EE3235 Analog Integrated Circuit Analysis and design I

Homework 4

Ideal OP circuit

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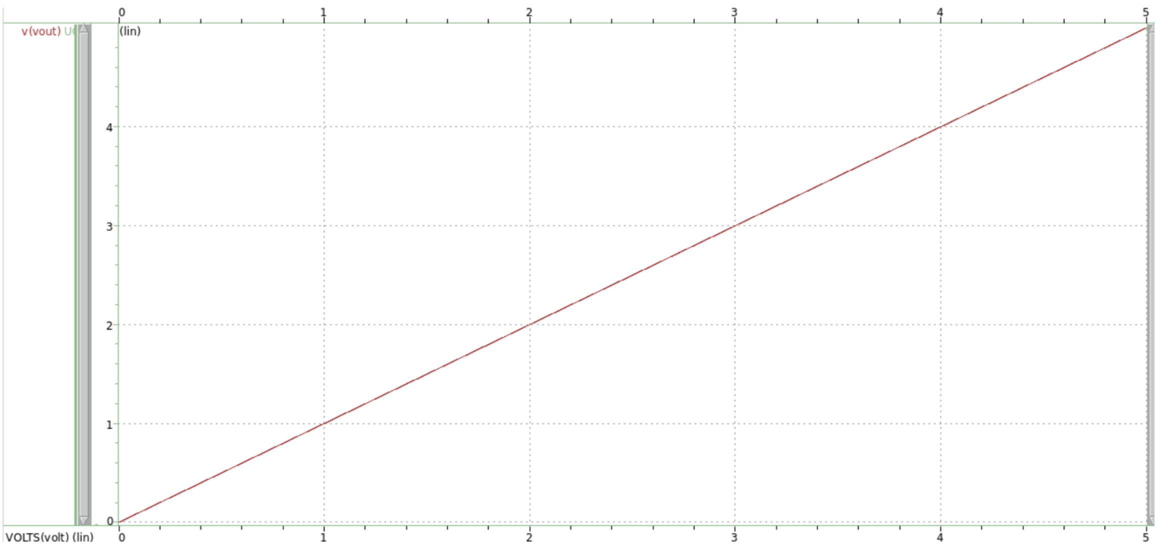
1. Unity-gain Amplifier
   (a) DC Sweep



X axis: Vin(V) – Y axis: Vout(V)

```
$DATA1 SOURCE='PrimeSim HSPICE' VERSION='R-2020.12-SP2 linux64' PARAM_COUNT=0
.TITLE '** 110061217 王彥智 hw4_1'
 derivative_of_vout temper          alter#
    0.9990          25.0000        1
```

Derivative of Vout when Vin is 2.5V: 0.9990(V/V)

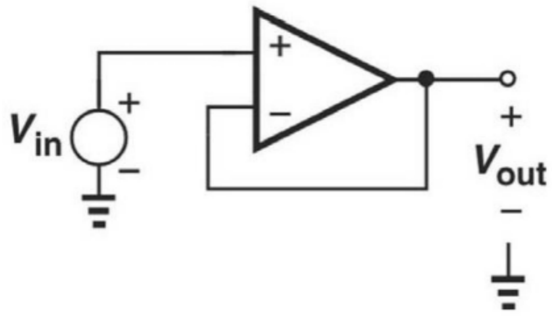
   (b) TF Analysis

```
 ****     small-signal transfer characteristics

      v(vout)/vin                              =  999.0010m
      input resistance at              vin     =  1.000e+20
      output resistance at v(vout)             =    0.
```

TF Analysis

Calculation of DC gain:



