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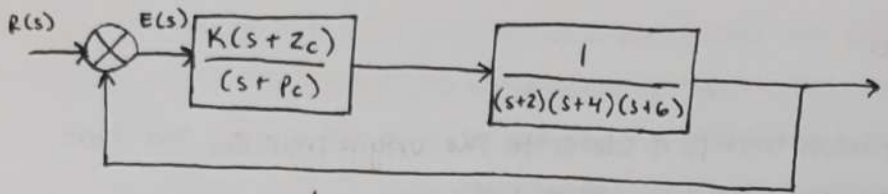
(9.4) For the unity-feedback system of Figure P9.1, let $G(s) = \frac{K}{(s+2)(s+4)(s+6)}$

(a) Design a compensator that will not significantly change the position of the uncompensated dominant poles that will result in 10% overshoot but yields $K_p = 20$.

model of lag compensator:



thus, $G(s) = \frac{1}{(s+2)(s+4)(s+6)} = \frac{1}{(s^2+6s+8)(s+6)}$

$$G(s) = \frac{1}{s^3 + 6s^2 + 6s^2 + 36s + 8s + 48}$$

$$G(s) = \frac{1}{s^3 + 12s^2 + 44s + 48}$$

solving for 10% overshoot:

$$\xi = \frac{-\ln(\%OS/100)}{\sqrt{\pi^2 + \ln^2(\%OS/100)}} = \frac{-\ln(0.1)}{\sqrt{\pi^2 + \ln^2(0.1)}}$$

$\xi = .5911 \leftarrow$ damping ratio

angle of damping ratio: (from real positive axis)

$\theta = 180° - \cos^{-1}(\xi) = 180° - \cos^{-1}(.5911)$

$\theta = 180° - 53.76° = 126.235°$

Find the value of K using the magnitude criterion:

$$K = \frac{1}{|G(s)|} = |s^3 + 12s^2 + 44s + 48|$$

we need to find the dominant poles, which can be done accurately with the use of MATLAB. with our MATLAB calculation, we see that the location of the dominant poles are:

$s = -2.028 \pm 2.768j$

consequently, $K = |s^3 + 12s^2 + 44s + 48| \Big|_{s = -2.028 + 2.768j}$

$K = 45.546$

(9.4a)

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Solving for $K_{P0} = \lim_{s \to 0} G(s)$:

$$\lim_{s \to 0} G(s) = \lim_{s \to 0} \frac{K}{(s+2)(s+4)(s+6)} = \frac{45.546}{48}$$

$K_{P0} = .948875$

consequently, $\frac{z_c}{p_c} = \frac{K_{PN}}{K_{P0}}$, where $K_{PN} = 20$

Since we are creating a lag compensator, we know that p_c is closer to the origin than z_c, and that $z_c >>> p_c$. So, if we create an arbitrary pole value where $p_c = 0.01$:

$$\frac{z_c}{0.01} = \frac{20}{.948875} \rightarrow z_c = \frac{20(0.01)}{.948875} = .21077$$

- $p_c = 0.01$
- $z_c = .21077$

$$\rightarrow G_c(s) = \frac{(s+.21077)}{(s+0.01)}$$

therefore,

$$G_{LC}(s) = G(s) \cdot G_c(s) = \frac{K(s+.21077)}{(s+0.01)(s+2)(s+4)(s+6)}$$

$$G_{LC}(s) = \frac{K(s+.21077)}{(s+0.01)(s^3+12s^2+44s+48)} = \frac{K(s+.21077)}{s^4 + 12.01s^3 + 44.12s^2 + 48.44s + .48}$$

we can find the location of the dominant poles by using MATLAB software, as it is the most accurate way. with our MATLAB calculation, we see that the dominant poles are

$s = -1.986 \pm 2.71j$

now, to solve for the value of K:

$$K = \frac{1}{|G_{LC}(s)|} = \left| \frac{s^4 + 12.01s^3 + 44.12s^2 + 48.44s + .48}{s + .21077} \right|_{s = -1.986 + 2.71j}$$

$K = 49.3$

solving for $K_{P0} = \lim_{s \to 0} G_{LC}(s)$

$$\lim_{s \to 0} G_{LC}(s) = \lim_{s \to 0} \frac{K(s+.21077)}{(s+0.01)(s+2)(s+4)(s+6)} = \frac{10.3906}{.48} = 21.647$$

if we review the characteristics between our uncompensated and lag-compensated systems:

uncompensated	lag-compensated
$K = 45.546$	$K = 49.3$
$K_p = .948875$	$K_p = 21.647$
$e(\infty) = 1/1.948875$	$e(\infty) = 1/22.647$
$e(\infty) = .513116$	$e(\infty) = .044156$
second-order poles @ $s = -2.028 \pm 2.768j$	second order poles @ $s = -1.986 \pm 2.71j$

★ based on these observations, we can see that our lag compensator design has satisfied the conditions that were needed, such as yielding a $K_p = 20$ while not significantly changing the location of the dominant second order poles. our steady state error has also improved by a lot and is allmost zero.

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(9.12) A unity feedback control system has the following forward transfer function: $G(s) = \dfrac{K}{s^2(s+4)(s+12)}$

(a) Design a lead compensator to yield a closed-loop step response with 20.5% overshoot and a settling time of 3 seconds. Be sure to specify the value of K.

damping ratio:

$$\zeta = \frac{-\ln(\%OS/100)}{\sqrt{\pi^2 + \ln^2(\%OS/100)}} = \frac{-\ln(.205)}{\sqrt{\pi^2 + \ln^2(.205)}} = .45038 = \zeta$$

real part of lead compensated dominant second-order poles:

$$\sigma = 4/T_s = 4/3 = 1.333$$

imaginary part of lead compensated dominant second-order poles:

$$\omega_d = |\sigma| \tan(180° - \cos^{-1}(\zeta)) = 1.333 \tan(180° - \cos^{-1}(.45038))$$

$$\omega_d = 2.6426$$

location of lead compensated dominant second-order poles: $(-\sigma \pm \omega_d j)$

$$s = -1.333 \pm 2.6426j$$

definition of lead compensator: $\dfrac{s+z_c}{s+p_c}$, $p_c \ggg z_c$. assume $z_c = 0.01$

using angle criterion to find lead compensator pole:

$$-\angle s+p_c \Big|_{s=-1.333+2.6426j} = -180° + \angle \frac{s^2(s+4)(s+12)}{(s+0.01)}\Bigg|_{s=-1.333+2.6426j}$$

$$-\tan^{-1}\left(2.6426/p_c - 1.333\right) = -184.44°$$

$$\frac{2.6426}{p_c - 1.333} = 0.0776$$

$$p_c - 1.333 = 34.054$$

$$p_c = 35.388$$

lead compensator with compensator pole and zero:

$\dfrac{(s+0.01)}{(s+35.388)}$, $p_c \ggg z_c$, and z_c is very close to origin.

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(9.12) transfer function with lead compensator:

$$G_{LC}(s) = \frac{K(s+0.01)}{s^2(s+4)(s+12)(s+35.388)}$$

magnitude criterion to solve for value of gain, K:

$$K = \frac{1}{|G_{LC}(s)|} = \left| \frac{s^2(s+4)(s+12)(s+35.388)}{(s+0.01)} \right| \Bigg|_{s=-1.333+2.6426j}$$

$K = 4173.66$

transfer function with lead compensator and $K = 4173.66$

$$G_{LC}(s) = \frac{4173.66(s+0.01)}{s^2(s+4)(s+12)(s+35.388)}$$

(b) Is your second-order approximation valid?

