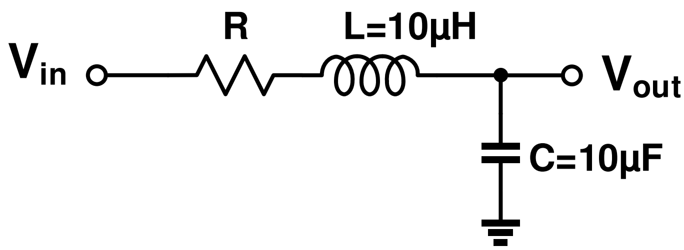
Aniruddhan S., Qadeer Khan, Saurabh Saxena

1. In the RLC circuit below,




derive the transfer function *H(s)=V*$_{out}$*(s)/V*$_{in}$*(s)* and prove that the circuit is equivalent to a standard 2$^{nd}$ order system with transfer function:

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

a) Find the expressions for damping factor (ζ), quality factor (Q = 1/2ζ), natural frequency ($w_n$) and poles $p_1$, $p_2$ (roots of s) and their respective frequencies, $w_{p1}$ and $w_{p2}$ in terms of R, L and C.
b) Considering L=10µH and C=10µF, fill the values in the following table for the corresponding values of R.
c) Show $p_1$ and $p_2$ calculated in (b) on the s-plane and comment on the movement of poles w.r.t. damping factor (ζ).

| R (Ω) | ζ | Q=1/2ζ | $p_1$ $(\sigma + j\omega)$ | $p_2$ $(\sigma + j\omega)$ | $w_{p1}$ (rad/s) | $w_{p2}$ (rad/s) |
|---|---|---|---|---|---|---|
| 0.02 | | | | | | |
| 0.1 | | | | | | |
| 0.4 | | | | | | |
| 1 | | | | | | |
| 1.4 | | | | | | |
| 2 | | | | | | |
| 5 | | | | | | |
| 10 | | | | | | |
| 20 | | | | | | |
| 100 | | | | | | |

d) Enter the circuit in LTspice and perform following simulations for all values of R given in the table:
   i. Plot AC magnitude and phase response for $V_{out}(s)/V_{in}(s)$. Comment on the behavior of AC magnitude and phase response w.r.t. damping factor, ζ.
   ii. Plot the transient response by applying a unit step (0 to 1V with initial delay of 1ms and $T_{rise}$ = 1ns) for the time span of 10ms. Comment on the effect of varying ζ on the transient response.
   iii. After observing the behavior of AC and transient behavior w.r.t. ζ in (i) & (ii), it is now understood that both AC and transient response are interrelated. How can you intuitively guess the approximate value of ζ by simply looking at either AC magnitude or transient response?

Aniruddhan S., Qadeer Khan, Saurabh Saxena

2. For the non-inverting amplifier shown in Figure-A and considering op-amp model shown in Figure-B where *A(s)=Vo(s)/Vi(s)*

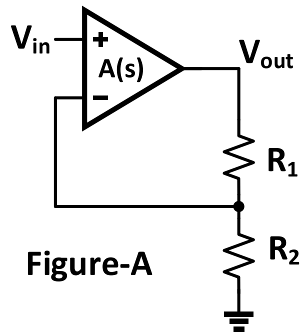



**Figure-A**

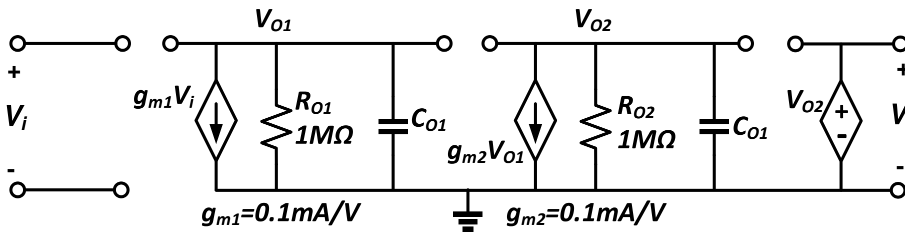



**Figure-B**

a) Find the loop gain transfer function, LG(s), DC gain $A_o$, poles $p_{1\_lg}$, $p_{2\_lg}$ (roots of s) and their respective frequencies, $w_{p1\_lg}$ and $w_{p2\_lg}$ in terms of $g_{m1}$, $R_{o1}$, $C_{o1}$, $g_{m2}$, $R_{o2}$ and $C_{o2}$.

b) Find the closed loop transfer function, $H(s)=V_{out}(s)/V_{in}(s)$, poles $p_{1\_cl}$, $p_{2\_cl}$ (roots of s) and their respective frequencies, $w_{p1\_cl}$ and $w_{p2\_cl}$ in terms of $g_{m1}$, $R_{o1}$, $C_{o1}$, $g_{m2}$, $R_{o2}$ and $C_{o2}$.

c) Prove that, the circuit in Figure-A behaves similar to the RLC circuit of problem-1 for feedback factor, β=1 (i.e. $R_1$=0 or $R_2$=∞) and find the expressions for damping factor (ζ), quality factor (Q), natural frequency ($w_n$) in terms of loop gain pole frequencies, $w_{p1\_lg}$ and $w_{p2\_lg}$ and DC gain, $A_o$.

d) Considering $g_{m1}=g_{m2}$=0.1mA/V and $R_{o1}=R_{o2}$=1MΩ, fill the values in following table for the corresponding values of $C_{o1}$ and $C_{o2}$ β = 1

| $C_{o1}$ (F) | $C_{o2}$ (F) | Loop Gain | | | | Closed Loop | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $w_{p1\_lg}$ (rad/s) | $w_{p2\_lg}$ (rad/s) | $w_{ugf}$ (rad/s) | PM (deg.) | ζ | Q=1/2 ζ | $w_{p1\_cl}$ (rad/s) | $w_{p2\_cl}$ (rad/s) |
| 1e-9 | 1e-9 | | | | | | | | |
| 10e-9 | 1e-10 | | | | | | | | |
| 4e-8 | 2.5e-11 | | | | | | | | |
| 1e-7 | 1e-11 | | | | | | | | |
| 1.41e-7 | 7.07e-12 | | | | | | | | |
| 2e-7 | 5e-12 | | | | | | | | |
| 5e-7 | 2e-12 | | | | | | | | |
| 1e-6 | 1e-12 | | | | | | | | |
| 2e-6 | 5e-13 | | | | | | | | |
| 1e-5 | 1e-13 | | | | | | | | |

e) Verify that increasing the spacing between loop gain poles, $w_{p1\_lg}$ and $w_{p2\_lg}$ has similar effect on damping factor as increasing R has in the RLC circuit of problem-1.

f) Show the locations of both loop gain poles $p_{1\_lg}$, $p_{2\_lg}$ and corresponding closed loop poles, $p_{1\_cl}$, $p_{2\_cl}$ on s-plane for different values of $\zeta$ calculated in the above table.

g) Plot phase margin (PM) vs. $\zeta$ and find the range of $\zeta$ for which phase margin can be approximated as 100 times of $\zeta$ with +/-10% inaccuracy.

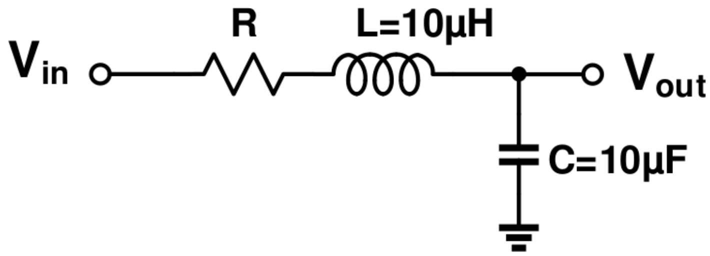
h) Enter the circuit in LTspice and perform following simulations for all the values of $w_{p1\_lg}$, $w_{p2\_lg}$:

   i. Plot the AC magnitude and phase response of the loop gain transfer function for all values of $w_{p1\_lg}$, $w_{p2\_lg}$ and corresponding AC magnitude and phase response of the closed loop transfer function. Comment on effect of increasing and decreasing phase margin on the closed loop AC magnitude and phase response.

   ii. Plot the step response by applying a unit step (0 to 1V with initial delay of 1ms and $T_{rise}$ = 1ns) for the time span of 10ms. Comment on the effect of varying phase margin and $\zeta$ on the transient response. Find the phase margin and corresponding value of $\zeta$ for the fastest settling (when output settles within 95% of the final value).

   iii. Change the value of feedback factor, $\beta$ from 1 to 1/10 (i.e. $R_1=10R_2$) and observe explain the effect of increasing closed loop gain ($k=1/\beta$) on phase margin, damping factor and unity gain frequency ($w_{ugf}$).

