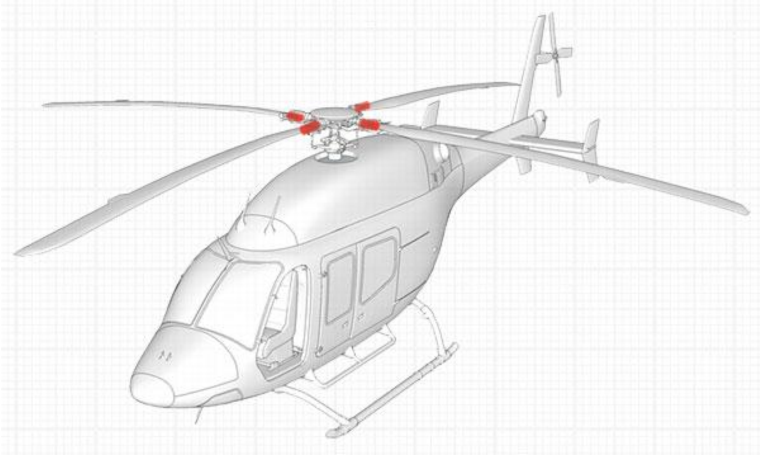
# PITCH, ROLL AND YAW DAMPER

-and its importance



Prepared by

A.Kaviyarasu
Assistant Professor
Department of Aerospace Engineering
Madras Institute Of Technology
Chromepet, Chennai

# Pitch Damper and its importance

Sealevel:

$$\frac{q(s)}{\delta_e(s)} = -72.7\frac{s(s+2.59)(s+0.0003)}{(s^2+6.07s+55.03)(s^2-0.0007s+0.0032)}$$

15,000 ft:

$$\frac{q(s)}{\delta_e(s)} = -41.1\frac{s(s+1.54)(s-0.0002)}{(s^2+3.62s+30.08)(s^2-0.0012s+0.0038)}$$

30,000 ft:

$$\frac{q(s)}{\delta_e(s)} = -21.7\frac{s(s+0.86)(s-0.0019)}{(s^2+2.03s+15.50)(s^2-0.0022s+0.0044)}$$

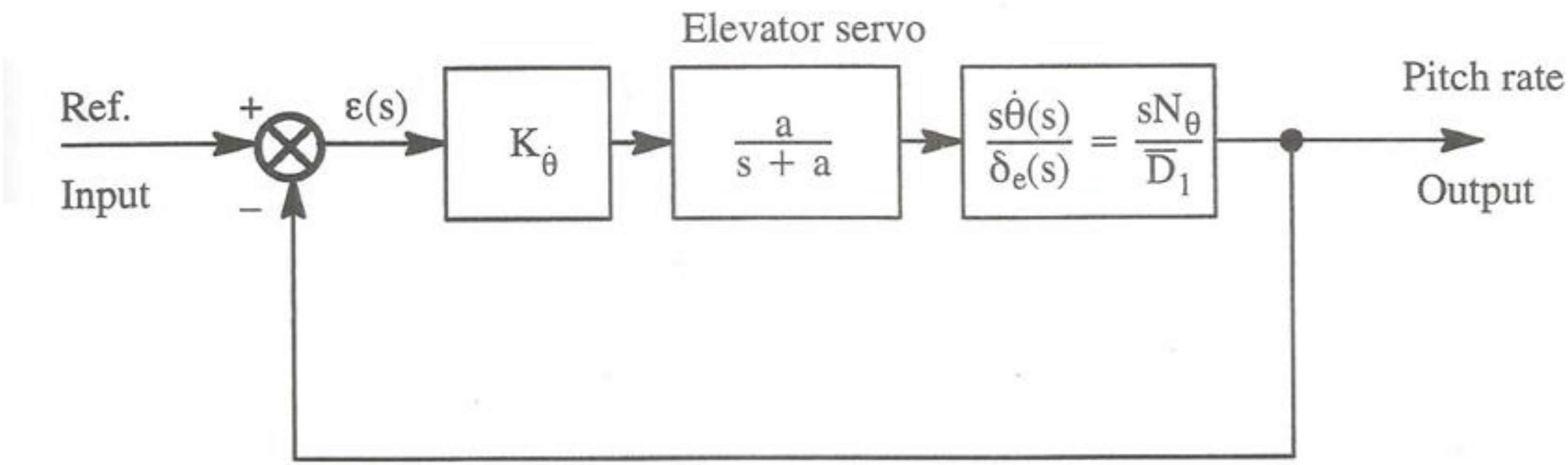
45,000 ft:

$$\frac{q(s)}{\delta_e(s)} = -10.7\frac{s(s+0.44)(s-0.0054)}{(s^2+1.03s+7.49)(s^2-0.0042s+0.0046)}$$

60,000 ft:

$$\frac{q(s)}{\delta_e(s)} = -5.21\frac{s(s+0.22)(s-0.0118)}{(s^2+0.507s+3.62)(s^2-0.0080s+0.0046)}$$

- Most high performance airplane suffers from low period damping at high altitude and low speed flight condition.
- The effect can be easily noted in the above transfer function equation.
- It is clear that, the open loop short period damping ratio and frequency both deteriorate rapidly with altitude.
- To maintain the acceptable handling qualities of aircraft there is a need of much high damping ratio system. This can be achieved with a Pitch damper.

