V/V$

$f_T = 10MHz$

$f_{3dB} = \frac{10^7}{10^5} = 100Hz$





b from (1)

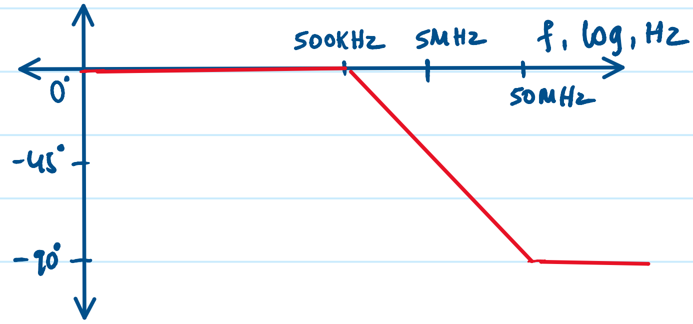
$V_{out} = -V_{im} + V_{ip}$

$\Rightarrow \frac{V_{out}}{V_{ip} - V_{im}} = 1V/V = 0dB$

$f_{3dB,CL} = (1 + \beta A_0) f_{3dB,OL}$

$= [1 + 0.5(10^5)](100)$

$f_{3dB,CL} = 5MHz$



Problem 3 (Contd.)

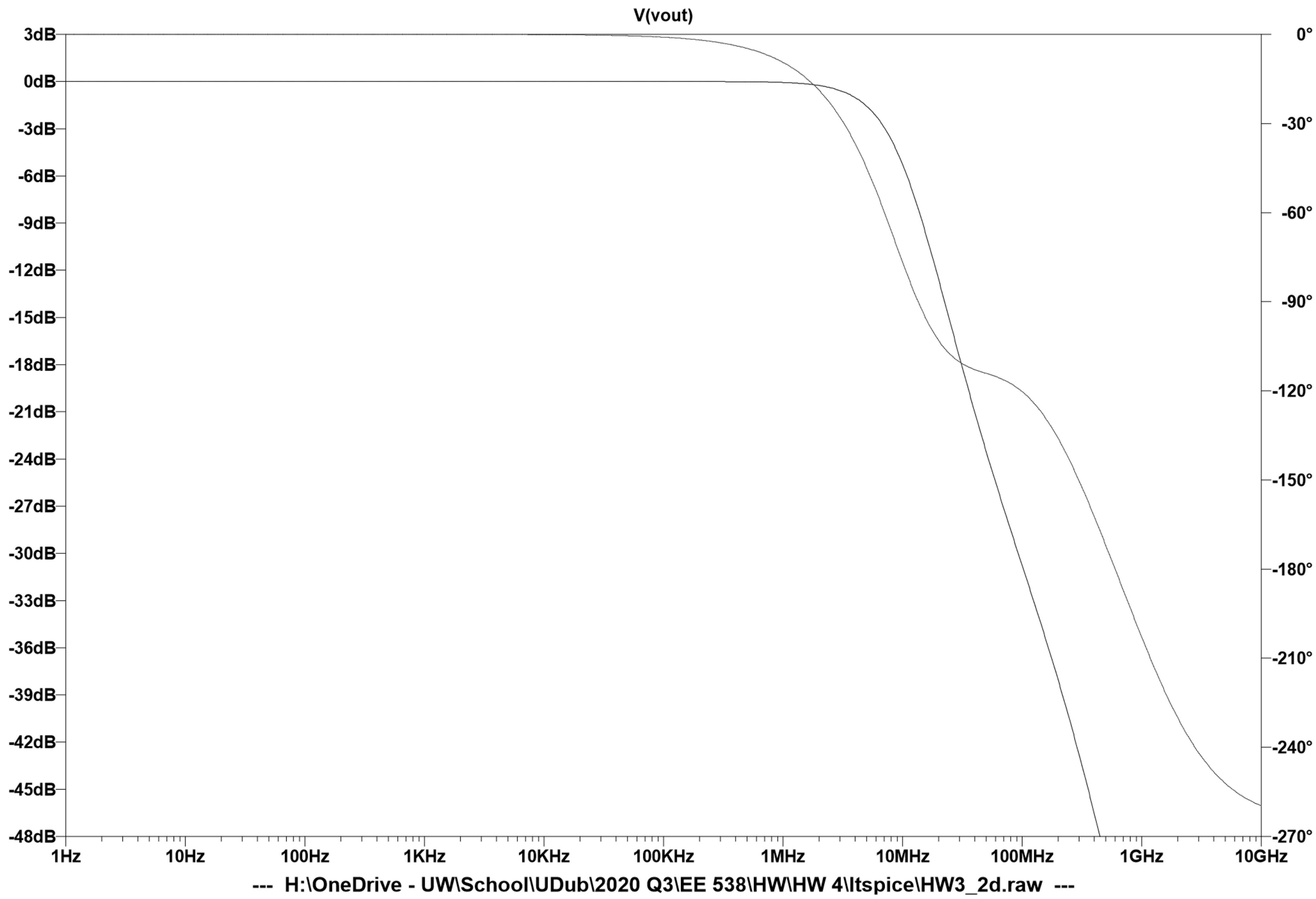
03 May 2020 01:34 AM

(c) For ideal Opamp

(1) V_{im}: $R_{in} = R_3 = 10K\Omega$

(2) V_{ip}: $R_{in} = R_1 + R_2 = 20K\Omega$

(d) AD8691



Gain = $77.35 \mu dB \approx 0 dB$

f_{3dB} = 7.07 MHz

Problem 3 (Contd.)

03 May 2020 02:18 AM

HW4_2d

Cursor 1

	V(vout)
Freq: 9.9638896KHz	Mag: 77.358867µdB
	Phase: -93.73759m°
	Group Delay: 26.132632ns

Cursor 2

	V(vout)
Freq: 7.0788176MHz	Mag: -2.9702896dB
	Phase: -60.184566°
	Group Delay: 18.436907ns

Ratio (Cursor2 / Cursor1)

Freq: 7.0688537MHz	Mag: -2.970367dB
	Phase: -60.090828°
	Group Delay: -7.6957244ns

* H:\OneDrive - UW\School\UDub\2020 Q3\EE 538\HW\HW 4\ltspice\HW4_2d.asc

```
        --- Transfer Function ---

Transfer_function:                 -1             transfer
vim#Input_impedance:               10000          impedance
output_impedance_at_V(vout):       0.00186035     impedance
```

* H:\OneDrive - UW\School\UDub\2020 Q3\EE 538\HW\HW 4\ltspice\HW4_2d.asc

```
        --- Transfer Function ---

Transfer_function:                 1.00002        transfer
vip#Input_impedance:               20000          impedance
output_impedance_at_V(vout):       0.00186035     impedance
```

Vim, Input impedance = 10KΩ

Vip, Input impedance = 20KΩ