1)




$$\frac{V_{out}}{V_{in}} = \frac{\frac{1}{sC}}{\frac{1}{sC} + sL + R}$$

$$= \frac{1}{1 + s^2 LC + RsC}$$

$$= \boxed{\frac{\frac{1}{LC}}{\frac{1}{LC} + s^2 + \frac{Rs}{L}}}$$

$$\omega_n = \sqrt{\frac{1}{LC}}$$

$$\frac{1}{\sqrt{LC}} 2\eta = \frac{R}{L}$$

$$\boxed{\eta = \frac{1}{2} R \sqrt{\frac{C}{L}}}$$

$$Q = \frac{1}{2\eta} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

$$\frac{1}{s^2 + \omega_n^2 + 2\eta\omega_n s}$$

$$s = \frac{-2\eta\omega_n \pm \sqrt{4\eta^2\omega_n^2 - (4)\omega_n^2}}{2}$$

$$= \boxed{\omega_n\left(-\eta \pm \sqrt{\eta^2 - 1}\right)}$$

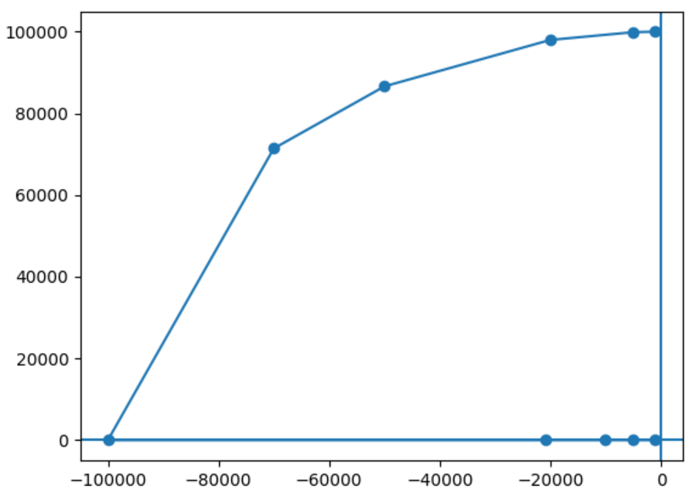
$$\omega_{p1}, \omega_{p2} = \text{mag}\,|p_1|, \text{mag}(p_2)$$

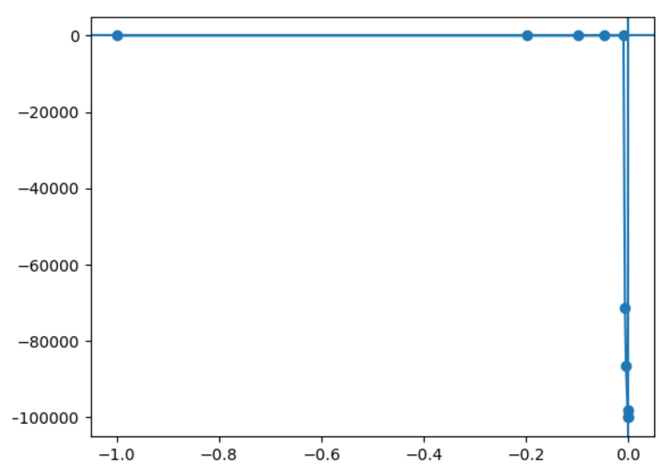
b)

```python
from cmath import *
from tabulate import tabulate

R = [0.02, 0.1, 0.4, 1, 1.4, 2, 5, 10, 20, 100]

L = 1e-5
C = 1e-5

w_n = sqrt(1/(L * C))

def eta(R):
    return R/2 * sqrt(C/L)

def Q(R):
    return 1/(2 * eta(R))

def s_1(R):
    return w_n * (-eta(R) + sqrt(eta(R)**2 - 1))

def s_2(R):
    return w_n * (-eta(R) - sqrt(eta(R)**2 - 1))


lis = [[r, eta(r), Q(r), s_1(r), s_2(r), abs(s_1(r)), abs(s_2(r))] for r in R]

print(tabulate(lis, headers = ["R", "eta", "Q", "s1", "s2", "abs(s1)", "abs(s2)"]))
```

| R | eta | Q | s1 | s2 | abs(s1) | abs(s2) |
|---|---|---|---|---|---|---|
| 0.02 | (0.01+0j) | (50+0j) | (-999.9999999999999+99994.99987499374j) | (-999.9999999999999-99994.99987499374j) | 100000 | 100000 |
| 0.1 | (0.05+0j) | (10+0j) | (-5000+99874.92177719087j) | (-5000-99874.92177719087j) | 100000 | 100000 |
| 0.4 | (0.2+0j) | (2.5+0j) | (-20000+97979.5897113271j) | (-20000-97979.5897113271j) | 100000 | 100000 |
| 1 | (0.5+0j) | (1+0j) | (-49999.99999999999+86602.54037844385j) | (-49999.99999999999-86602.54037844385j) | 100000 | 100000 |
| 1.4 | (0.7+0j) | (0.7142857142857143+0j) | (-69999.99999999999+71414.28428542848j) | (-69999.99999999999-71414.28428542848j) | 100000 | 100000 |
| 2 | (1+0j) | (0.5+0j) | (-99999.99999999999+0j) | (-99999.99999999999-0j) | 100000 | 100000 |
| 5 | (2.5+0j) | (0.2+0j) | (-20871.21525220800 7+0j) | (-479128.784747791 9-0j) | 20871.2 | 479129 |
| 10 | (5+0j) | (0.1+0j) | (-10102.051443364422+0j) | (-989897.9485566354-0j) | 10102.1 | 989898 |
| 20 | (10+0j) | (0.05+0j) | (-5012.562893380056+0j) | (-1994987.4371066198-0j) | 5012.56 | 1.99499e+06 |
| 100 | (50+0j) | (0.01+0j) | (-1000.1000200048792+0j) | (-9998999.899979994-0j) | 1000.1 | 9.999e+06 |

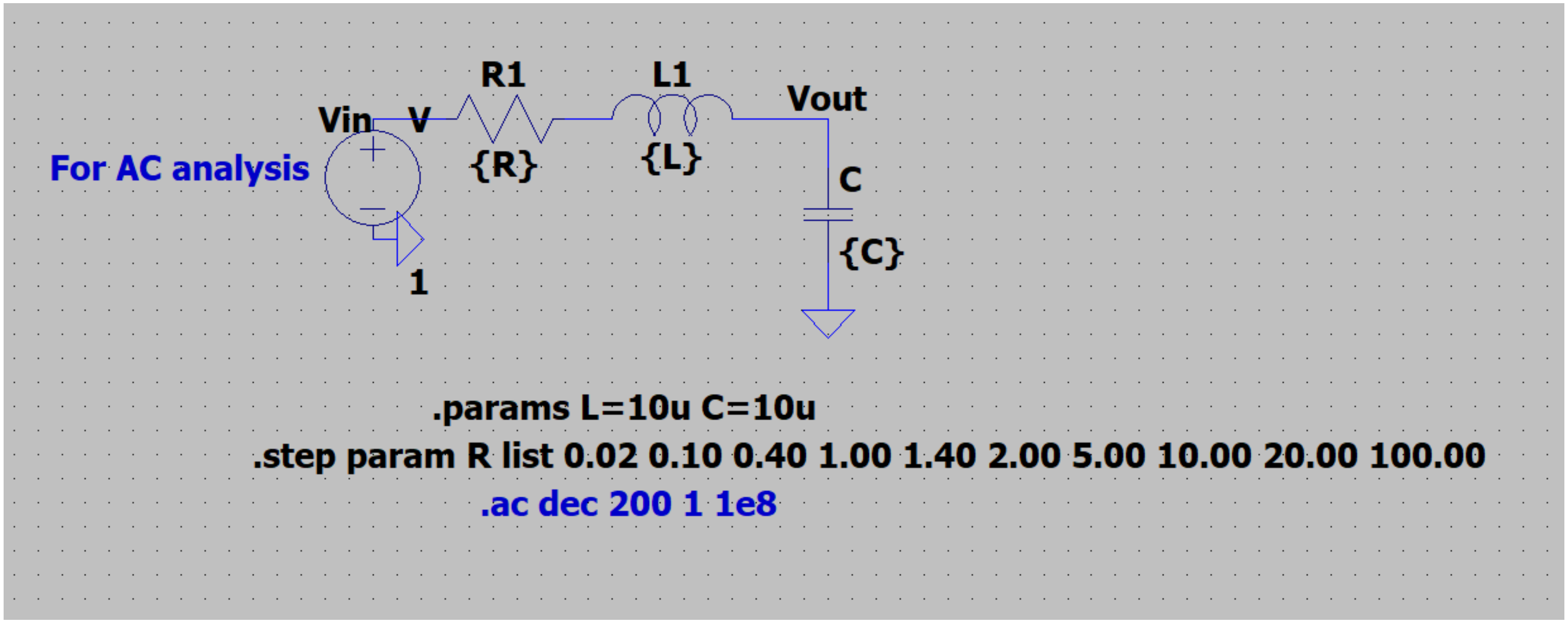
c)