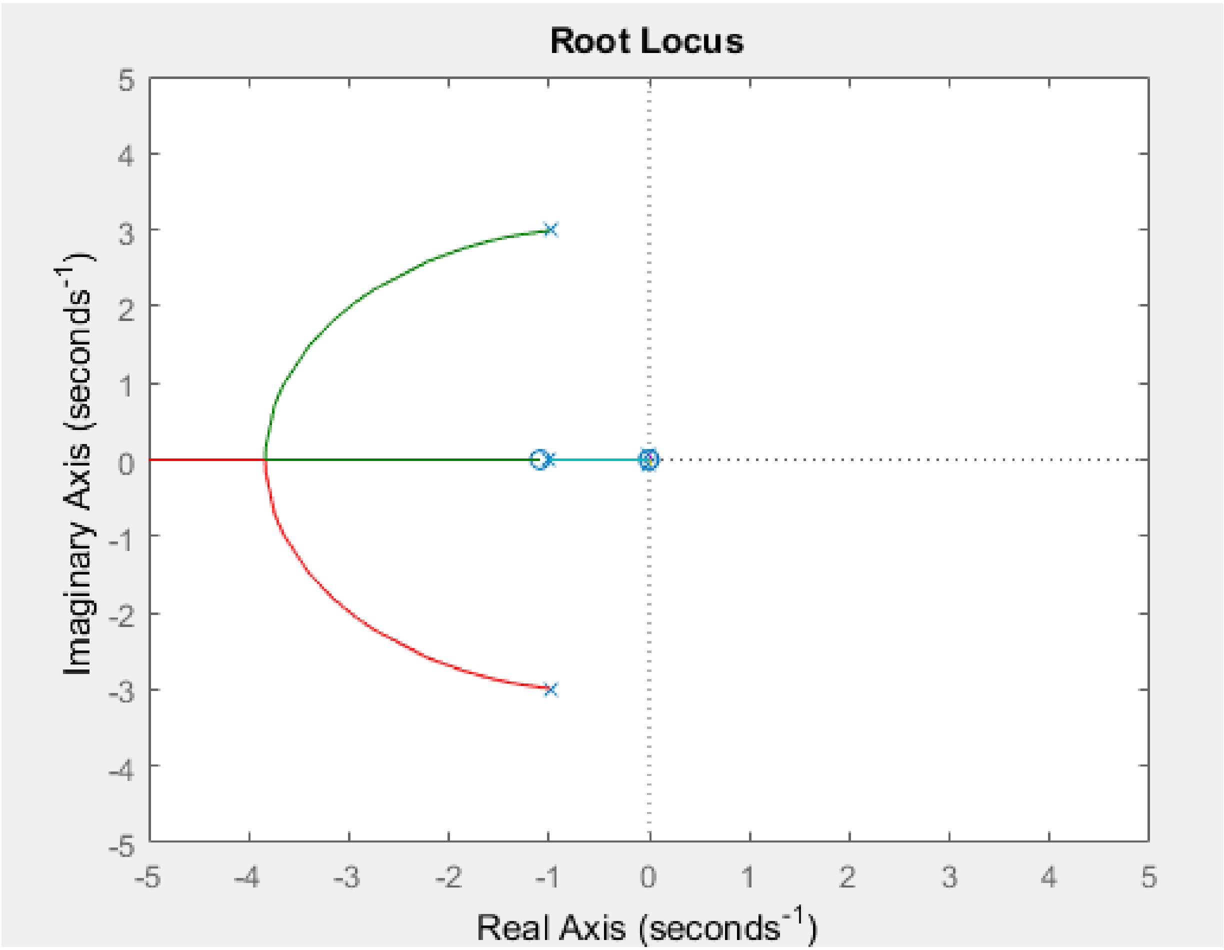

Elevator servo
Ref.
Input
+
−
ε(s)
$K_{\dot{\theta}}$
$\frac{a}{s + a}$
$\frac{s\dot{\theta}(s)}{\delta_e(s)} = \frac{sN_\theta}{\bar{D}_1}$
Pitch rate
Output

- It is noted that pitch rate of the aircraft was used as an feedback.
- If the pitch damping gain K is selected for best possible closed loop damping ratio at sea level it is seen that the performance of such a damper rapidly deteriorates with altitude.
- To solve the problem, a idea of gain scheduling is used
- Pitch rate feedback gain K is scheduled with as altitude (mach number as required) to achieve the desired closed loop performance.
- To achieve a damping ratio of about 0.61 at 60,000 feet requires 4-5 times sea level gain.
- There is another even worse problem at altitude, the undamped natural frequency deteriorates to the point where the airplane become sluggish.
- To get faster response (high damping natural freq) responses some times requires some of attack feedback.

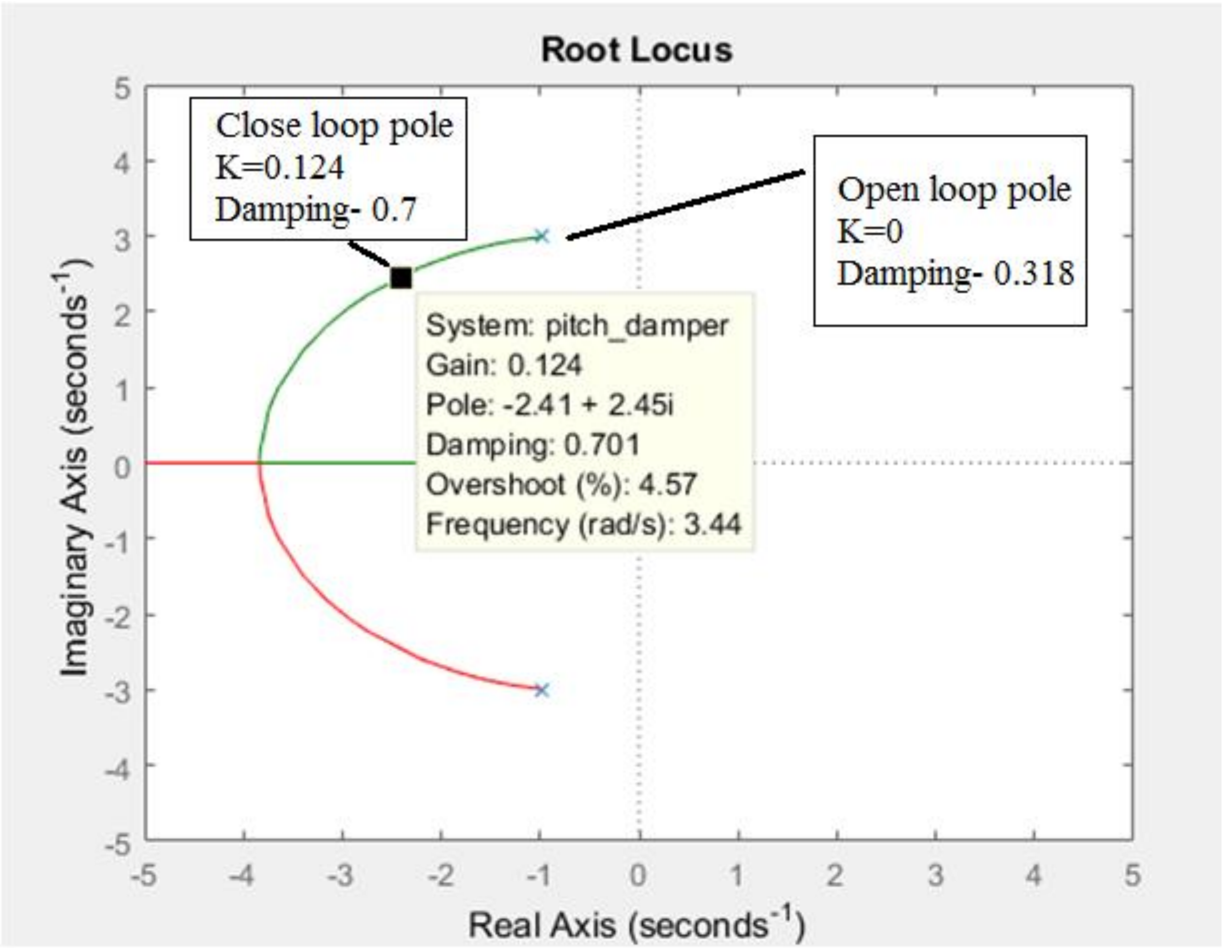
$$\frac{\dot{\theta}}{\delta_e} = \frac{-18.1s\left(s+0.00716\right)\left(s+1.09\right)}{\left(s^2+1.98s+9.92\right)\left(s^2+0.0088s+0.00506\right)}$$