· We can determine the validity by finding all poles of the closed-loop transfer function. using the characteristic equation, $1 + KG(s) = 0$:

$$1 + \frac{4173.66(s+0.01)}{s^2(s+4)(s+12)(s+35.388)} = 0 \rightarrow s^2(s+4)(s+12)(s+35.388) + 4173.66(s+0.01) = 0$$

using MATLAB, the roots of the closed-loop transfer function are:

$s_1 = -0.01$

$s_2 = -1.33 \pm 2.65j$

$s_3 = -13.488$

$s_4 = -35.2247$

· since the value of the higher order poles is more than 5x the value of the real part of the dominant poles, our second order approximation is valid.

(c) Use MATLAB or any other computer program to simulate and compare the transient response of the compensated system to the predicted transient response.

· we need the closed-loop transfer function of the uncompensated and compensated system, and the values of K at their dominant poles.

$$\cdot\ K = \frac{1}{|G(s)|} = |s^2(s+4)(s+12)| \Big|_{s=-1.333 \pm 2.6426j}$$

$\cdot\ K = 361.445$

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(9.15) Given the unity feedback system of Figure P9.1, with $G(s) = \frac{K}{(s+2)(s+4)(s+6)(s+8)}$

Find the transfer function of a lag-lead compensator that will yield a settling time 0.5 second shorter than that of the uncompensated system. The compensated system will also have a damping ratio of 0.5, and improve the steady-state error by a factor of 30. The compensator zero is -5; also, find the compensated system's gain. Justify any 2nd order approximations or verify the design through simulation.

settling time of uncompensated system : $T_s = 4/\zeta\omega_n$

dominant poles of uncompensated system (MATLAB):

$s = -1.531 \pm 2.652j$

$T_s = 4/1.531 = 2.613s$

settling time of compensated system = $2.613 - .50 = 2.113s$

real part of compensated second-order dominant poles:

$\sigma = 4/T_s = 4/2.113 = 1.893$

imaginary part of compensated second-order dominant poles:

$\omega_d = |\sigma| \tan(180° - \cos^{-1}(\zeta)) = 1.893 \cdot \tan(180° - \cos^{-1}(0.5))$

$\omega_d = -3.278j$

location of second-order dominant poles (compensated):

$s = -1.893 \pm 3.278j$

magnitude criterion to solve for value of gain, K (uncompensated):

$K = \frac{1}{|G(s)|} = |(s+2)(s+4)(s+6)(s+8)|\,|_{s=-1.531 \pm 2.652j}$

$K = 354.44$

angle criterion of compensated dominant poles to solve for lead-compensator pole (assume $Z_c = -5$)

$180° - \left(\angle (s+2)(s+4)(s+6)(s+8)\,|_{s=-1.893+3.278j} + \angle s+p\,|_{s=-1.893+3.278j}\right) + \angle s+5\,|_{s=-1.893+3.278j}$

$\tan^{-1}\left(\frac{3.278}{P_c - 1.893}\right) = 14.42°$

$\frac{3.278}{P_c - 1.893} = 0.257$

$12.75 = P_c - 1.893$

$P_c = 14.64$

now, we have defined our lead compensator as:

$\frac{(s+5)}{(s+14.64)}$, $P_c >>> Z_c$, Z_c is closer to origin.

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(9.15) transfer function with lead compensator:

$$G_{LC}(s) = \frac{K(s+5)}{(s+2)(s+4)(s+6)(s+8)(s+14.64)}$$

magnitude criterion to solve for value of gain, K (lead-compensated):

$$K = \frac{1}{|G_{LC}(s)|} = \left|\frac{(s+2)(s+4)(s+6)(s+8)(s+14.64)}{(s+5)}\right|\Bigg|_{s=-1.893+3.278j}$$

$K = 1359.3$

solving for lag-compensator by finding K_{PU}:

$$K_{PU} = \lim_{s\to 0} G(s) = \lim_{s\to 0}\frac{354.44}{(s+2)(s+4)(s+6)(s+8)} = \frac{354.44}{(2)(4)(6)(8)} = .9238$$

$$e(\infty) = \frac{1}{1+K_{PU}} = \frac{1}{1.9238} = .5186$$

solving for lag compensator by finding K_{PN}:

$$K_{PN} = \lim_{s\to 0} G_{LC}(s) = \lim_{s\to 0}\frac{1359.3(s+5)}{(s+2)(s+4)(s+6)(s+8)(s+14.64)} = \frac{(1359.3)(5)}{(2)(4)(6)(8)(14.64)}$$

$K_{PN} = 1.209$ $\quad e(\infty) = \frac{1}{1+K_{PN}} = \frac{1}{2.209} = .4527$

improvement of steady-state error with lead compensation: $\frac{K_{PN}}{K_{PU}} = \frac{.4527}{.5186} = .8728$

improvement of steady-state error by a factor of 30: $\frac{30}{.8728} = 34.3719$

if the lag compensator pole has an arbitrary value of $P_c = 0.01$, $z_c = 34.3719 \cdot 0.01 = .3437$

thus, the lag compensator is fully defined as: $(s+.3437)/(s+0.01)$

transfer function with lag and lead compensator:

$$G_{LLC}(s) = \frac{K(s+5)(s+.3437)}{(s+0.01)(s+2)(s+4)(s+6)(s+8)(s+14.64)}$$

dominant poles of lag-lead transfer function (MATLAB):

$s = -1.82 \pm 3.153j$

magnitude criterion to solve for value of gain, K (lag-lead compensated):

$$K = \frac{1}{|G_{LLC}(s)|} \cdot \left|\frac{(s+0.01)(s+2)(s+4)(s+6)(s+8)(s+14.64)}{(s+5)(s+.3437)}\right|\Bigg|_{s=-1.82+3.153j}$$

$K = 1359.1$

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(9.20) For the unity feedback system in Figure P9.1, with $G(s) = \dfrac{K}{(s+4)(s+6)(s+10)}$

do the following:

(a) Design a controller that will yield no more than 25% overshoot and no more than a 2-second settling time for a step input and zero steady state error for step and ramp inputs.

damping ratio at 25% overshoot:

$$\zeta = \frac{-\ln(\%OS/100)}{\sqrt{\pi^2 + \ln^2(\%OS/100)}} = \frac{-\ln(.25)}{\sqrt{\pi^2 + \ln^2(.25)}} = .4037$$

location of uncompensated dominant poles (MATLAB):

$s = -2.708 \pm 6.137j$

magnitude criterion to solve for value of gain, K (uncompensated):

$$K = \frac{1}{|G(s)|} = \left|(s+4)(s+6)(s+10)\right| \Big|_{s=-2.708 \pm 6.137j}$$

$K = 416.26$

real part of PD compensated second order dominant poles:

$T_s = 4/\sigma \rightarrow \sigma = 4/T_s \rightarrow \sigma = 4/2 = 2$

imaginary part of PD compensated second-order dominant poles:

$w_d = |\sigma| \tan(180° - \cos^{-1}(\zeta))$

$w_d = 2\tan(180° - \cos^{-1}(.4037)) = -4.532j$

location of PD compensated dominant poles ($-\sigma \pm w_d j$):

$s = -2 \pm 4.532j$

angle criterion to solve for PD compensator zero:

$-180° = \angle s+z_c |_{s=-2+4.532j} - \angle(s)(s+4)(s+6)(s+10)|_{s=-2+4.532j}$

$-180° = \angle s+z_c |_{s=-2+4.532j} - 258.07$

$78.07° = \angle s+z_c |_{s=-2+4.532j}$

$$78.07° = \tan^{-1}\left(\frac{4.532}{z_c - 2}\right)$$

$$4.733 = \frac{4.532}{z_c - 2}$$

$z_c = 2.958$

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(9.20) transfer function of PD-compensated:

$$G_{PD}(s) = \frac{K(s+2.957)}{s(s+4)(s+6)(s+10)}$$

magnitude criterion to solve for value of gain, K (PD compensated):

$$K = \frac{1}{|G_{PD}(s)|} = \left|\frac{(s)(s+4)(s+6)(s+10)}{(s+2.957)}\right|\Bigg|_{s=-2+4.532j}$$

$K = 294.58$

solving for PI compensater: (assume $z_c = 0.01$):

$$G_{PI}(s) = \frac{(s+0.01)}{s}$$

transfer function of PID controller:

$$G_{PID}(s) = \frac{K(s+0.01)(s+2.957)}{s^2(s+4)(s+6)(s+10)}$$

magnitude criterion to solve for value of gain, K (PID controller):

$$K = \frac{1}{|G_{PID}(s)|} = \left|\frac{(s^2)(s+4)(s+6)(s+10)}{(s+0.01)(s+2.957)}\right|\Bigg|_{s=-2+4.532j}$$

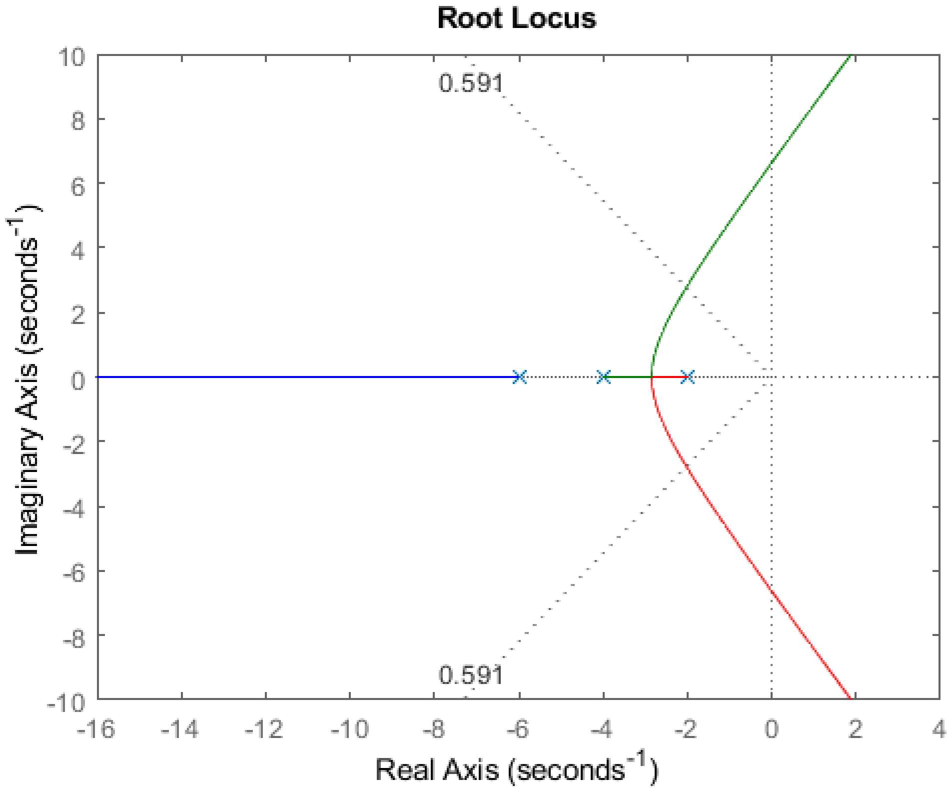
$K = 294.78$

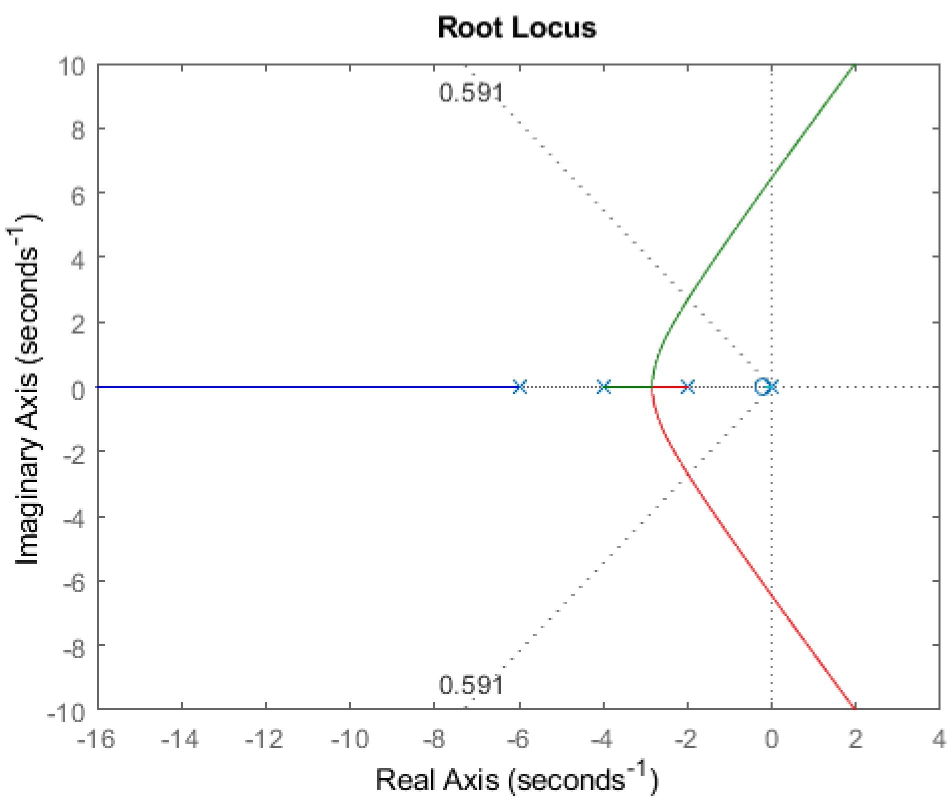
(b) Use MATLAB and verify your design.