$$V_{out} = (V_{in} - V_{out}) \times A_o$$

$$\therefore \frac{V_{out}}{V_{in}} = \frac{A_o}{A_o + 1}$$

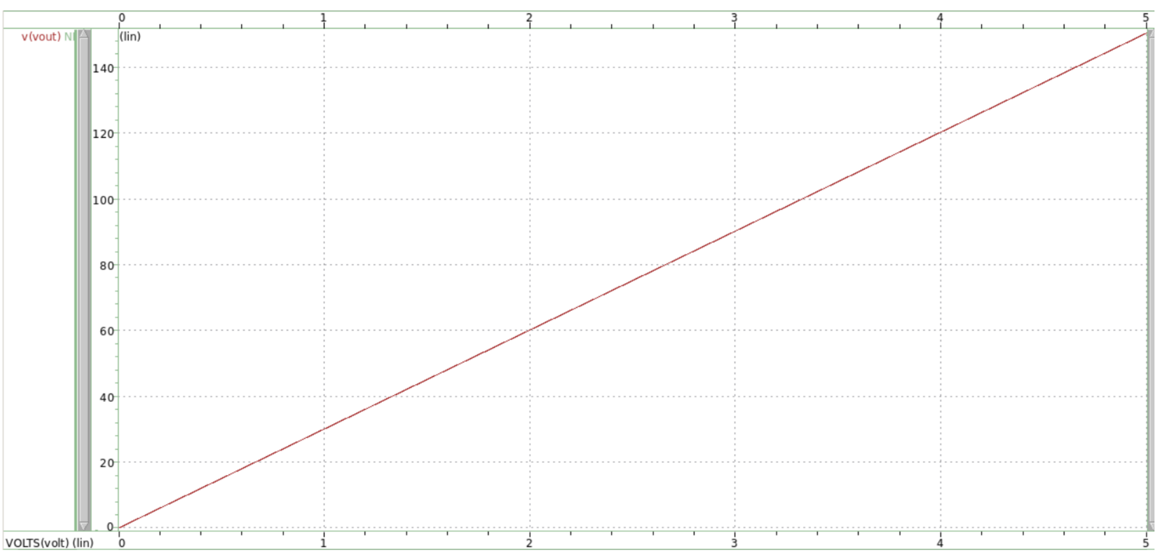
$$\rightarrow A_o = 60\,dB = 1000$$

$$\therefore DC\ gain = \frac{V_{out}}{V_{in}} = \frac{1000}{1001} \cong 999.000999\,m\ (V/V)$$

Error:

$$\frac{999.001 - 999.0009}{999.0009} = 10^{-5}\%$$

2. Noninverting Amplifier
   (a) DC Sweep



X axis: Vin(V) – Y axis: Vout(V)

```
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.TITLE '** 110061217 王彥智 hw4_2'
 derivative_of_vout temper          alter#
   30.0679           25.0000        1
```

Derivative of Vout when Vin is 2.5V: 30.0679(V/V)

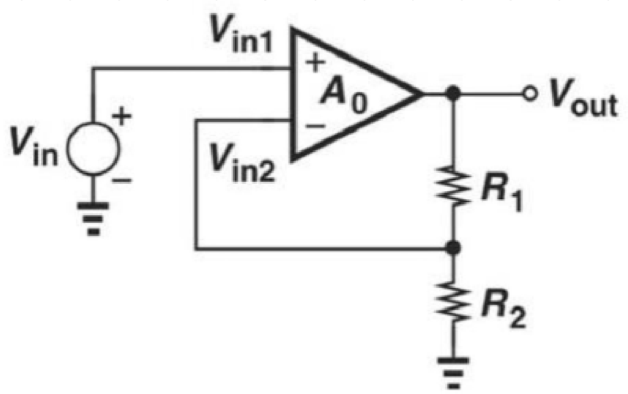
(b) TF Analysis

```
****     small-signal transfer characteristics

     v(vout)/vin                              =   30.0679
     input resistance at           vin        =  1.000e+20
     output resistance at v(vout)             =    0.
```

TF Analysis

Calculation of DC gain:



$$V_{out} = (V_{in} - V_{in2}) A_0$$

$$V_{in2} = \frac{R_2}{R_1 + R_2} V_{out}$$

$$\therefore \frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \frac{R_2}{R_1 + R_2} A_0}$$

$$\rightarrow A_0 = 1000, \quad R_1 = 30k\Omega \quad R_2 = 1k\Omega$$

$$\therefore \text{DC gain} = \frac{V_{out}}{V_{in}} = 30.067895 \ (V/V) ※$$

Error:

$$\frac{30.0679 - 30.097895}{30.0679} = 1.6 * 10^{-5}\%$$

(c) How do you design your circuit to meet the SPEC? Describe your design considerations.

$$\frac{V_{out}}{V_{in}} \approx \left(1+\frac{R_1}{R_2}\right)\left(1-\left(1+\frac{R_1}{R_2}\right)\frac{1}{1000}\right) = 30$$