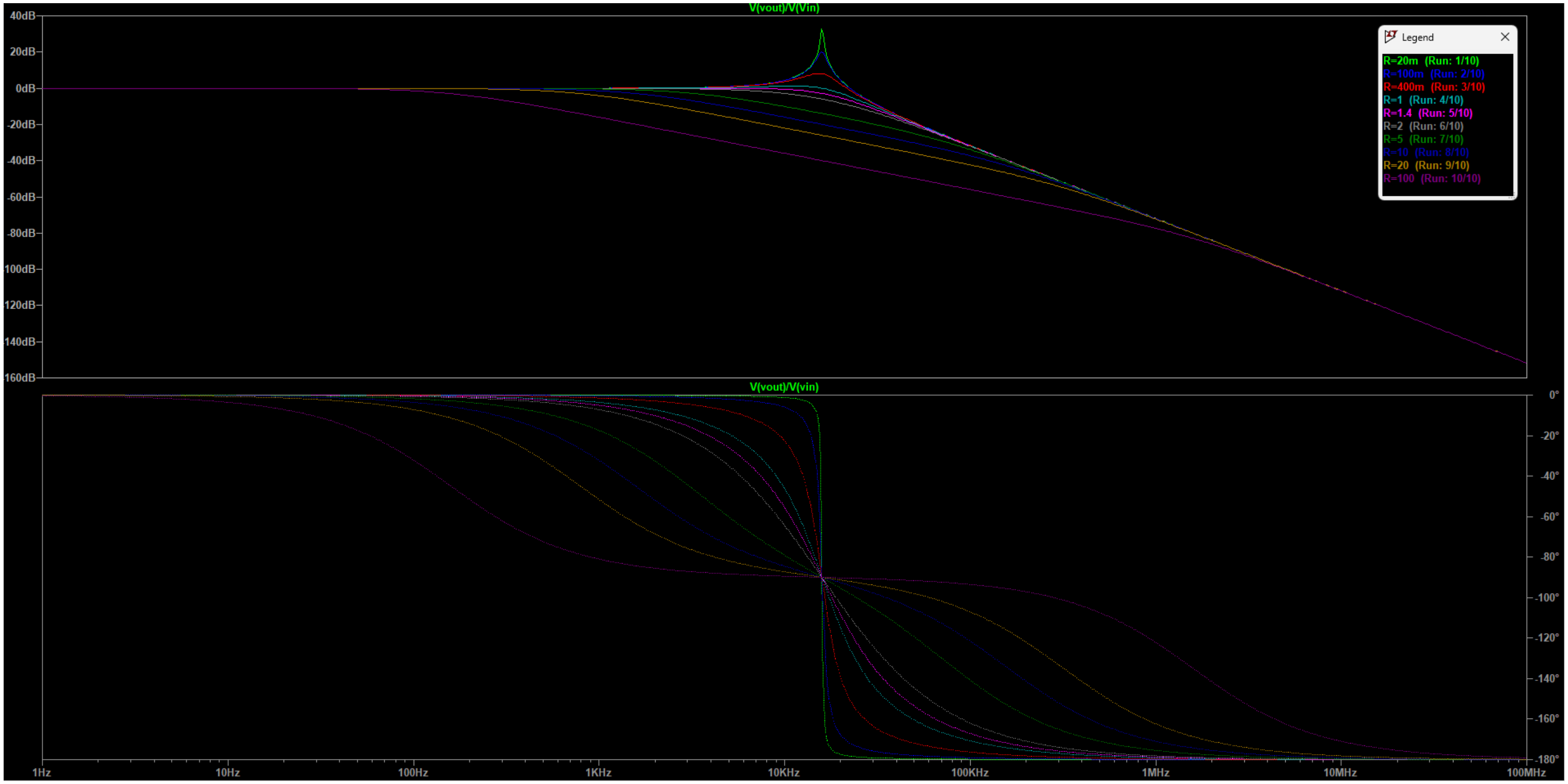


**Question 1d**
i)

Circuit Diagram from LTSpice

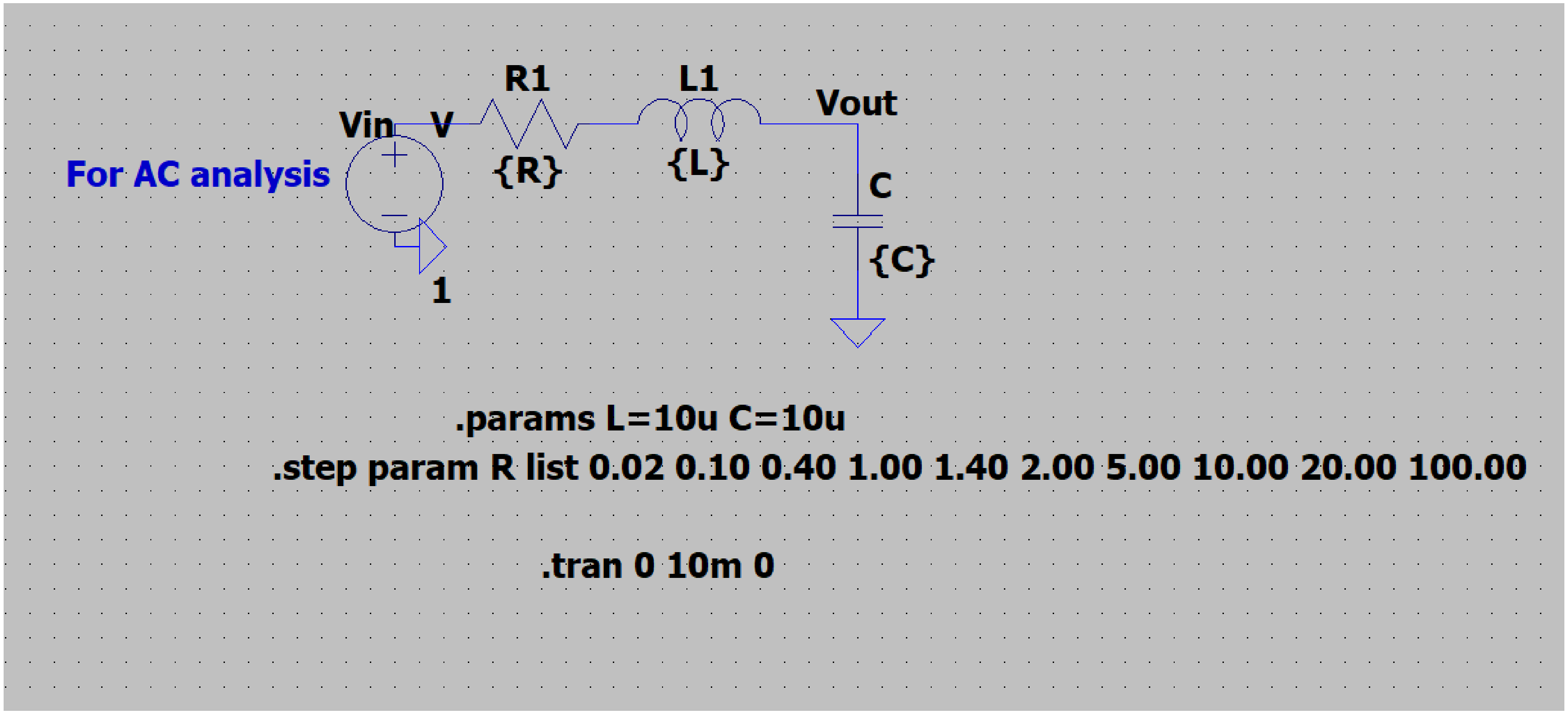


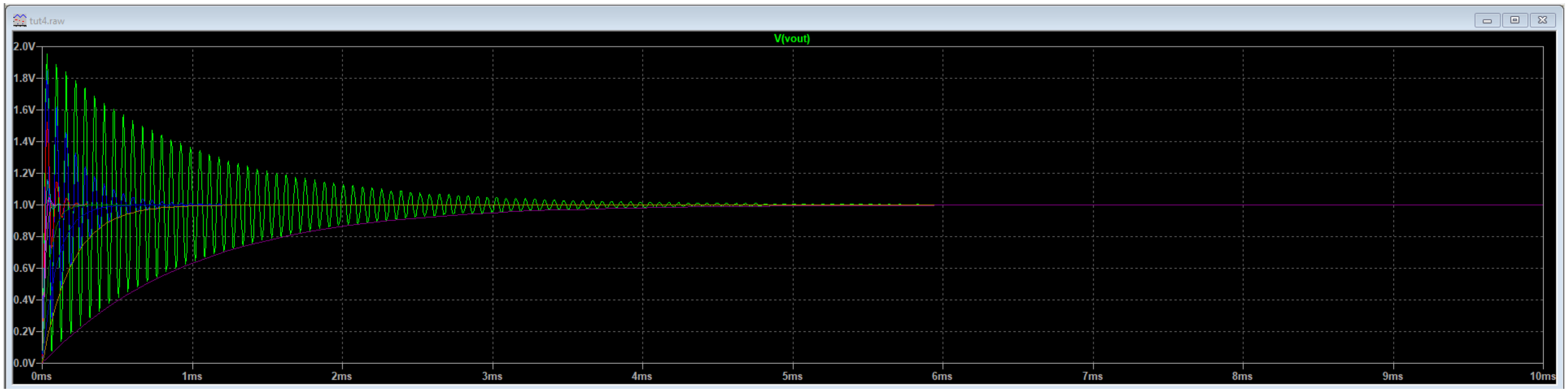



Simulation files in LTSpice have been attached.

Clearly, the damping factor is proportional to R. As we increase the damping factor, the |H(s)| becomes more smoother, and the sharp peak is no longer seen. Also, phase(H(s)) becomes smoother.

ii)


For AC analysis
Vin
V
1
R1
{R}
L1
{L}
Vout
C
{C}
.params L=10u C=10u
.step param R list 0.02 0.10 0.40 1.00 1.40 2.00 5.00 10.00 20.00 100.00
.tran 0 10m 0




As we increase the damping factor, the ringing decreases, then it reaches critical damping, after which there is no ringing.

iii)

By looking at AC response, we can see the quality factor. If the quality factor is large, the damping factor is small and vice versa. If the damping factor is equal to 1, the quality factor is ½.

By looking at the transient response:

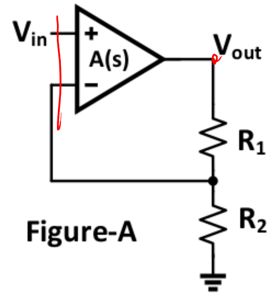
- Damping factor > 1: Overdamped, so there is no ringing
- Damping factor < 1: Underdamped, ringing is present
- Damping factor = 1: Critically damped. Fastest settling time is for damping factor = 1.

**So, we can find the value of R at which settling time is fastest, that will be damping factor = 1.**

2. For the non-inverting amplifier shown in Figure-A and considering op-amp model shown in Figure-B where $A(s)=Vo(s)/Vi(s)$

$V_{out} = A\left[V_{in} - \frac{V}{n}\right]$

$\frac{1}{n} = \frac{R_2}{R_1+R_2}$




$A \Delta V$

$\frac{A \Delta V R_2}{R_1+R_2}$

Figure-A

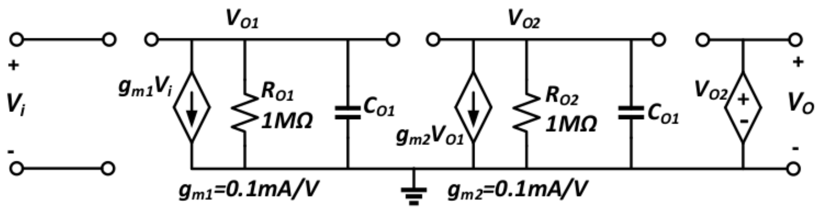



Figure-B