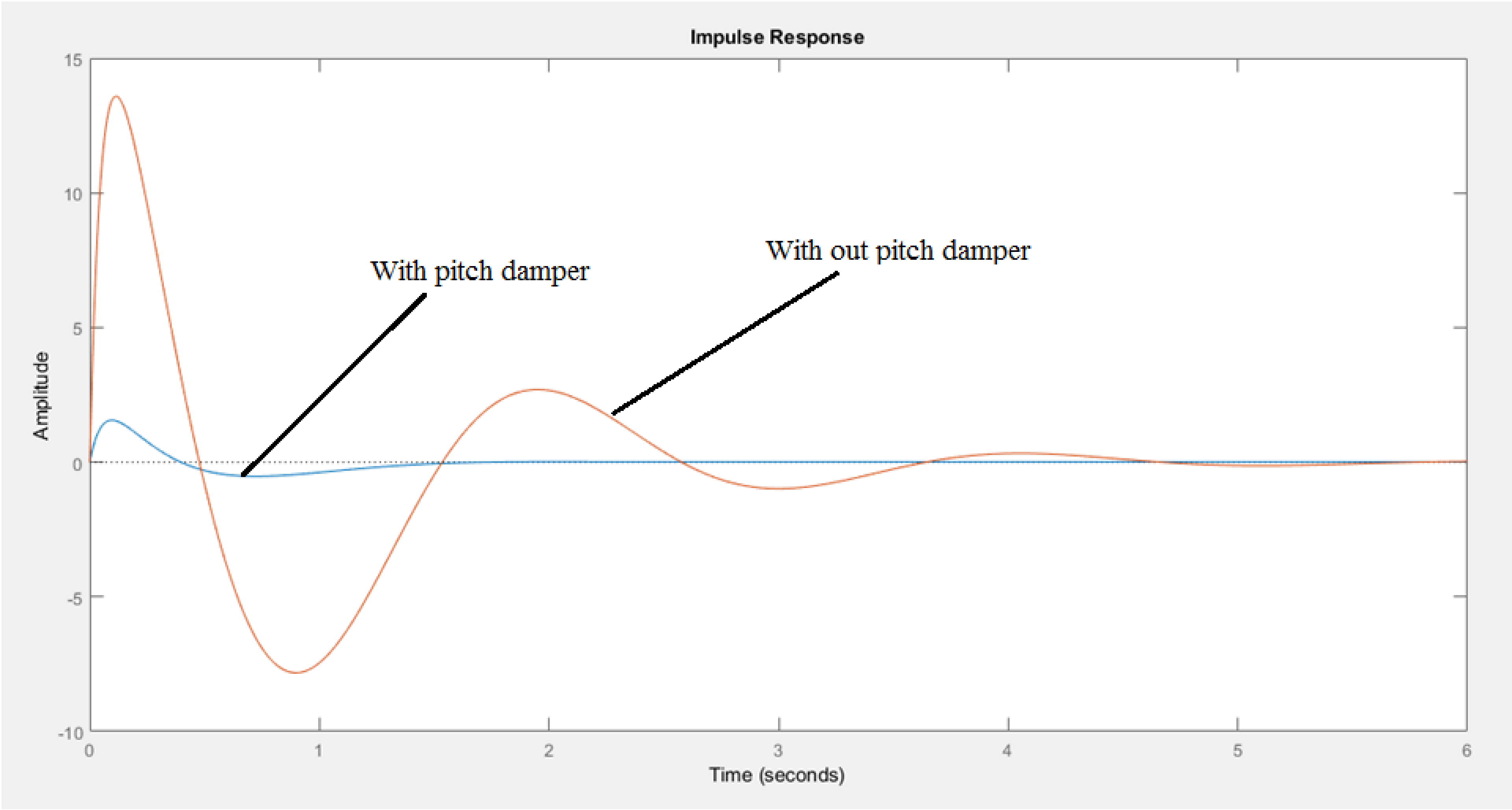
$$Servo\,TF = \frac{-20}{\left(s+20\right)}$$