令 $R_1/R_2 = x$

$$\rightarrow (x+1)(1-(1+x)/1000) = 30$$

$$(x+1)(1000-(1+x)) = -30000$$

$$x^2 - 998x - 999 = -30000$$

$$x^2 - 998x + 29001 = 0$$

$$\therefore x = \frac{998 \pm \sqrt{998^2 - 4 \times 29001}}{2} \rightarrow x = 29.9584 \text{ or } \underline{968.0415}$$

gain error too large

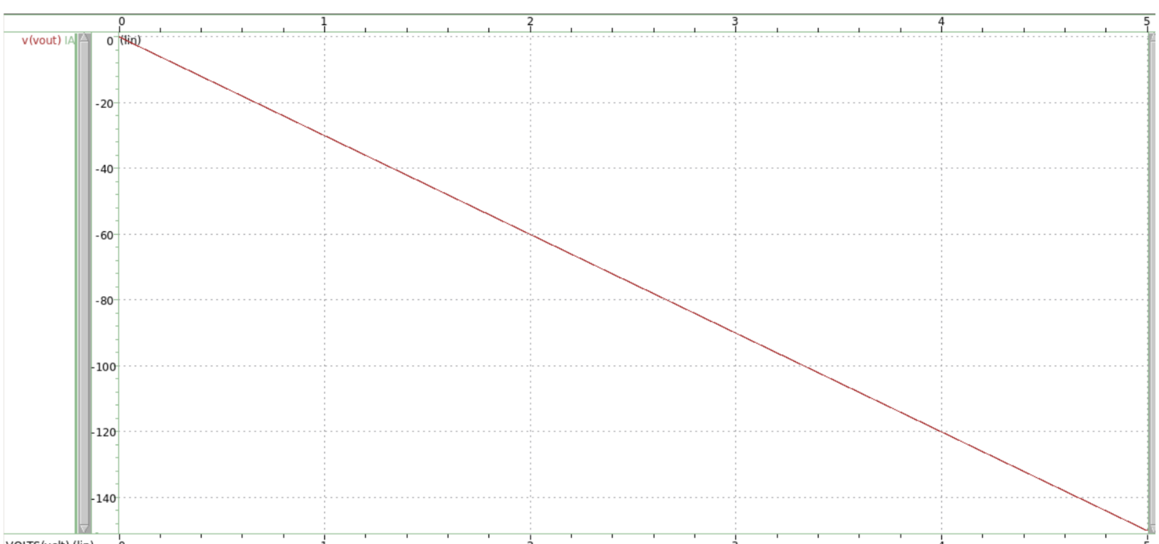
$$\therefore \text{choose } \frac{R_1}{R_1} = 29.9584 \approx 30$$

$\therefore$ choose $R_1 = 30k\Omega$, $R_2 = 1k\Omega$

$$\text{error}: \frac{30.0979 - 30}{30} = 0.226\% < 1\% \checkmark$$

3. Inverting Amplifier

(a) DC Sweep



X axis: Vin(V) – Y axis: Vout(V)

```
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.TITLE '** 110061217 王彥智 hw4_3'
 derivative_of_vout temper         alter#
  -30.0388          25.0000        1
```

Derivative of Vout when Vin is 2.5V: -30.0388(V/V)

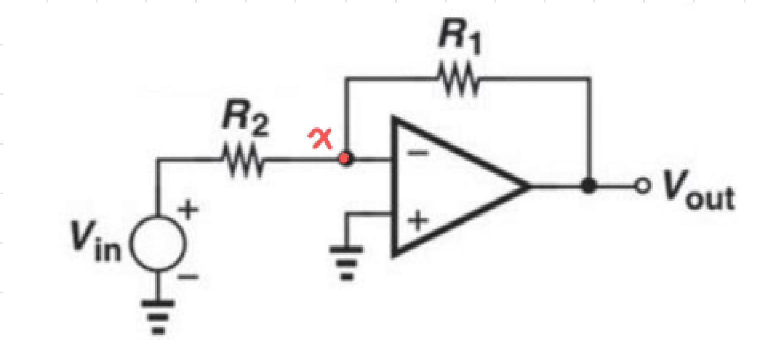
(b) TF Analysis

```
****     small-signal transfer characteristics

      v(vout)/vin                                  =  -30.0388
      input resistance at              vin         =    1.0310k
      output resistance at v(vout)                 =    0.
```