a) Find the loop gain transfer function, LG(s), DC gain $A_o$, poles $p_{1\_lg}$, $p_{2\_lg}$ (roots of s) and their respective frequencies, $w_{p1\_lg}$ and $w_{p2\_lg}$ in terms of $g_{m1}$, $R_{o1}$, $C_{o1}$, $g_{m2}$, $R_{o2}$ and $C_{o2}$.

$$A(s) = \boxed{\frac{g_{m1}}{\left(\frac{1}{R_{o1}} + sC_{o1}\right)} \quad \frac{g_{m2}}{\left(\frac{1}{R_{o2}} + sC_{o2}\right)}}$$

$$LG(s) = \frac{A(s) R_2}{R_1+R_2}$$

DC gain $= \boxed{g_m g_2 R_{o1} R_{o2}}$

Poles are $\frac{-1}{R_{o1}C_{o1}}$ & $\frac{-1}{R_{o2}C_{o2}}$

$w_1 = \frac{1}{R_{o1}C_{o1}}$ $\quad w_2 = \frac{+1}{R_{o2}C_{o2}}$

b) Find the closed loop transfer function, $H(s)=V_{out}(s)/V_{in}(s)$, poles $p_{1\_cl}$, $p_{2\_cl}$ (roots of s) and their respective frequencies, $w_{p1\_cl}$ and $w_{p2\_cl}$ in terms of $g_{m1}$, $R_{o1}$, $C_{o1}$, $g_{m2}$, $R_{o2}$ and $C_{o2}$.

$$\frac{1}{n} = \frac{R_2}{R_1+R_2} \qquad H(s) = \frac{1}{\frac{1}{A}+\frac{1}{n}}$$

$$\frac{g_{m1}}{\left(\frac{1}{R_{o1}}+sC_{o1}\right)} \qquad \frac{g_{m2}}{\left(\frac{1}{R_{o2}}+sC_{o2}\right)}$$

$$= \frac{1}{\frac{1}{A}+\frac{R_2}{R_1+R_2}}$$

$$= \frac{1}{\frac{\left(\frac{1}{R_{o1}}+sC_{o1}\right)\left(\frac{1}{R_{o2}}+sC_{o2}\right)}{g_{m1}g_{m2}}+\frac{R_2}{R_1+R_2}} = \frac{g_{m1}g_{m2}}{\left(\frac{1}{R_{o1}}+sC_{o1}\right)\left(\frac{1}{R_{o2}}+sC_{o1}\right)+\frac{R_2}{R_1+R_2}g_{m1}g_{m2}}$$

$$s_1, s_2 = \frac{-\left(\frac{C_{o1}}{R_{o1}}+\frac{C_{o2}}{R_{o2}}\right) \pm \sqrt{\left(\frac{C_{o1}}{R_{o1}}+\frac{C_{o2}}{R_{o2}}\right)^2 - 4C_oC_1\left[\frac{1}{R_{o1}R_{o2}}+\frac{R_2}{R_1+R_2}g_{m1}g_{m2}\right]}}{2C_oC_{o2}}$$

$$= -(p_1+p_2) \pm \frac{1}{2}\sqrt{(p_1-p_2)^2 - 4p_1p_2\beta A_o}$$

their respective frequencies, $w_{p1\_cl}$ and $w_{p2\_cl}$ in terms of $g_{m1}$, $R_{o1}$, $C_{o1}$, $g_{m2}$, $R_{o2}$ and $C_{o2}$.