# Pitch damper root locus plot focusing on short period roots

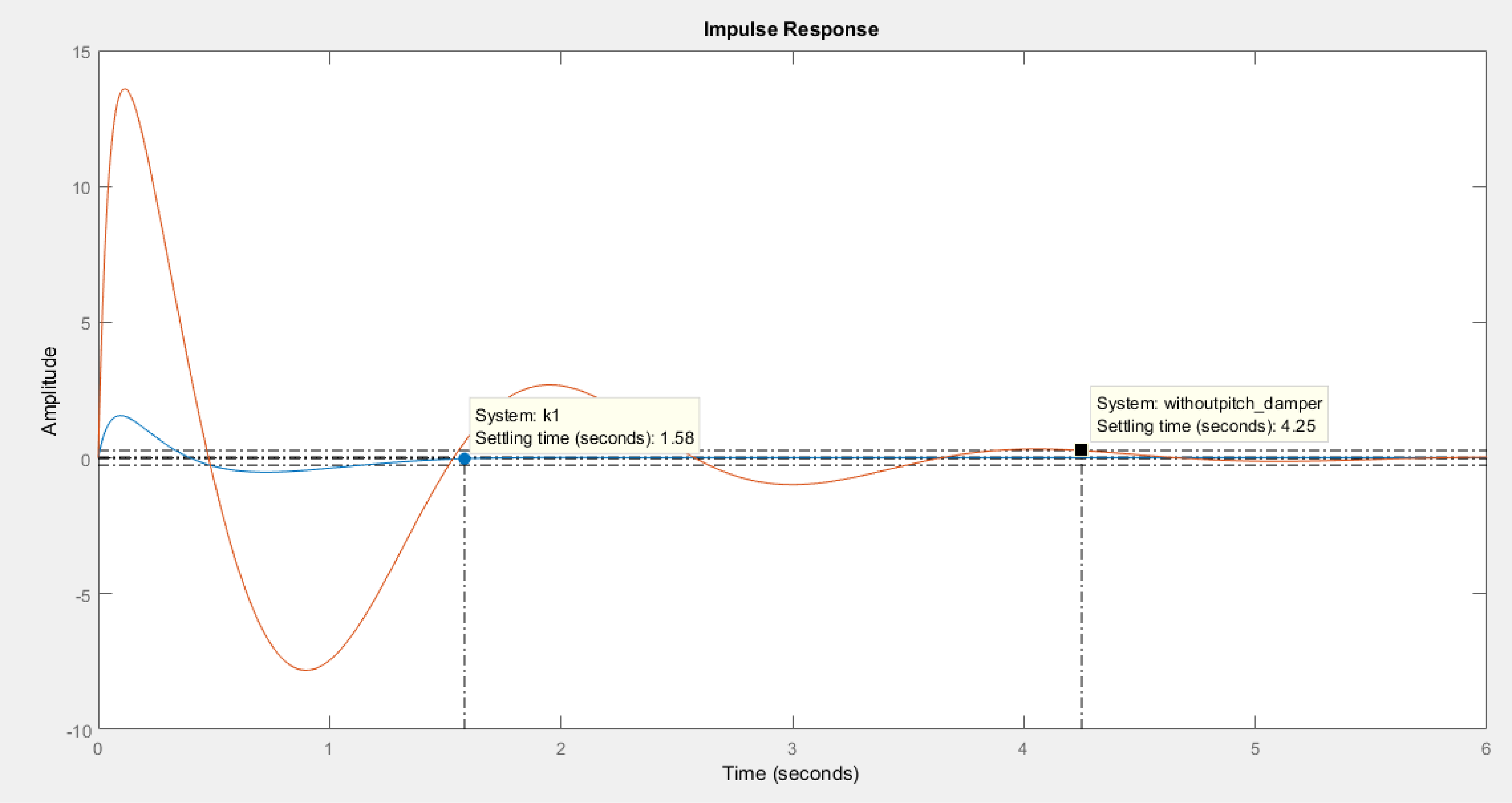


# Pitch damper root locus plot focusing on short period roots






Impulse Response of pitch damper



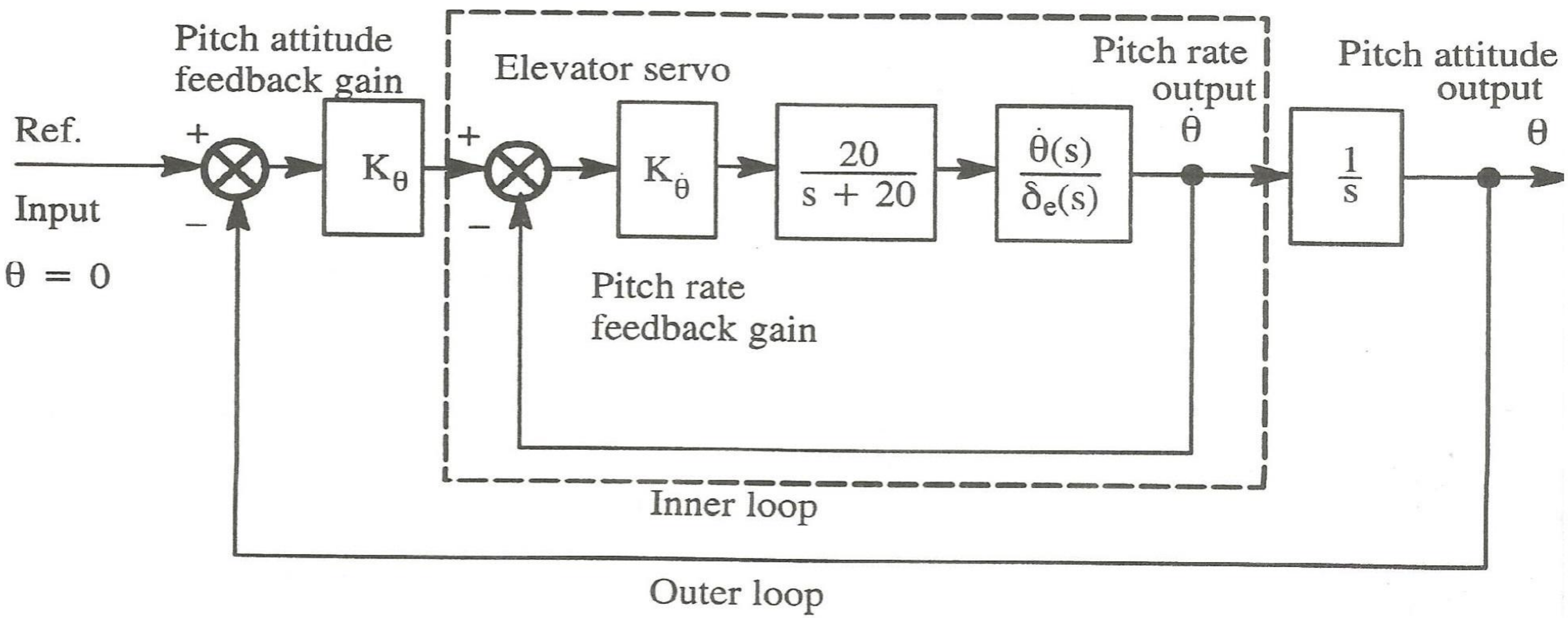

Impulse Response of pitch damper

- Pitch damper will tends to oppose any pitch rate away from the reference input.

- In a steady and level flight the reference pitch rate input is normally zero.

- However, if a pilot want to maneuver an airplane in the vertical plane (push up or pull down ) a non-zero pitch rate is desired.

- The above problem has been overcome by two methods
  - Use computed pith rate as reference input during pull up and pull down maneuver
  - Use a washout circuit in the feedback path.



Pitch attitude feedback gain
Elevator servo
Pitch rate output
$\dot{\theta}$
Pitch attitude output
$\theta$
Ref.
Input
$\theta = 0$
+
−
$K_\theta$
+
−
$K_{\dot{\theta}}$
$\frac{20}{s + 20}$
$\frac{\dot{\theta}(s)}{\delta_e(s)}$
$\frac{1}{s}$
Pitch rate feedback gain
Inner loop
Outer loop

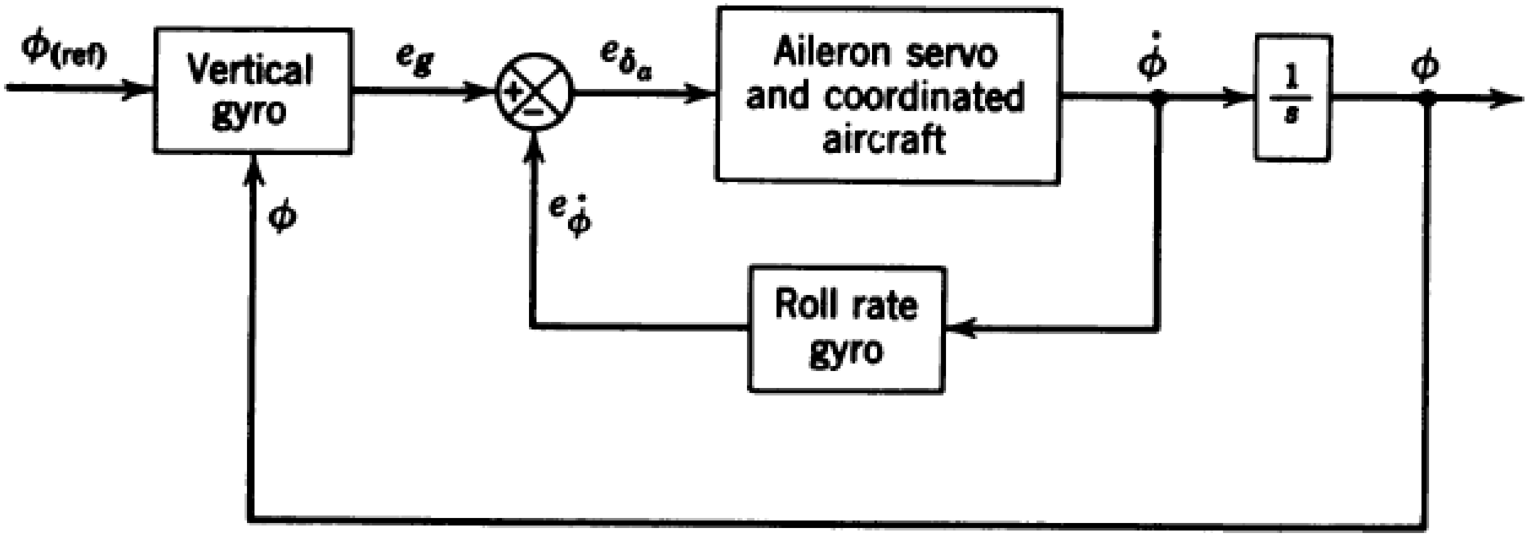
- It is noted that in the above figure, there are two loops, one is the inner loop (pith rate feedback) which is responsible for control the short period damping or oscillation where as the outer loop (pitch angle feedback) which is responsible control the phugoid damping or oscillation.

- The pitch damper helps to improve the short period damping of the aircraft where as the "washout circuit" and "computed pitch rate" are needed to perform longitudinal aircraft maneuvering.


Cobra
Suhoj T-50

# Roll damper

- To improve the roll out characteristic of an aircraft roll rate feedback is used.
- It helps to increase the rollout mode stability of an aircraft.
- Roll rate feedback helps to improve the effect of artificial increase in wing span.
- As a result the aircraft behaves very stable in lateral axis.