TF Analysis

Calculation of DC gain:



$$\begin{cases} \dfrac{V_{in} - V_x}{R_2} = \dfrac{V_x - V_{out}}{R_1} \\ V_{out} = (V_{in1} - V_{in2}) A_0 = V_x A_0 \end{cases}$$

$$\therefore \frac{V_{out}}{V_{in}} = -\frac{1}{\frac{R_2}{R_1} + \frac{1}{A_0}\left(1+\frac{R_2}{R_1}\right)}$$

$\rightarrow A_0 = 1000$, $R_2 = 1k\Omega$ $R_1 = 31k\Omega$

$\therefore$ Ac gain $= \dfrac{V_{out}}{V_{in}} = -30.038759$ (V/V)

Error:

$$\frac{30.0388 - 30.038759}{30.038759} = 1.36 * 10^{-4}\%$$

(c) How do you design your circuit to meet the SPEC? Describe your design considerations.

$$\frac{V_{out}}{V_{in}} \approx -\frac{R_1}{R_2}\left(1 - \frac{1}{A_0}\left(1 + \frac{R_1}{R_2}\right)\right) = -30$$

令 $R_1/R_2 = x$

$$-x\left(1 - \frac{1}{1000}(1+x)\right) = -30$$

$\therefore x(1000 - (1+x)) = 30$

$\therefore 999x - x^2 = 30000 \rightarrow x^2 - 999x + 30000 = 0$

$\therefore x = \frac{999 \pm \sqrt{999^2 - 4 \times 30000}}{2} = 30.99146$ or $\underline{968.0085}$

gain error too large

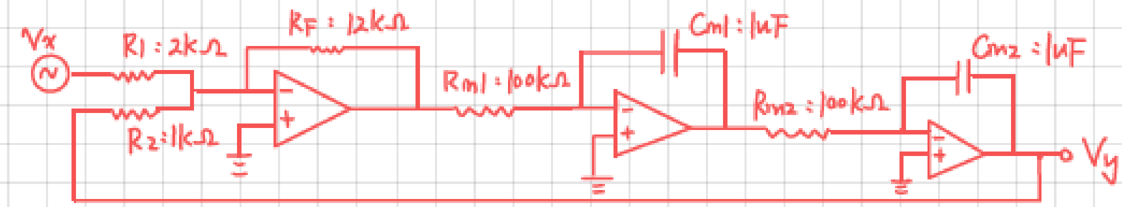
$\rightarrow$ choose $\frac{R_1}{R_2} = 30.99146 \approx 31k$

$\rightarrow$ choose $R_1 = 31k\Omega$, $R_2 = 1\,k\Omega$

error: $\frac{30.038759 - 30}{30} \approx 0.129\% < 1\%$ ✓

4. Voltage Adder + Integrator

(a) Describe your design consideration and show the schematic.



$$V_y(t) = \int\left(\int -600V_x(t) - 1200V_y(t)\,dt\right)dt$$

$$= -10\int\left(-10\int\left(-6V_x(t) - 12V_y(t)\,dt\right)\right)dt$$

let $-6V_x(t) - 16V_y(t) = V_{out0}$

1. One Voltage Adder:

$$\rightarrow V_{out0} = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right) = -6V_x(t) - 12V_y(t)$$

let $V_1 = V_x(t)$ $\quad V_2 = V_y(t)$

$\therefore$ choose $R_F = 12k\Omega$, $R_1 = 2k\Omega$ $\quad R_2 = 1k\Omega$ #

let $V_{out1} = -10\int V_{out0}\,dt$

2. first integrator:

$$V_{out1} = \frac{-1}{RC}\int V_{in}\,dt = -10\int V_{out0}\,dt$$

let $V_{in} = V_{out0} \longrightarrow \frac{1}{RC} = 10$

$\therefore$ choose $R = 100k$ $\quad C = 1uF$ #

3. second integrator:

$$V_y = \frac{-1}{RC}\int V_{in}\,dt = -10\int V_{out1}\,dt$$

let $V_{in} = V_{out1} \longrightarrow \frac{1}{RC} = 10$

$\therefore$ choose $R = 100k$ $\quad C = 1uF$ #

(b) Suppose all initial conditions are 0 and $Vx(t)$ is an unit step input. Please do hand calculation to find the transient response of $Vy(t)$ and the period of the waveform at $Vy(t)$.