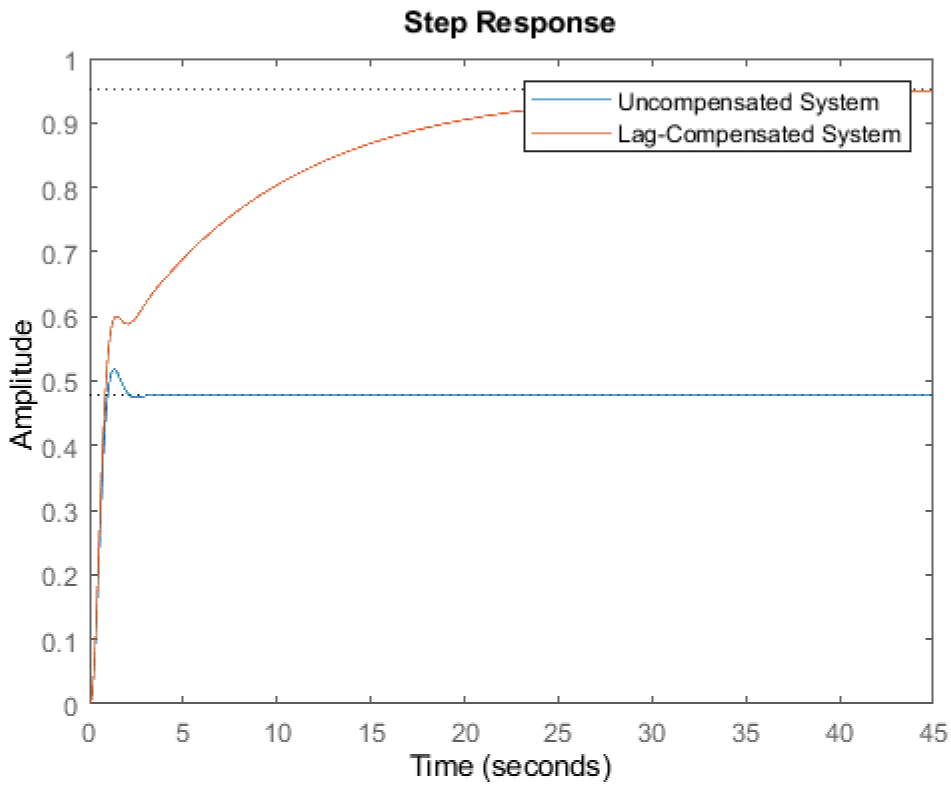
Table of Contents

Question 4 : Part B

```
Gs_uncompensated = tf(1, [1 12 44 48]);
figure(1)
rlocus(Gs_uncompensated)
damping = .591;
sgrid(damping, 0)
% Lag-Compensated Transfer Function
Gs_lagcompensated = tf([1 .21077], [1 12.01 44.12 48.44 .48]);
figure(2)
rlocus(Gs_lagcompensated)
sgrid(damping, 0)
% Gain of Uncompensated and Lag-Compensated Transfer Functions
Ku = 43.977;
Klc = 45.92;
% Closed-Loop Transfer Functions
Tu = feedback(Gs_uncompensated*Ku,1);
Tlc = feedback(Gs_lagcompensated*Klc,1);
% Step Response Plot of Closed-Loop Transfer Functions
figure(3)
step(Tu,Tlc)
legend("Uncompensated System","Lag-Compensated System")
```


Root Locus
0.591
0.591
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
10
8
6
4
2
0
-2
-4
-6
-8
-10
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4


Root Locus
0.591
0.591
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
10
8
6
4
2
0
-2
-4
-6
-8
-10
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4



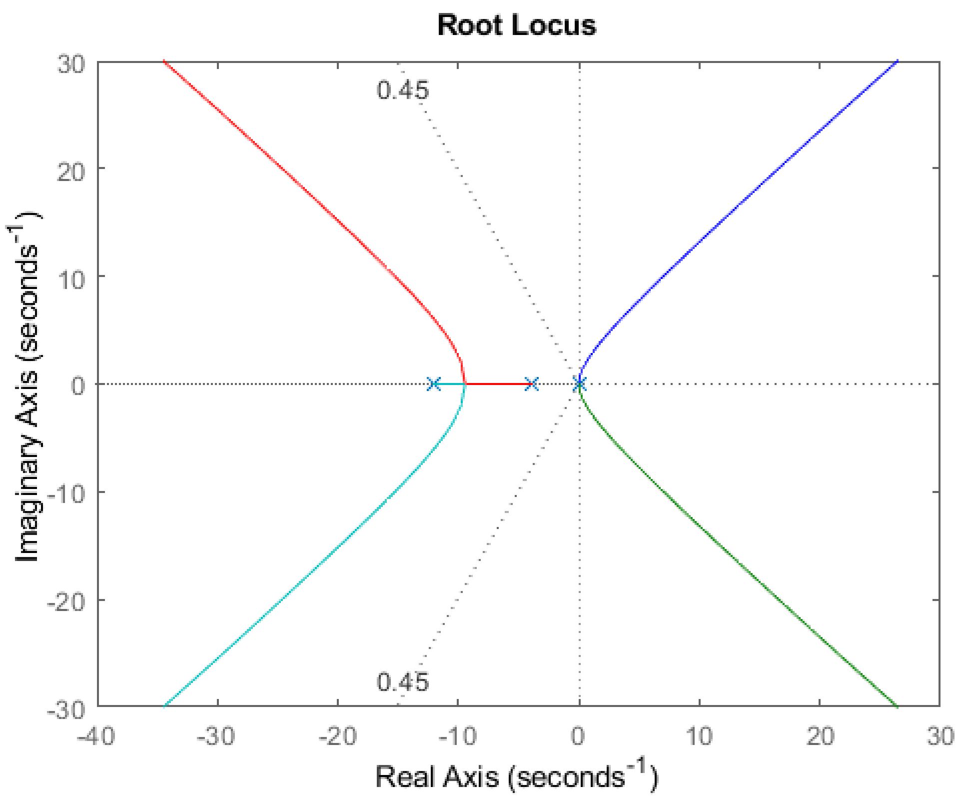
Question 4: Part C

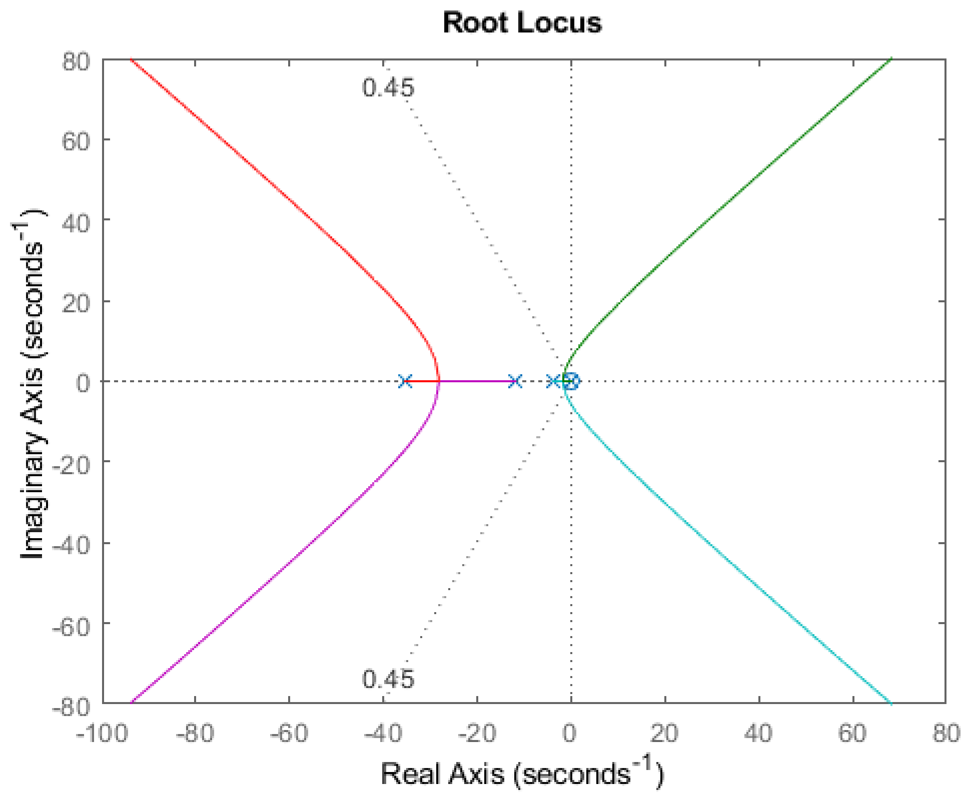
```
stepinfo(Tlc)


ans =

  struct with fields:

        RiseTime: 13.6403
    SettlingTime: 28.1310
     SettlingMin: 0.8576
     SettlingMax: 0.9510
       Overshoot: 0
      Undershoot: 0
            Peak: 0.9510
        PeakTime: 49.0345
```