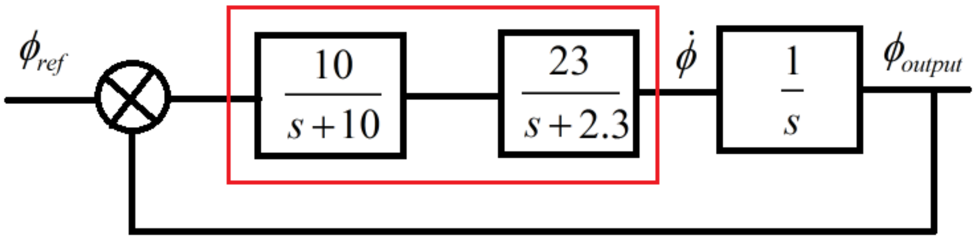



Block Diagram of Roll angle control system with roll rate as feedback

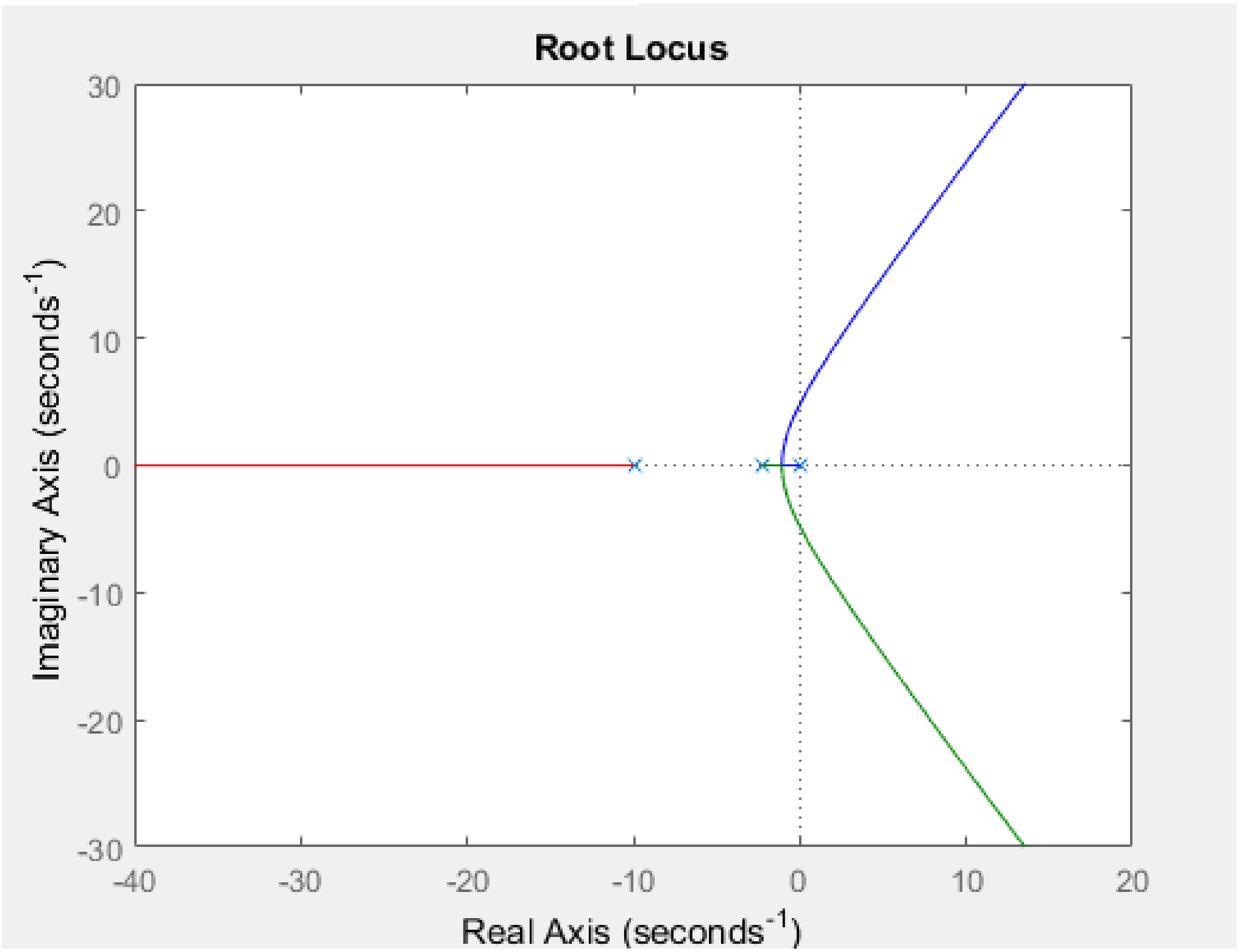
- The above figure is a block diagram of a roll angle control system. The reader probably wonders why the roll rate feedback is necessary.

- A look at a sketch of the root locus for the system without roll rate feedback shows why it is needed. As can be seen from Figure 1 (a), even a low gain drives the system unstable, and unity feedback results in a too lightly damped response.

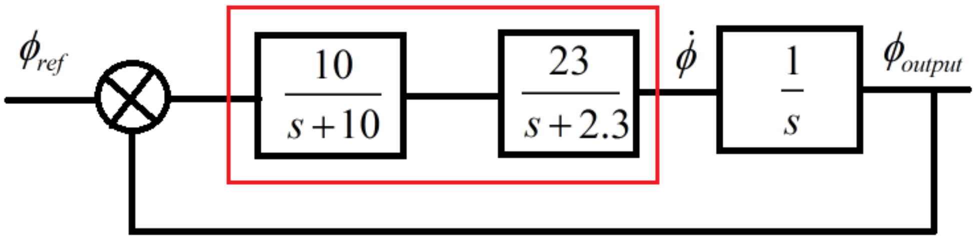
- Figure 1 (b) shows the effect of roll rate gyro feedback. By adding the inner loop with the roll rate feedback, a higher outer loop sensitivity can be used without producing instability.



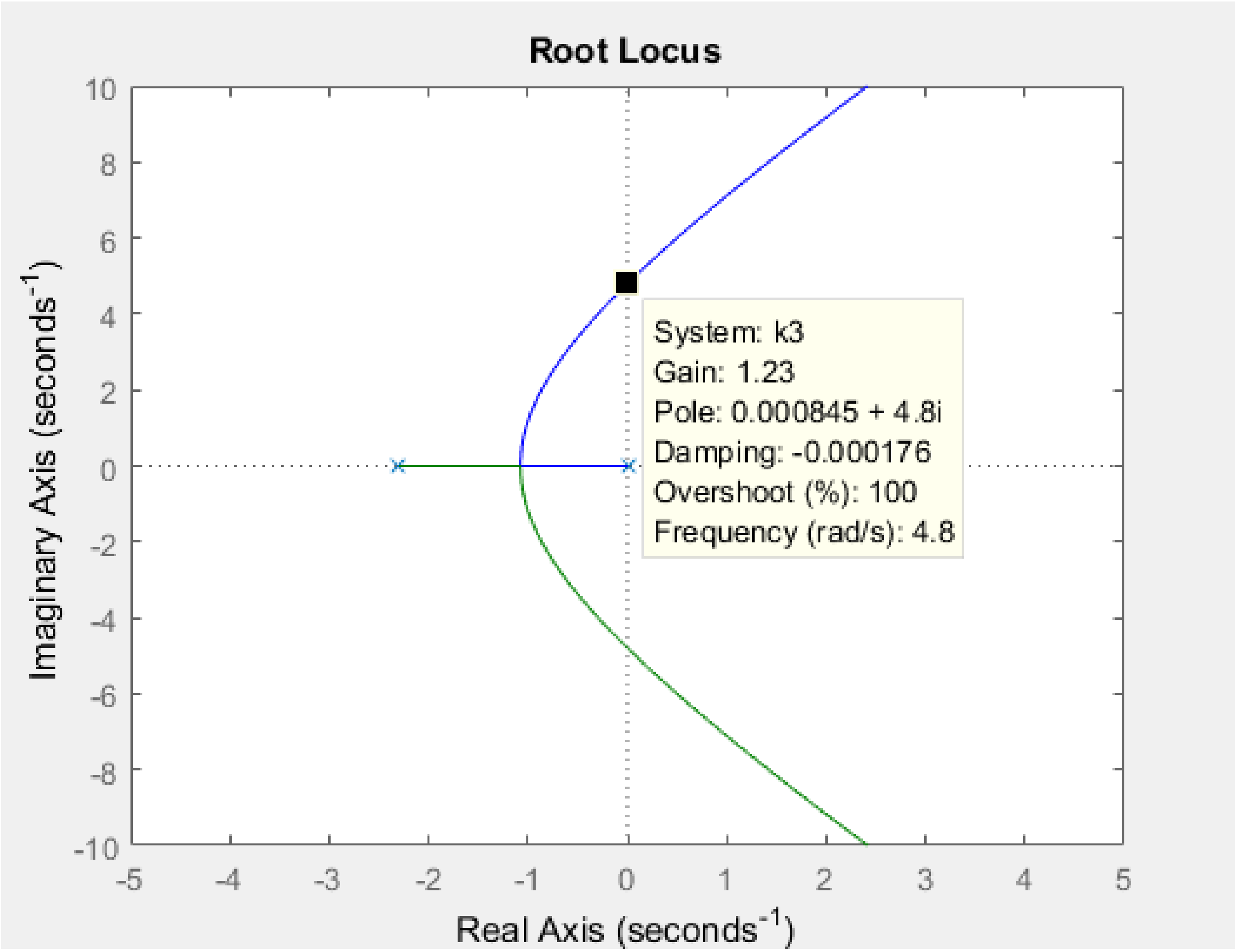
$\phi_{ref}$
$\frac{10}{s+10}$
$\frac{23}{s+2.3}$
$\dot{\phi}$
$\frac{1}{s}$
$\phi_{output}$