$Vy(t) = \int \left(\int -600Vx(t) - 1200Vy(t)\, dt \right) dt$

→ Laplace transform

$\overline{Vy}(s) = \frac{1}{s^2}\left(-600\,\overline{Vx}(s) - 1200\,\overline{Vy}(s)\right)$

$s^2\,\overline{Vy}(s) = -600\,\overline{Vx}(s) - 1200\,\overline{Vy}(s)$

$(s^2+1200)\,\overline{Vy}(s) = -600\,\overline{Vx}(s)$

$\because\ \overline{Vx}(s) = \mathcal{L}\{Vx(t)=u(t)\} = \frac{1}{s}$

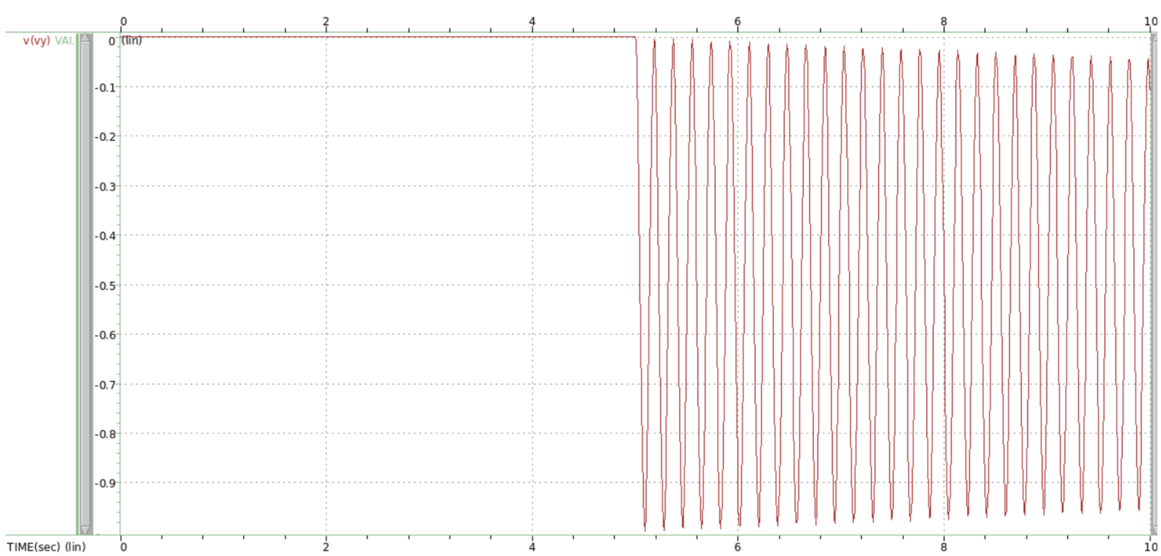
$\therefore\ \overline{Vy}(s) = \frac{-600}{s^2+1200} \times \frac{1}{s} = \frac{1}{2}\left(\frac{s}{s^2+1200} - \frac{1}{s}\right)$

$\therefore\ \mathcal{L}^{-1}\left(\frac{\overline{Vy}(s)}{\overline{Vx}(s)}\right) = \frac{1}{2}\left(\cos 20\sqrt{3}t - u(t)\right)$

period: $\cos(20\sqrt{3}(t+T)) = \cos(20\sqrt{3}t)$

$\therefore\ 20\sqrt{3}\,T = 2\pi \quad T = \frac{2\pi}{20\sqrt{3}} \approx 0.181379\ s$

(c) Let $Vx(t)$ be a unit step input. Plot the transient response of $Vy(t)$ and measure the period of $Vy(t)$.