Question 12 : PART C

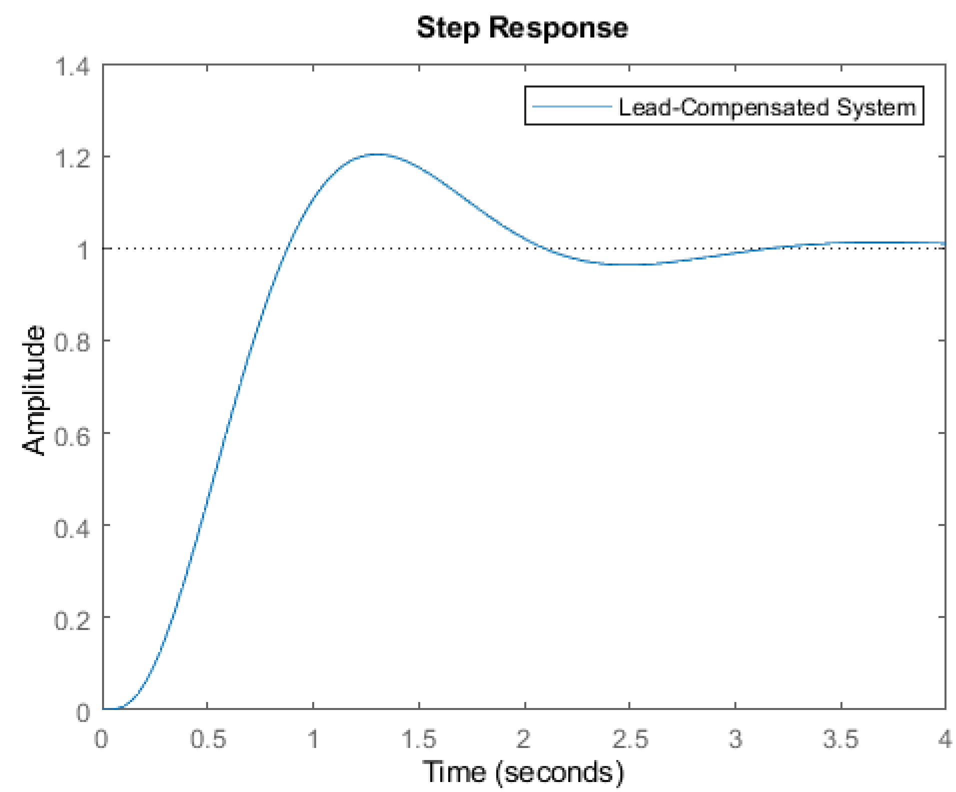
```
Gs_uncompensated = tf(1, [1 16 48 0 0]);
figure(4)
rlocus(Gs_uncompensated)
damping = .45038;
```

```
sgrid(damping, 0)
Gs_leadcompensated = tf([1 0.01], [1 51.39 614.2 1699 0 0]);
figure(5)
rlocus(Gs_leadcompensated)
sgrid(damping, 0)
% Gain of Lead-Compensated Transfer Function
Kc = 4173.66;
% Closed-Loop Lead-Compensated Transfer Function
Tlc = feedback(Gs_leadcompensated*Kc,1);
% Step Response Plot of Closed-Loop Transfer Function
figure(6)
step(Tlc)
legend("Lead-Compensated System")
```





Root Locus
0.45
0.45
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
80
60
40
20
0
-20
-40
-60
-80
-100
-80
-60
-40
-20
0
20
40
60
80



Step Response
Lead-Compensated System
Amplitude
Time (seconds)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4