5

c) Prove that, the circuit in Figure-A behaves similar to the RLC circuit of problem-1 for feedback factor, β=1 (i.e. $R_1$=0 or $R_2$=∞) and find the expressions for damping factor (ζ), quality factor (Q), natural frequency ($w_n$) in terms of loop gain pole frequencies, $w_{p1\_lg}$ and $w_{p2\_lg}$ and DC gain, $A_o$.

I) $\beta = \frac{1}{n} = 1$,

$$A(s)_{clh} = \frac{1}{\frac{1}{A}+1} = \frac{A}{A+1} = \cancel{\frac{g_m g_2}{\left(sC_{o1}+\frac{1}{R_{o1}}\right)\left(sC_{o2}+\frac{1}{R_{o2}}\right)}}$$

$$\cancel{\frac{g_m g_2}{\left(sC_{o1}+\frac{1}{R}\right)\left(\quad\right)}} + \cancel{1 \; (sC + \ldots)(sC + \tfrac{1}{R_2})}$$

$$= \frac{g_{m1} g_{m2}}{g_{m1} g_{m2} + \left(sC_{o1}+\frac{1}{R_1}\right)\left(sC_{o2}+\frac{1}{R_2}\right)}$$

$$= \frac{1}{1 + \frac{s^2 C_{o1} C_{o2}}{g_{m1} g_{m2}} + \frac{s}{g_{m1} g_{m2}}\left[\frac{C_{o1}}{R_1} + \frac{C_{o2}}{R_2}\right] + \frac{1}{R_1 R_2 g_{m1} g_{m2}}}$$

d) Considering $g_{m1}=g_{m2}=0.1mA/V$ and $R_{o1}=R_{o2}=1M\Omega$, fill the values in following table for the corresponding values of $C_{o1}$ and $C_{o2}$

| $C_{o1}$ (F) | $C_{o2}$ (F) | Loop Gain | | | | Closed Loop | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $w_{p1\_lg}$ (rad/s) | $w_{p2\_lg}$ (rad/s) | $w_{ugf}$ (rad/s) | PM (deg.) | $\zeta$ | $Q=1/2\zeta$ | $w_{p1\_cl}$ (rad/s) | $w_{p2\_cl}$ (rad/s) |
| 1e-9 | 1e-9 | | | | | | | | |
| 10e-9 | 1e-10 | | | | | | | | |
| 4e-8 | 2.5e-11 | | | | | | | | |
| 1e-7 | 1e-11 | | | | | | | | |
| 1.41e-7 | 7.07e-12 | | | | | | | | |
| 2e-7 | 5e-12 | | | | | | | | |
| 5e-7 | 2e-12 | | | | | | | | |
| 1e-6 | 1e-12 | | | | | | | | |
| 2e-6 | 5e-13 | | | | | | | | |
| 1e-5 | 1e-13 | | | | | | | | |



| c1 | c2 | w1 | w2 | wug | pm | eta | Q | pole1 | pole2 |
|---|---|---|---|---|---|---|---|---|---|
| 1e-09 | 1e-09 | 1000 | 1000 | 99995 | 1.14593 | 0.01 | 50 | 100000 | 100000 |
| 1e-08 | 1e-10 | 100 | 10000 | 99750.3 | 5.78223 | 0.0505 | 9.90099 | 100000 | 100000 |
| 4e-08 | 2.5e-11 | 25 | 40000 | 96083 | 22.6172 | 0.200125 | 2.49844 | 100000 | 100000 |
| 1e-07 | 1e-11 | 10 | 100000 | 78615.1 | 51.8346 | 0.50005 | 0.9999 | 100000 | 100000 |
| 1.41e-07 | 7.07e-12 | 7.0922 | 141443 | 64524.9 | 65.4842 | 0.706141 | 0.708074 | 100157 | 100157 |
| 2e-07 | 5e-12 | 5 | 200000 | 48586.8 | 76.3513 | 1.00002 | 0.499988 | 99295.4 | 100710 |
| 5e-07 | 2e-12 | 2 | 500000 | 19984 | 87.7169 | 2.50001 | 0.199999 | 20871.1 | 479131 |
| 1e-06 | 1e-12 | 1 | 1e+06 | 9999.5 | 89.4328 | 5 | 0.0999999 | 10102 | 989899 |
| 2e-06 | 5e-13 | 0.5 | 2e+06 | 4999.98 | 89.8625 | 10 | 0.05 | 5012.56 | 1.99499e+06 |
| 1e-05 | 1e-13 | 0.1 | 1e+07 | 1000 | 90 | 50 | 0.01 | 1000.1 | 9.999e+06 |

e) Verify that increasing the spacing between loop gain poles, $w_{p1\_lg}$ and $w_{p2\_lg}$ has similar effect on damping factor as increasing R has in the RLC circuit of problem-1.

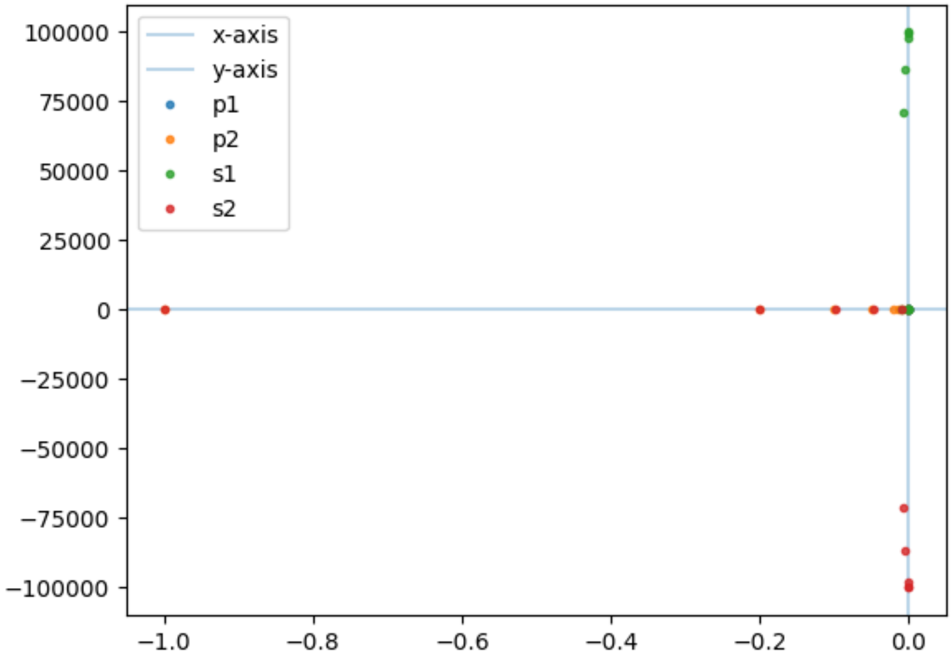
$$\eta = \frac{1}{2\sqrt{A_0}}\left[\sqrt{\frac{P_1}{P_2}} + \sqrt{\frac{P_2}{P_1}}\right]$$

As $P_1 \uparrow$ or $P_2 \uparrow$, $\zeta\uparrow$

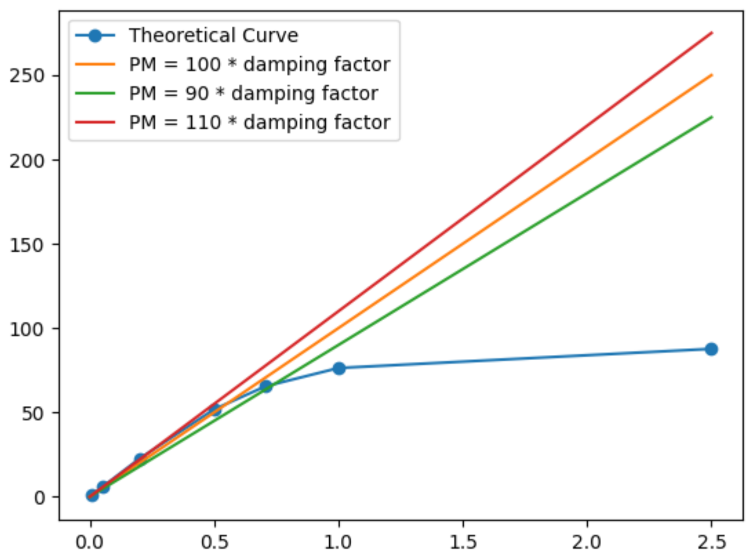
Clearly, as in above table, as $\eta$ increases

$w_{p2\_lg} - w_{p1\_lg} \uparrow$

f) Show the locations of both loop gain poles $p_{1\_lg}$, $p_{2\_lg}$ and corresponding closed loop poles, $p_{1\_cl}$, $p_{2\_cl}$ on s-plane for different values of $\zeta$ calculated in the above table.




g) Plot phase margin (PM) vs. $\zeta$ and find the range of $\zeta$ for which phase margin can be approximated as 100 times of $\zeta$ with +/-10% inaccuracy.