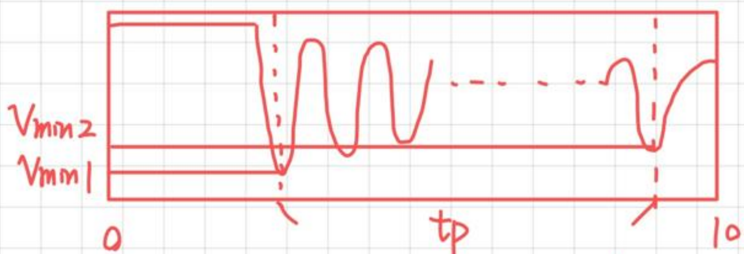
transient response of $Vy(t)$: X axis: t – Y axis: Vy(t)

```
$DATA1 SOURCE='PrimeSim HSPICE' VERSION='R-2020.12-SP2 linux64' PARAM_COUNT=0
.TITLE '** 110061217 王彥智 hw4_4'
 vmin1            vmin2            tp               temper
 alter#
   -0.9994          -0.9566          4.8019           25.0000
1
```

Period of the waveform

Calculation of period that I measured:

In the waveform:



and I counts how many periods there are in tp → 26

∴ Period measured : $\frac{tp}{26} = \frac{4.8019}{26} = 0.184688$ ※

(d) What is the error between calculated waveform period and the simulation waveform period?

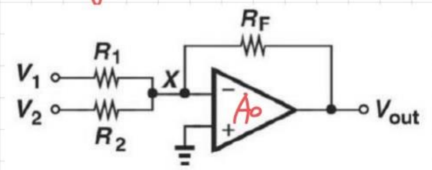
$$\frac{0.184688 - 0.181379}{0.181379} = 1.824\%$$

Error is 1.824%. I think it is because I didn't consider finite gain when I design, and if we consider finite gain:

1. Period will be different since the relationship between input and output is different.
2. The waveform is not sin function but sin function with damping (like the simulated result).

* Consider finite gain:

1. Voltage Adder



$$\begin{cases} \dfrac{V_1-V_x}{R_1} + \dfrac{V_2-V_x}{R_2} = \dfrac{V_x-V_{out}}{R_F} \quad \cdots (1) \\ (0-V_x)A_0 = V_{out} \end{cases}$$

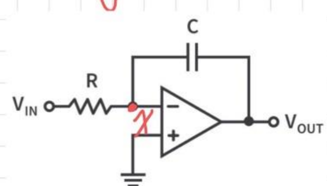
$$\therefore \frac{V_1}{R_1} + \frac{V_2}{R_2} + \left(\frac{R_1+R_2}{R_1R_2}\right)\cdot\frac{1}{A_0}\cdot V_{out} = \frac{-V_{out}}{R_F} - \frac{1}{R_FA_0}V_{out}$$

$$\therefore V_{out} = -\left[R_F\left(\frac{R_1+R_2}{R_1R_2}\right)\frac{1}{A_0} + \frac{1}{A_0} + 1\right]^{-1}\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2\right)$$

$\rightarrow$ Acording to my design:

$$V_{out} = -(18 + 0.001 + 1)^{-1} \times (6V_1 + 12V_2) ※$$

2. Integrator:



$$\frac{V_{in}-V_x}{R} = \frac{V_x - V_{out}}{1/sC} \quad \therefore \frac{V_{out}}{V_{in}} = \frac{-1}{\frac{1}{A_0}+(1+\frac{1}{A_0})sRC}$$

According to my design:

$$V_{out} = \frac{-1}{0.001 + 1.001 \times 0.1s} V_{in}$$

$\therefore$ Over all gain of my design:

$$\frac{V_y(s)}{V_x(s)} = \frac{-\frac{R_F}{R_2}}{\left[\frac{1}{A_0}+(1+\frac{1}{A_0})\times sRC\right]^2 + \frac{R_F}{R_1}} = \frac{-12}{(10^{-3}+0.1001s)^2+6}$$

By Laplace transform ($V_x(s) = \frac{1}{s}$)

$$V_y(t) = -6000000\left\{\frac{1}{12000001} - \frac{e^{-t/1001\times RC}\left[3\sin\left(\boxed{\frac{2000\sqrt{3}\,t}{1001\,RC}}\right)+2000\sqrt{3}\cos\left(\boxed{\frac{2000\sqrt{3}\,t}{1001\,RC}}\right)\right]}{2400000200000\sqrt{3}}\right\}$$

$\rightarrow$ we can see there is $e^{-t/1001\times RC}$ which cause damping, and also the period is different when we consider finite gain.

Calculation when we consider finite gain