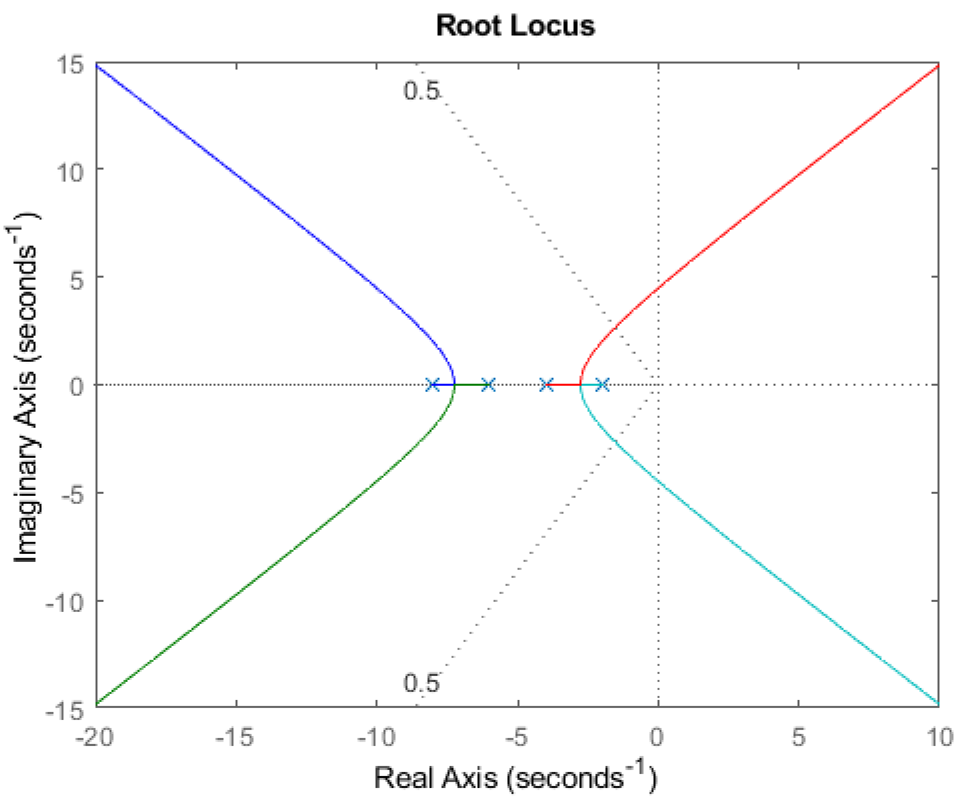
Question 15

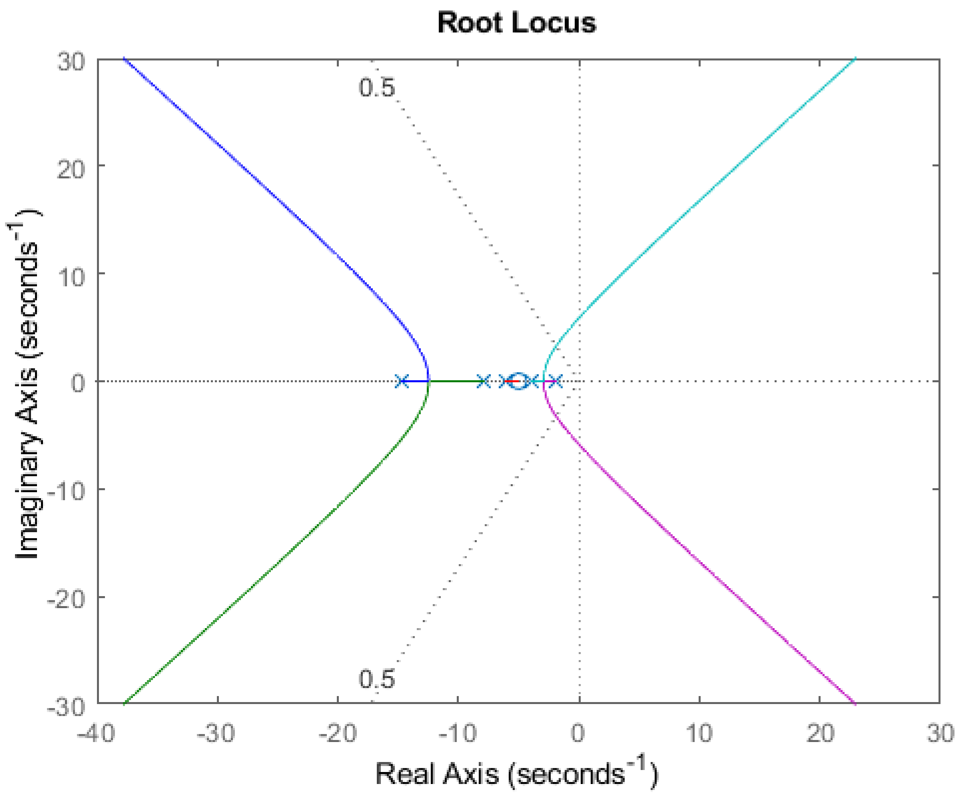
Uncompensated Transfer Function

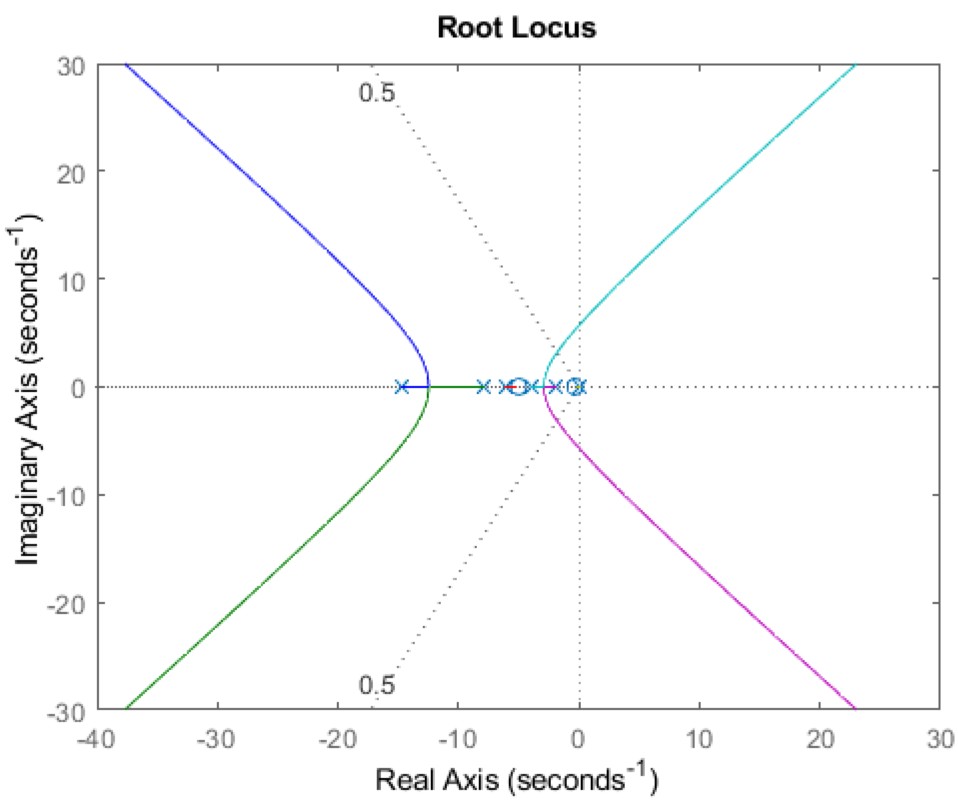
```
Gs_uncompensated = tf(1,[1 20 140 400 384]);
figure(7)
rlocus(Gs_uncompensated)
damping = .5;
sgrid(damping, 0)
% Lead Compensated Transfer Function
Gs_leadcompensated = tf([1,5], [1 34.64 432.8 2450 6240 5622]);
figure(8)
rlocus(Gs_leadcompensated)
sgrid(damping, 0)
% Lag-Lead Compensated Transfer Function
Gs_lagleadcompensated = tf([1 5.344 1.718], [1 34.65 433.1 2454 6264
 5684 56.22]);
figure(9)
rlocus(Gs_lagleadcompensated)
sgrid(damping, 0)
% Gain of Uncompensated, Lead, and Lag-Lead Transfer Functions
Ku   = 354.44;
Klc  = 1359.3;
Kllc = 1359.1;
% Closed-Loop Transfer Functions
Tu = feedback(Gs_uncompensated*Ku,1);
Tlc = feedback(Gs_leadcompensated*Klc,1);
Tllc = feedback(Gs_lagleadcompensated*Kllc,1);
% Step Response Plots
figure(10)
step(Tu,Tlc,Tllc)
stepinfo(Tu)
stepinfo(Tlc)
stepinfo(Tllc)
legend("Uncompensated", "Lead-Compensated", "Lag-Lead Compensated");
```