Range of values is approx

$\boxed{[0.01, 0.70]}$

## Question 2
## h)

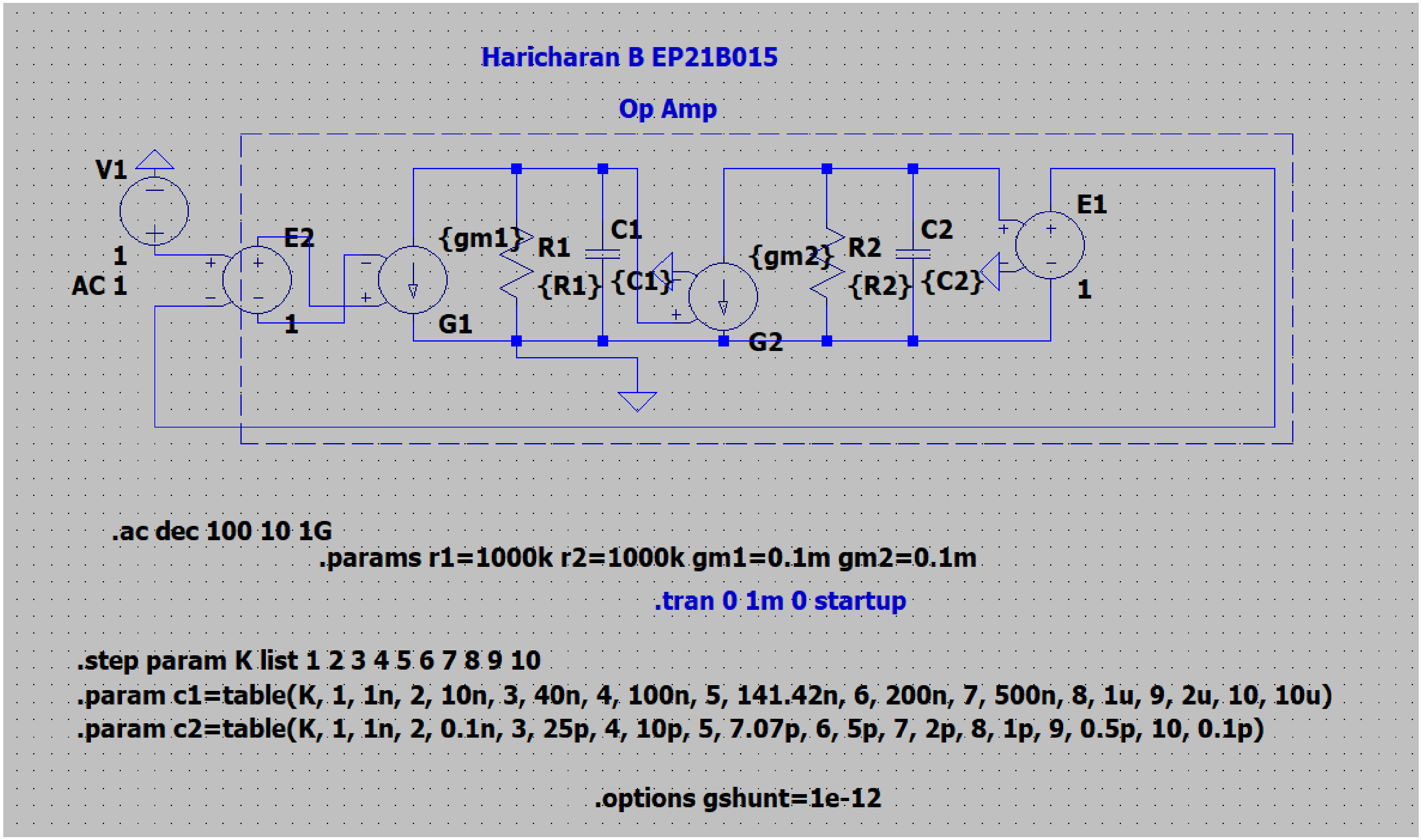
Explanation:
As the damping factor changes to 1, the oscillations gradually decrease. At damping factor = 1, it is critically damped. For damping factor > 1, it takes a longer time to reach the final value.

Graphically, phase margin is approx 75 degrees.

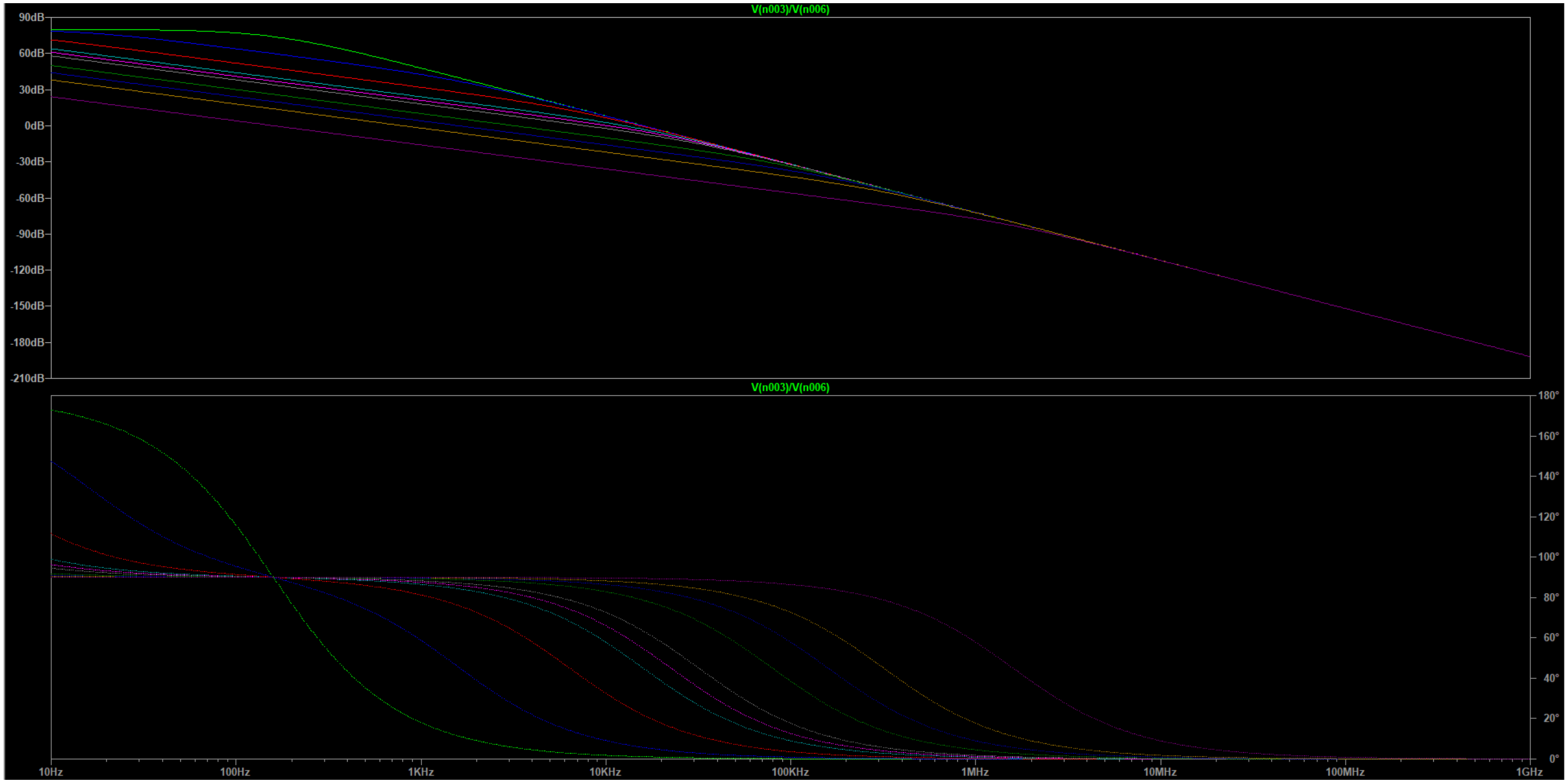
Damping factor is proportional to $beta^{1/2}$.