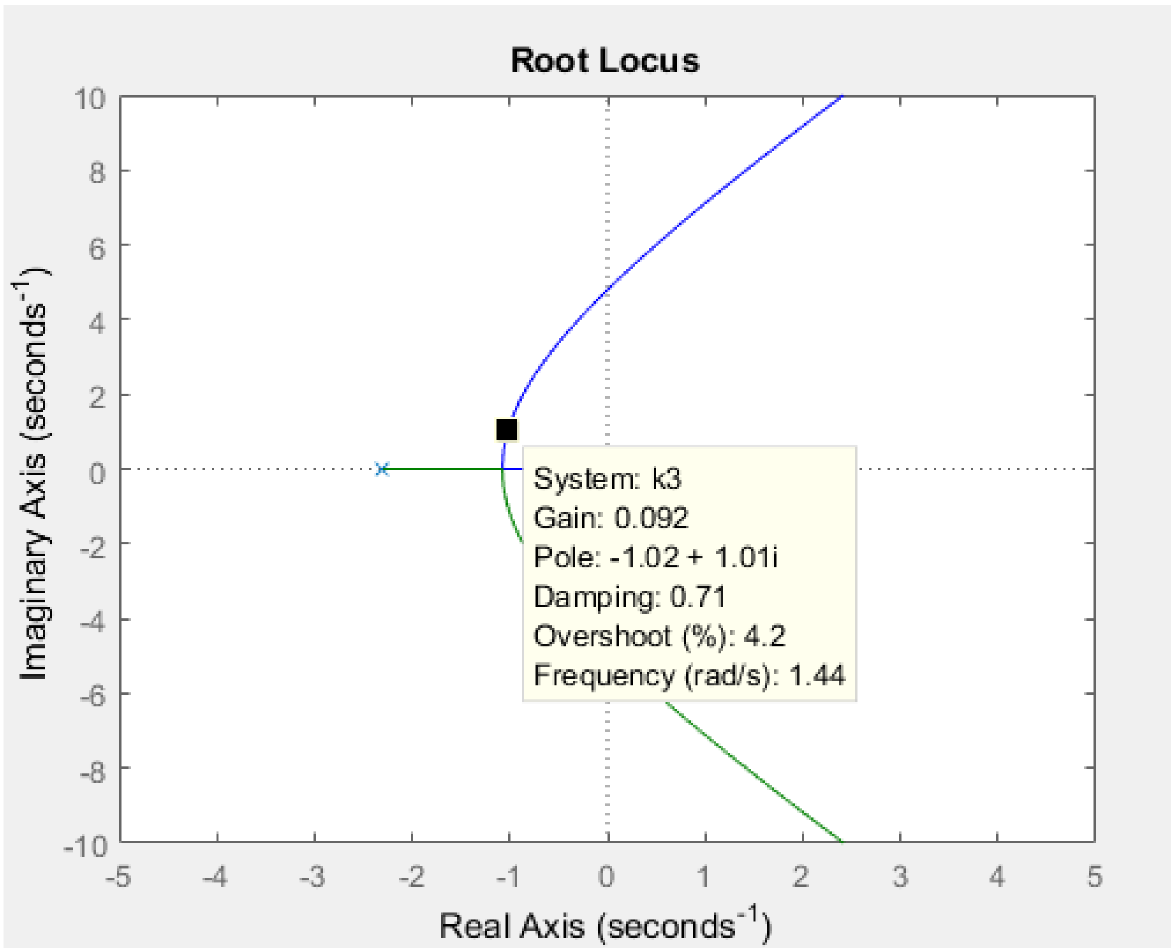
Root Locus
Imaginary Axis (seconds$^{-1}$)
Real Axis (seconds$^{-1}$)
30
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
20

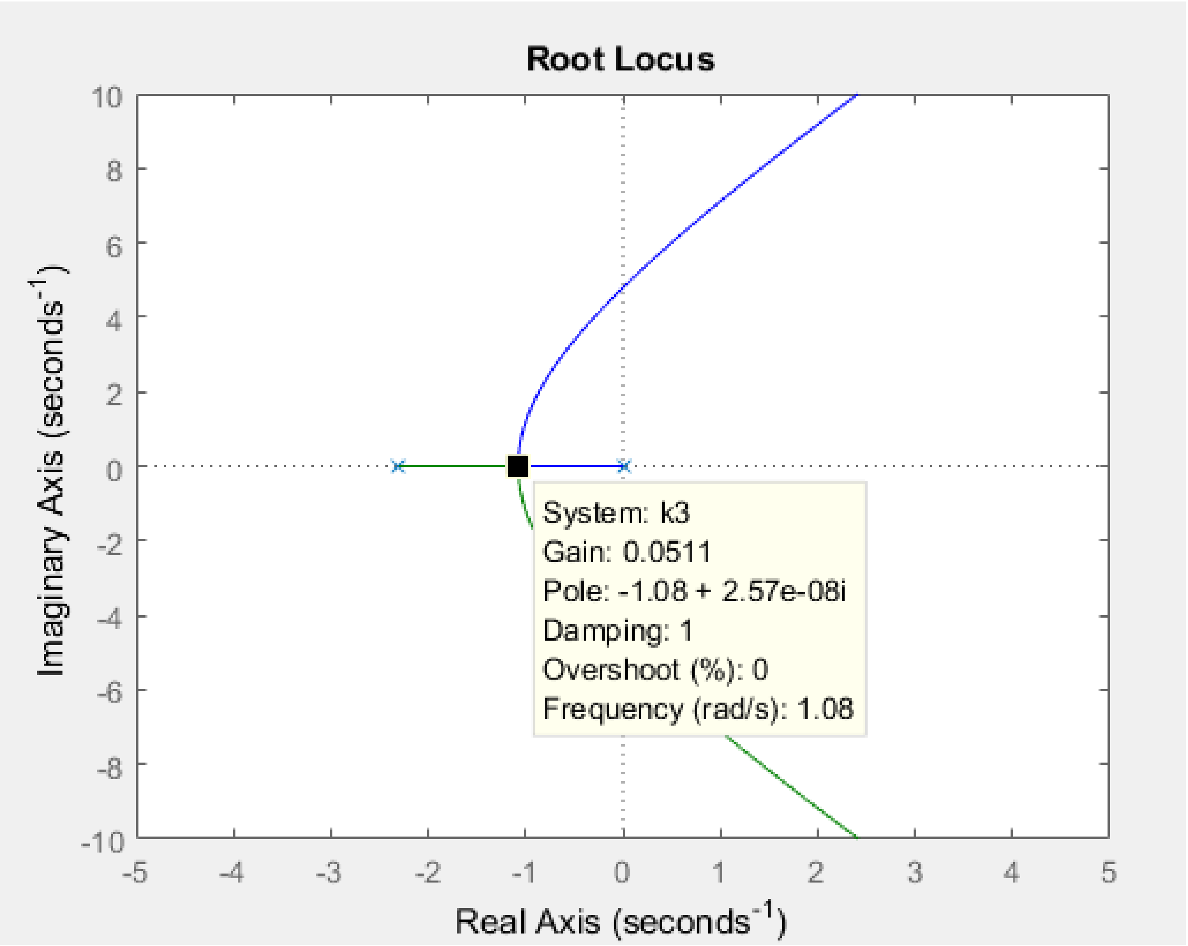


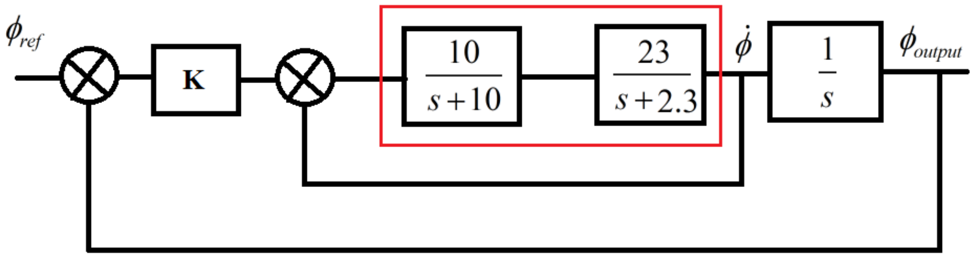
$\phi_{ref}$
10
s+10
23
s+2.3
$\dot{\phi}$
1
s
$\phi_{output}$