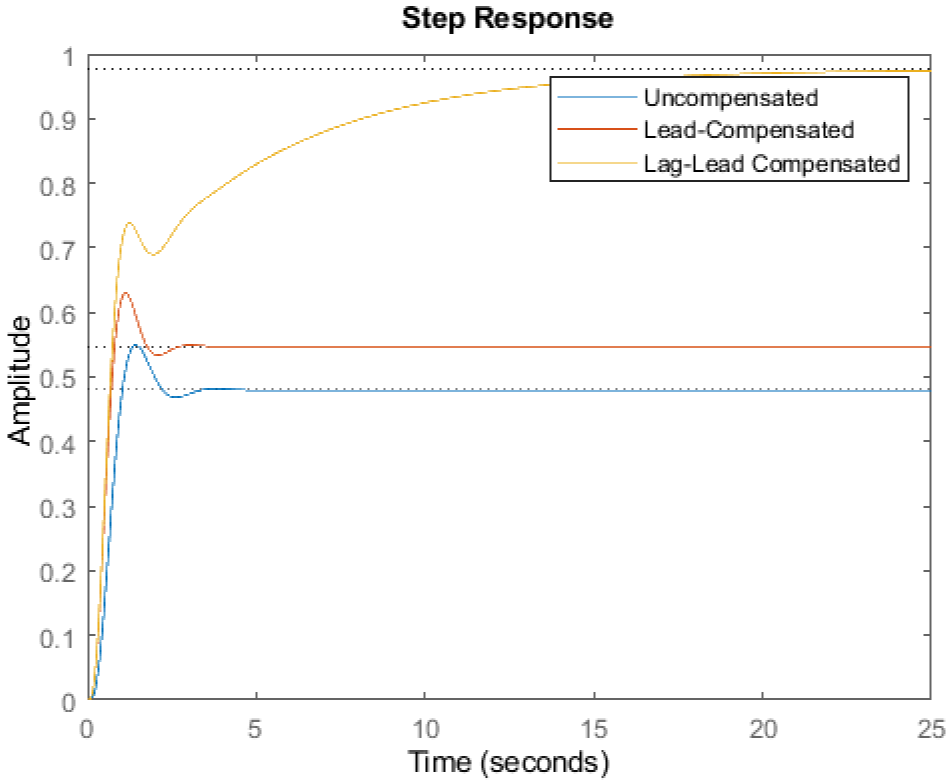
```
ans =

  struct with fields:

        RiseTime: 0.6054
    SettlingTime: 2.8199
     SettlingMin: 0.4346
     SettlingMax: 0.5497
       Overshoot: 14.5325
      Undershoot: 0
            Peak: 0.5497
        PeakTime: 1.4356


ans =
```

```
  struct with fields:

        RiseTime: 0.4763
    SettlingTime: 2.2683
     SettlingMin: 0.4970
     SettlingMax: 0.6297
       Overshoot: 15.0622
      Undershoot: 0
            Peak: 0.6297
        PeakTime: 1.1285


ans =

  struct with fields:

        RiseTime: 6.6664
    SettlingTime: 14.6827
     SettlingMin: 0.8789
     SettlingMax: 0.9738
       Overshoot: 0
      Undershoot: 0
            Peak: 0.9738
        PeakTime: 24.1914
```




Root Locus
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
0.5
0.5
30
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
20
30


Root Locus
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
0.5
0.5
30
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
20
30