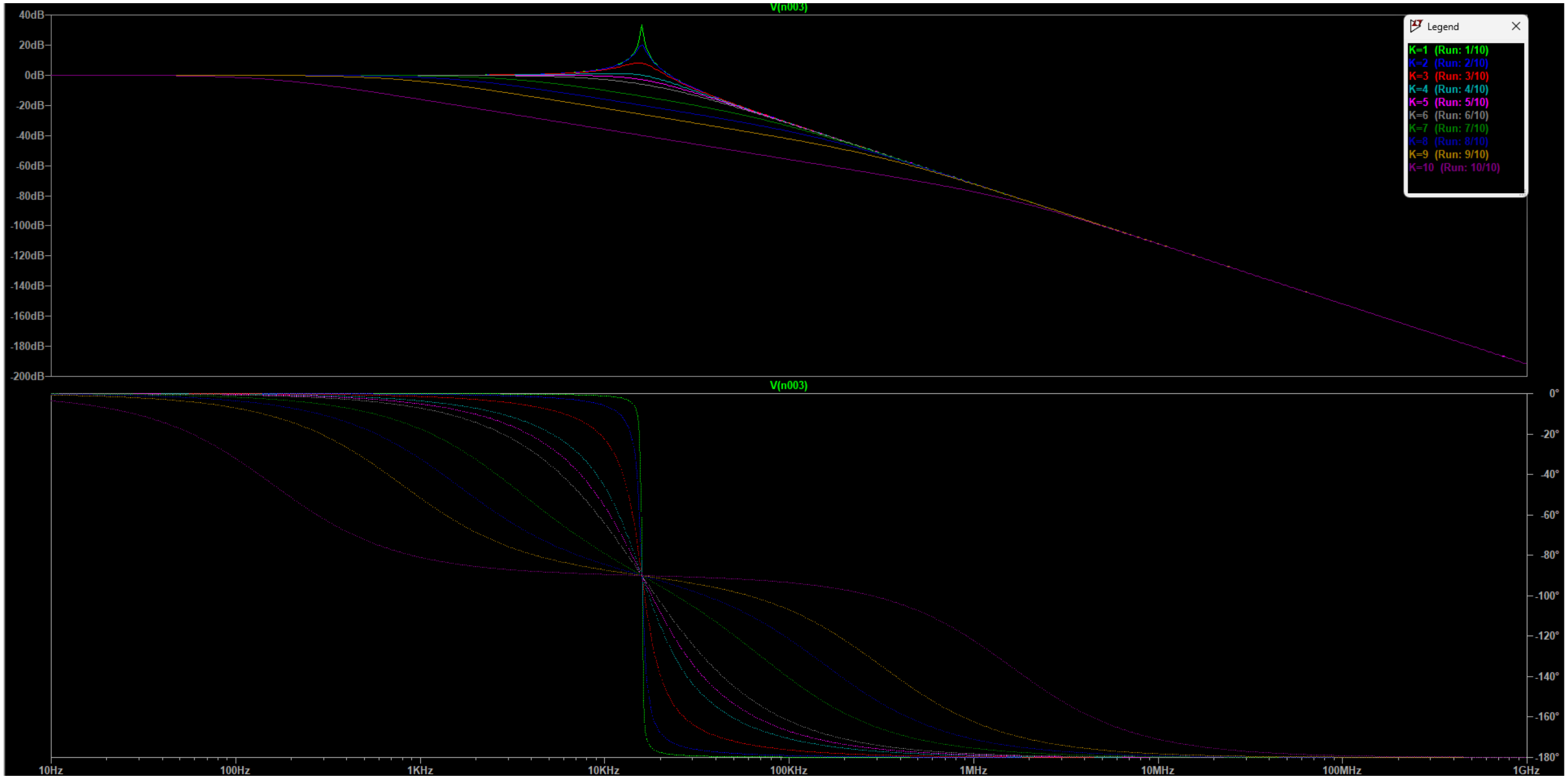
So, the new value of damping factor will be root (10) * beta. This can be also observed in the simulations.

i)