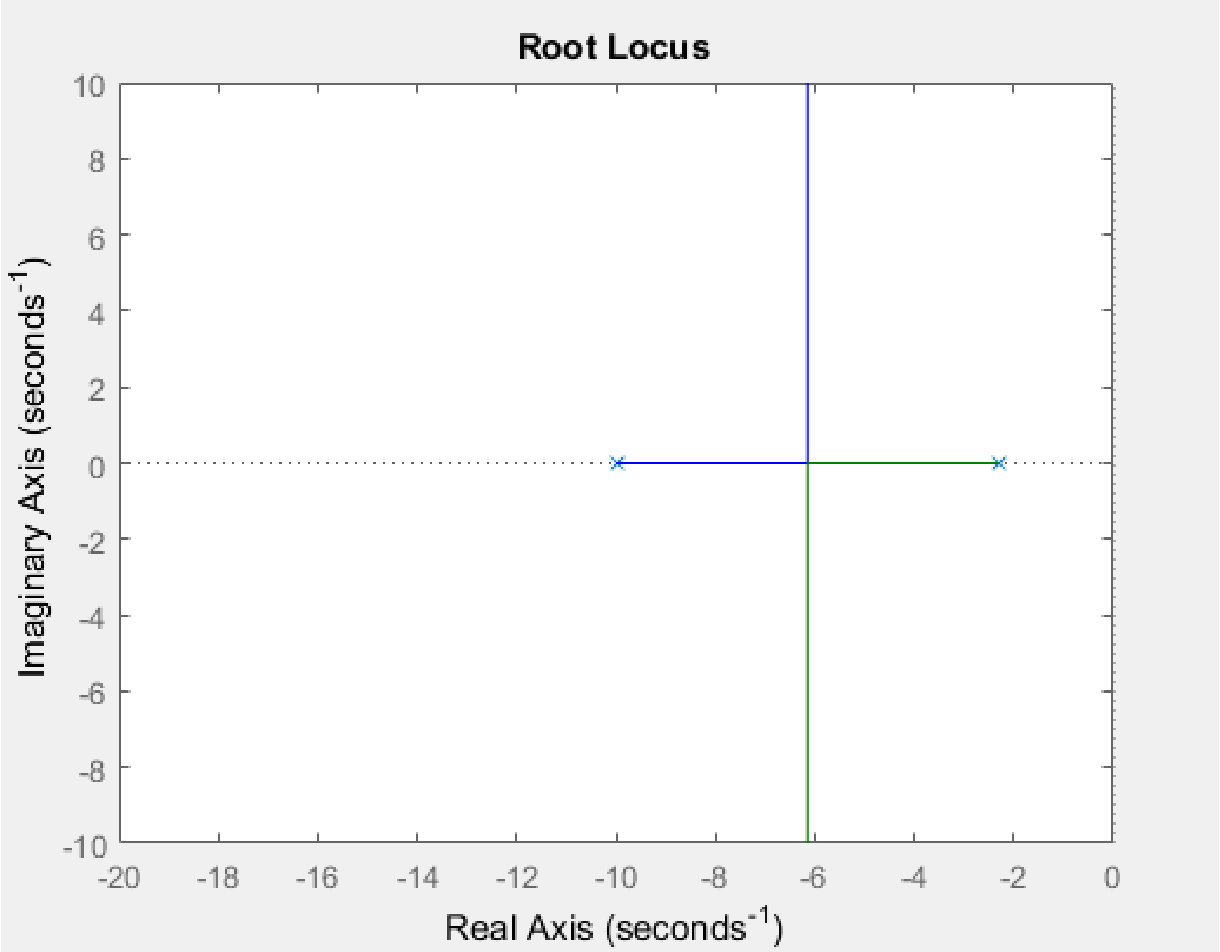



Root Locus
System: k3
Gain: 1.23
Pole: 0.000845 + 4.8i
Damping: -0.000176
Overshoot (%): 100
Frequency (rad/s): 4.8
Imaginary Axis (seconds-1)
Real Axis (seconds-1)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-5
-4
-3
-2
-1
0
1
2
3
4
5

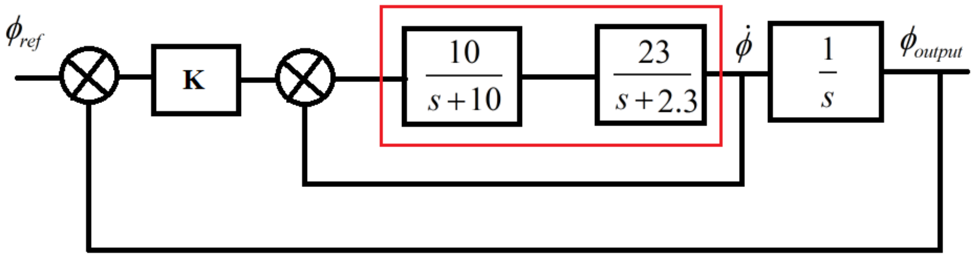

Root Locus
Imaginary Axis (seconds^-1)
Real Axis (seconds^-1)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-5
-4
-3
-2
-1
0
1
2
3
4
5
System: k3
Gain: 0.092
Pole: -1.02 + 1.01i
Damping: 0.71
Overshoot (%): 4.2
Frequency (rad/s): 1.44