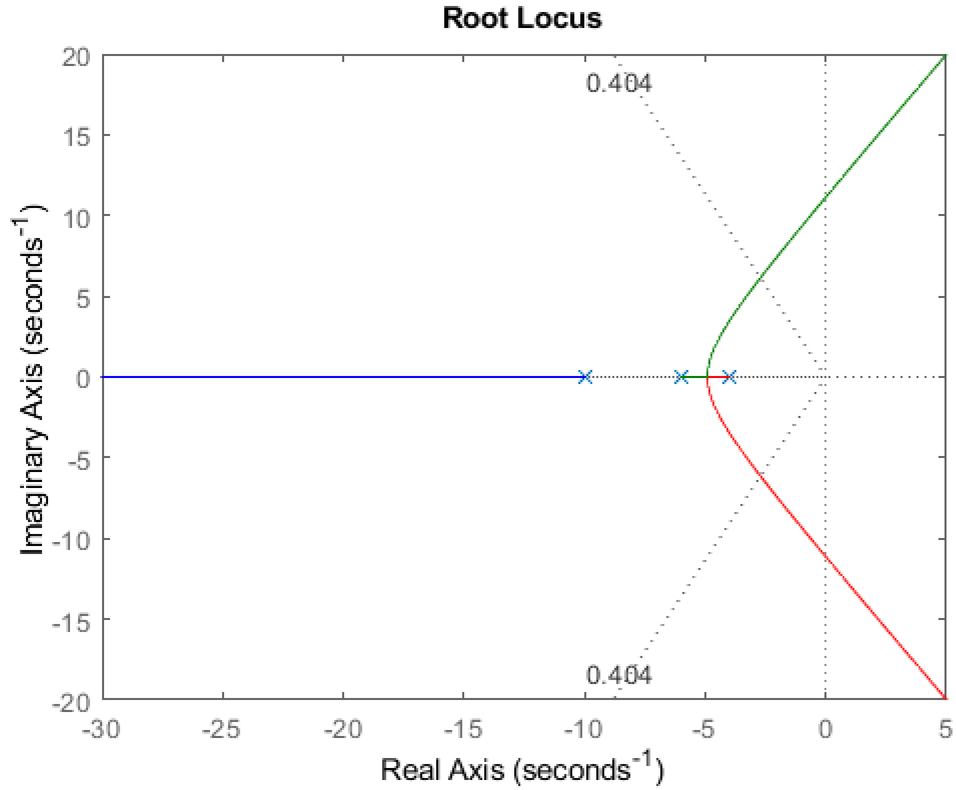


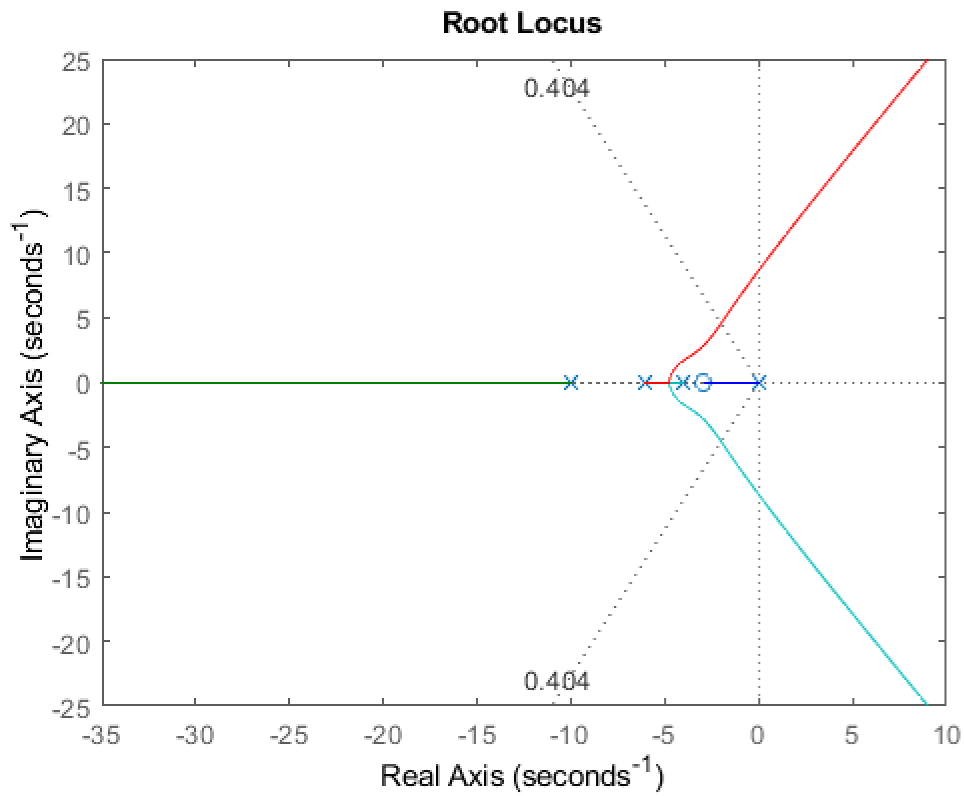
Question 20

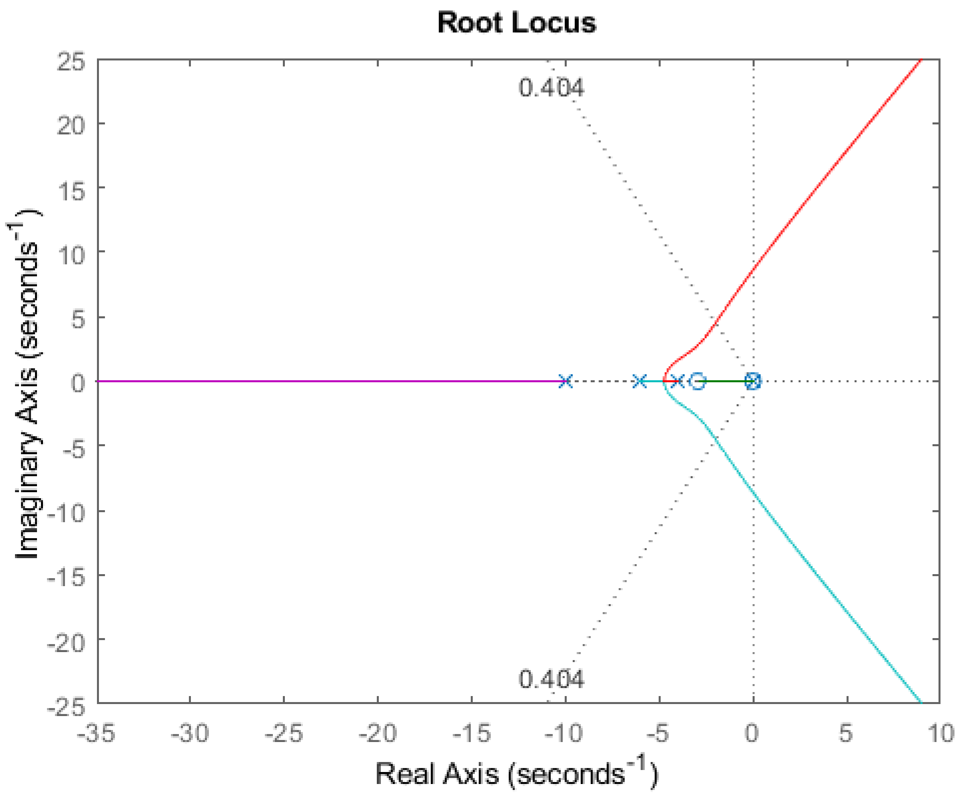
```
Gs_uncompensated = tf(1, [1 20 124 240]);
figure(11)
rlocus(Gs_uncompensated)
damping = .4037;
sgrid(damping, 0)
% PD Compensated Transfer Function
Gs_PDcompensated = tf([1 2.957], [1 20 124 240 0]);
figure(12)
rlocus(Gs_PDcompensated)
sgrid(damping, 0)
% PID Compensated Transfer Function
Gs_PIDcompensated = tf([1 2.967 .02957],[1 20 124 240 0 0]);
figure(13)
rlocus(Gs_PIDcompensated)
sgrid(damping, 0)
% Gain of Uncompensated, PD, PID Transfer Functions
Ku   =  416.26;
Kpd  =  294.58;
Kpid =  294.78;
% Closed-Loop Transfer Functions
Tu = feedback(Gs_uncompensated*Ku,1);
Tpd = feedback(Gs_PDcompensated*Kpd,1);
Tpid = feedback(Gs_PIDcompensated*Kpid,1);
```

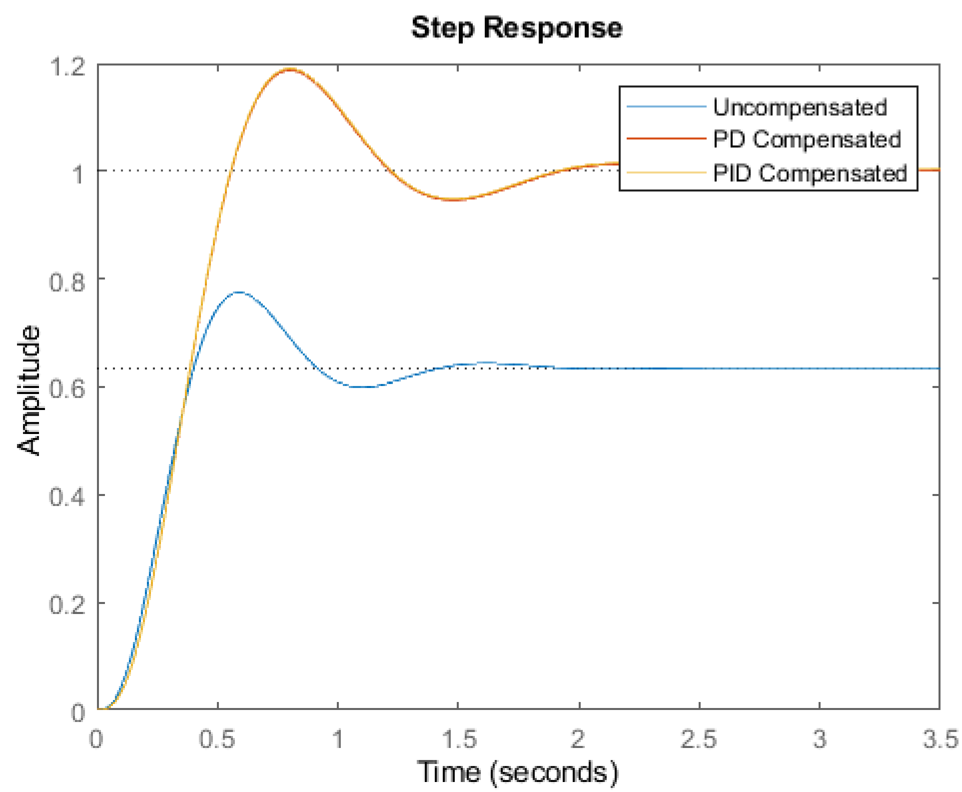
```
% Step Response Plots
figure(14)
step(Tu,Tpd,Tpid)
stepinfo(Tu)
stepinfo(Tpd)
stepinfo(Tpid)
legend("Uncompensated", "PD Compensated", "PID Compensated");
```

```
ans = 

  struct with fields:

        RiseTime: 0.2473
    SettlingTime: 1.3204
     SettlingMin: 0.5736
     SettlingMax: 0.7744
       Overshoot: 22.0850
      Undershoot: 0
            Peak: 0.7744
        PeakTime: 0.5874


ans = 

  struct with fields:

        RiseTime: 0.3455
    SettlingTime: 1.7793
     SettlingMin: 0.9040
     SettlingMax: 1.1869
       Overshoot: 18.6930
      Undershoot: 0
            Peak: 1.1869
        PeakTime: 0.8007


ans = 

  struct with fields:

        RiseTime: 0.3445
    SettlingTime: 1.7636
     SettlingMin: 0.9060
     SettlingMax: 1.1906
       Overshoot: 19.0553
      Undershoot: 0
            Peak: 1.1906
        PeakTime: 0.8008
```


Root Locus
0.404
0.404
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
20
15
10
5
0
-5
-10
-15
-20
-30
-25
-20
-15
-10
-5
0
5


Root Locus
0.404
0.404
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})
25
20
15
10
5
0
-5
-10
-15
-20
-25
-35
-30
-25
-20
-15
-10
-5
0
5
10


Root Locus
0.404
0.404
25
20
15
10
5
0
-5
-10
-15
-20
-25
-35
-30
-25
-20
-15
-10
-5
0
5
10
Imaginary Axis (seconds^{-1})
Real Axis (seconds^{-1})


Step Response
Uncompensated
PD Compensated
PID Compensated
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
Amplitude
Time (seconds)

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