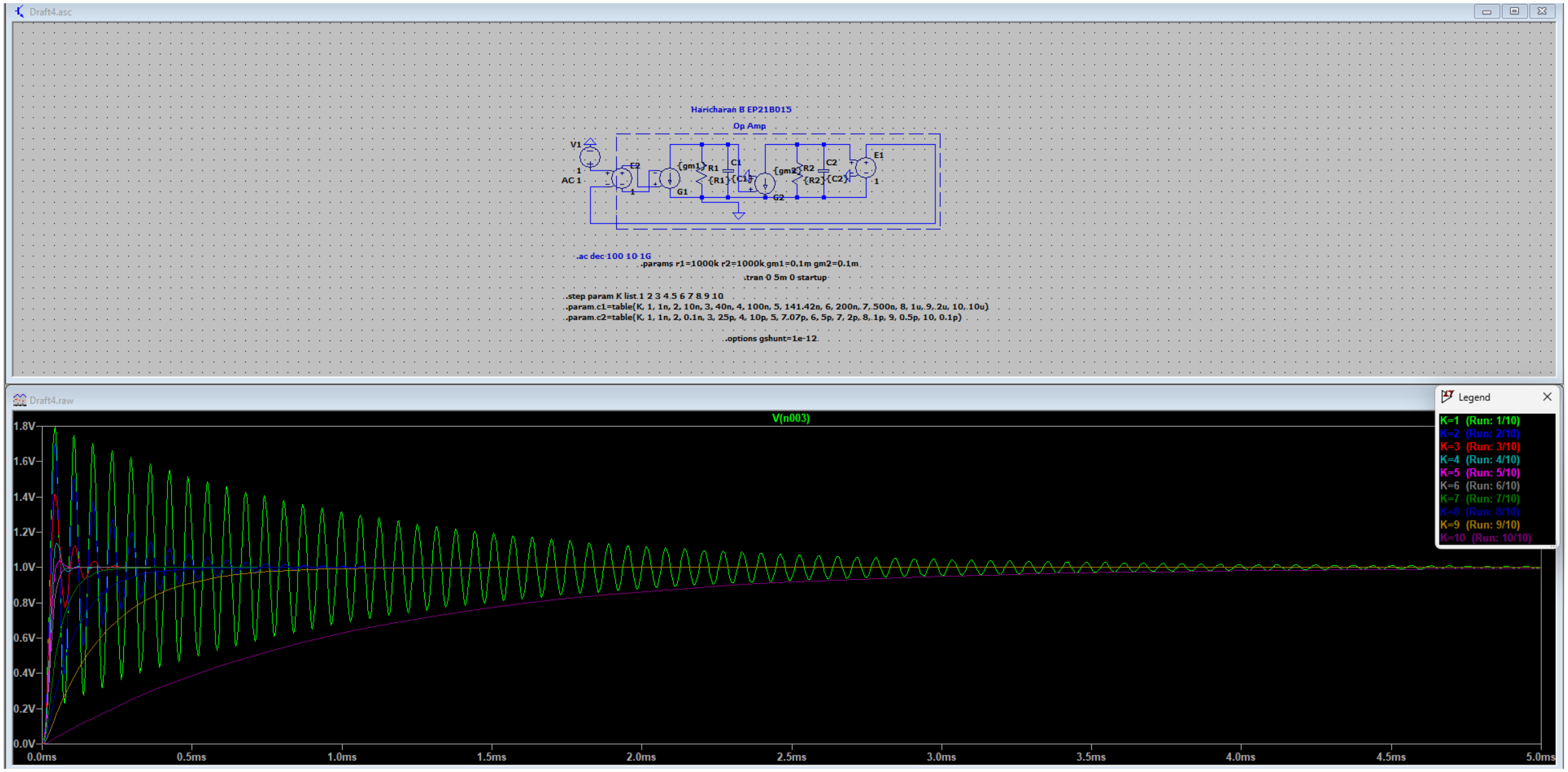

Haricharan B EP21B015
Op Amp
V1
1
AC 1
E2
1
{gm1}
G1
R1
{R1}
C1
{C1}
{gm2}
G2
R2
{R2}
C2
{C2}
E1
1
.ac dec 100 10 1G
.params r1=1000k r2=1000k gm1=0.1m gm2=0.1m
.tran 0 1m 0 startup
.step param K list 1 2 3 4 5 6 7 8 9 10
.param c1=table(K, 1, 1n, 2, 10n, 3, 40n, 4, 100n, 5, 141.42n, 6, 200n, 7, 500n, 8, 1u, 9, 2u, 10, 10u)
.param c2=table(K, 1, 1n, 2, 0.1n, 3, 25p, 4, 10p, 5, 7.07p, 6, 5p, 7, 2p, 8, 1p, 9, 0.5p, 10, 0.1p)
.options gshunt=1e-12

Loop gain Transfer function

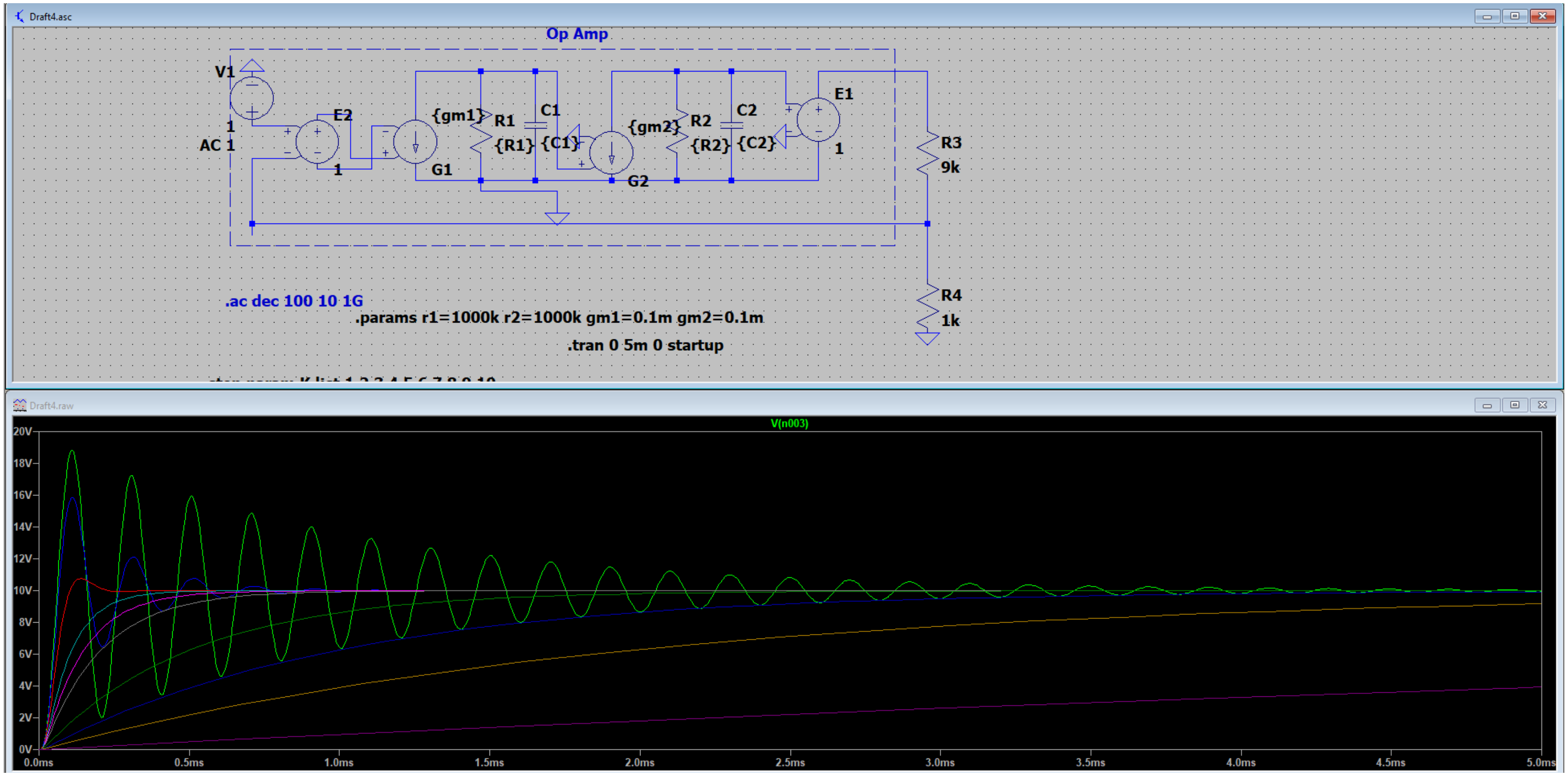



V(n003)
40dB
20dB
0dB
-20dB
-40dB
-60dB
-80dB
-100dB
-120dB
-140dB
-160dB
-180dB
-200dB
Legend
K=1 (Run: 1/10)
K=2 (Run: 2/10)
K=3 (Run: 3/10)
K=4 (Run: 4/10)
K=5 (Run: 5/10)
K=6 (Run: 6/10)
K=7 (Run: 7/10)
K=8 (Run: 8/10)
K=9 (Run: 9/10)
K=10 (Run: 10/10)
V(n003)
0°
-20°
-40°
-60°
-80°
-100°
-120°
-140°
-160°
-180°
10Hz
100Hz
1KHz
10KHz
100KHz
1MHz
10MHz
100MHz
1GHz

ii)


Draft4.asc
Haricharan B EP21B015
Op Amp
V1
1
AC 1
E2
{gm1}
R1
{R1}
C1
{C1}
G1
{gm2}
R2
{R2}
C2
{C2}
G2
E1
.ac dec 100 10 1G
.params r1=1000k r2=1000k gm1=0.1m gm2=0.1m
.tran 0 5m 0 startup
.step param K list 1 2 3 4 5 6 7 8 9 10
.param c1=table(K, 1, 1n, 2, 10n, 3, 40n, 4, 100n, 5, 141.42n, 6, 200n, 7, 500n, 8, 1u, 9, 2u, 10, 10u)
.param c2=table(K, 1, 1n, 2, 0.1n, 3, 25p, 4, 10p, 5, 7.07p, 6, 5p, 7, 2p, 8, 1p, 9, 0.5p, 10, 0.1p)
.options gshunt=1e-12
Draft4.raw
V(n003)
Legend
K=1 (Run: 1/10)
K=2 (Run: 2/10)
K=3 (Run: 3/10)
K=4 (Run: 4/10)
K=5 (Run: 5/10)
K=6 (Run: 6/10)
K=7 (Run: 7/10)
K=8 (Run: 8/10)
K=9 (Run: 9/10)
K=10 (Run: 10/10)
1.8V
1.6V
1.4V
1.2V
1.0V
0.8V
0.6V
0.4V
0.2V
0.0V
0.0ms
0.5ms
1.0ms
1.5ms
2.0ms
2.5ms
3.0ms
3.5ms
4.0ms
4.5ms
5.0ms

iii)



Draft4.asc
Op Amp
V1
AC 1
1
E2
1
{gm1}
R1
{R1}
C1
{C1}
G1
{gm2}
R2
{R2}
C2
{C2}
G2
E1
1
R3
9k
R4
1k
.ac dec 100 10 1G
.params r1=1000k r2=1000k gm1=0.1m gm2=0.1m
.tran 0 5m 0 startup
Draft4.raw
V(n003)
20V
18V
16V
14V
12V
10V
8V
6V
4V
2V
0V
0.0ms
0.5ms
1.0ms
1.5ms
2.0ms
2.5ms
3.0ms
3.5ms
4.0ms
4.5ms
5.0ms