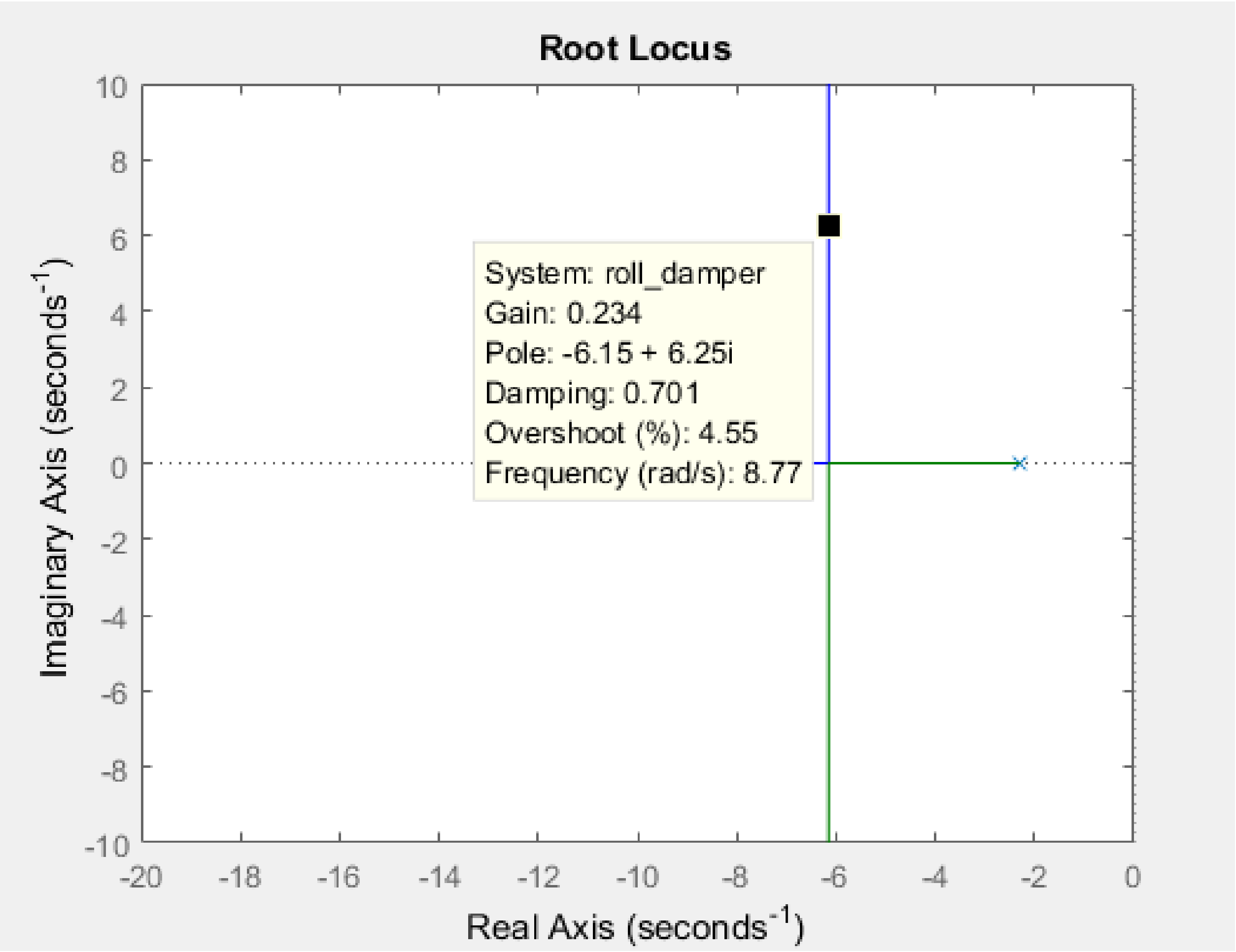

Root Locus
Imaginary Axis (seconds⁻¹)
Real Axis (seconds⁻¹)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-5
-4
-3
-2
-1
0
1
2
3
4
5
System: k3
Gain: 0.0511
Pole: -1.08 + 2.57e-08i
Damping: 1
Overshoot (%): 0
Frequency (rad/s): 1.08



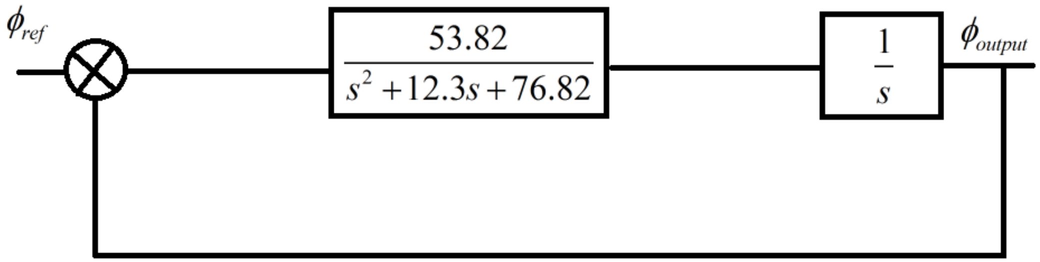



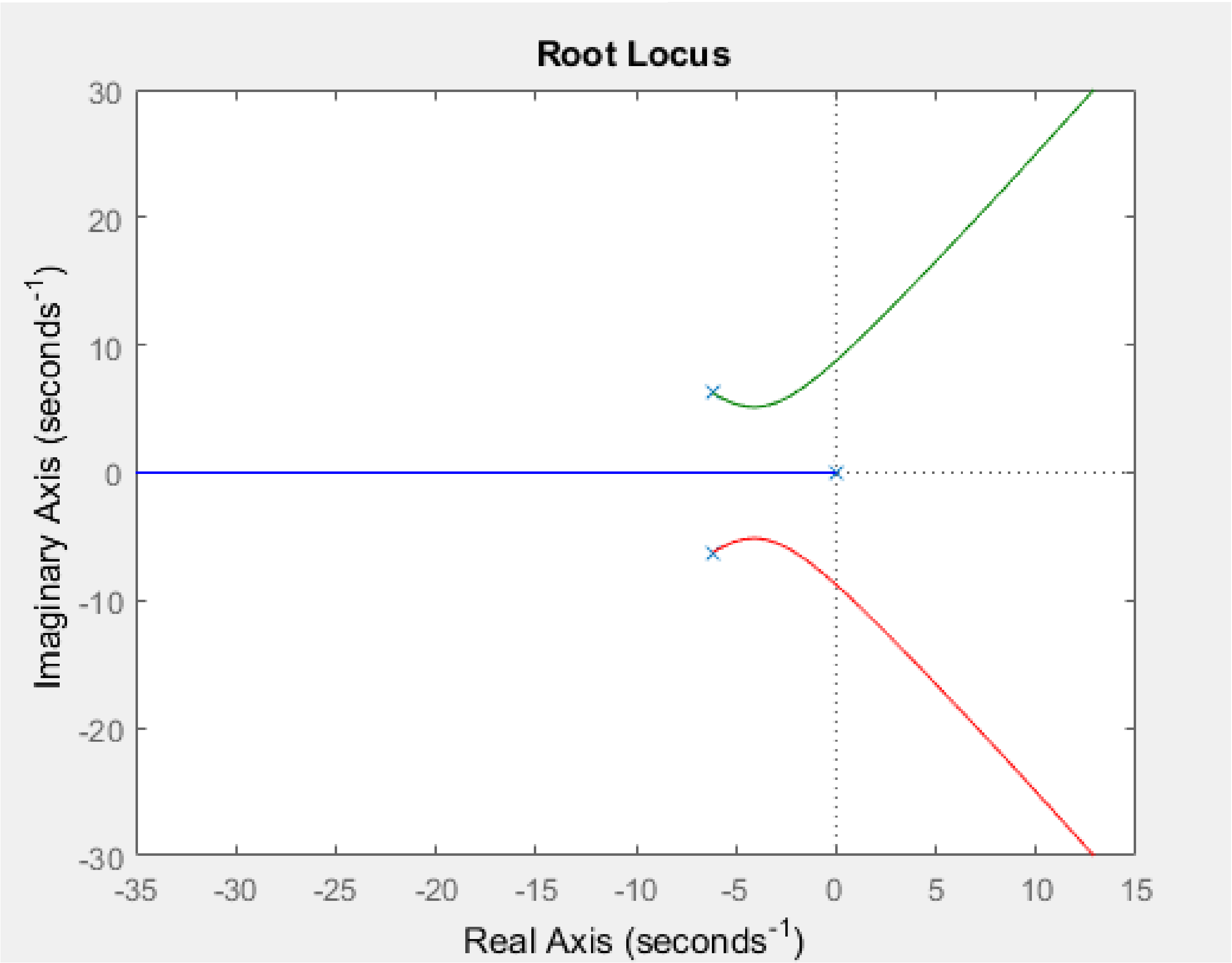

Inner loop gain at damping of about 0.7

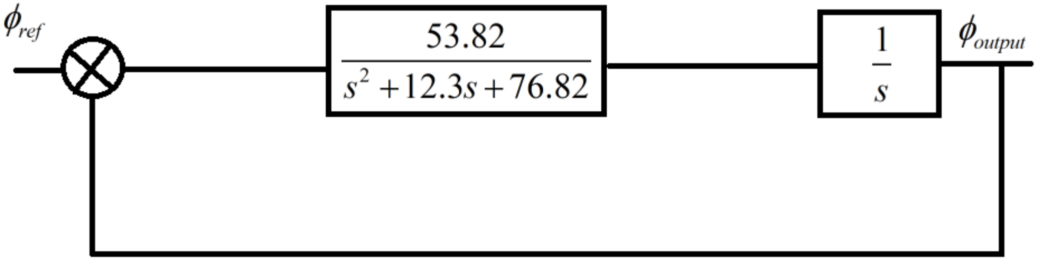


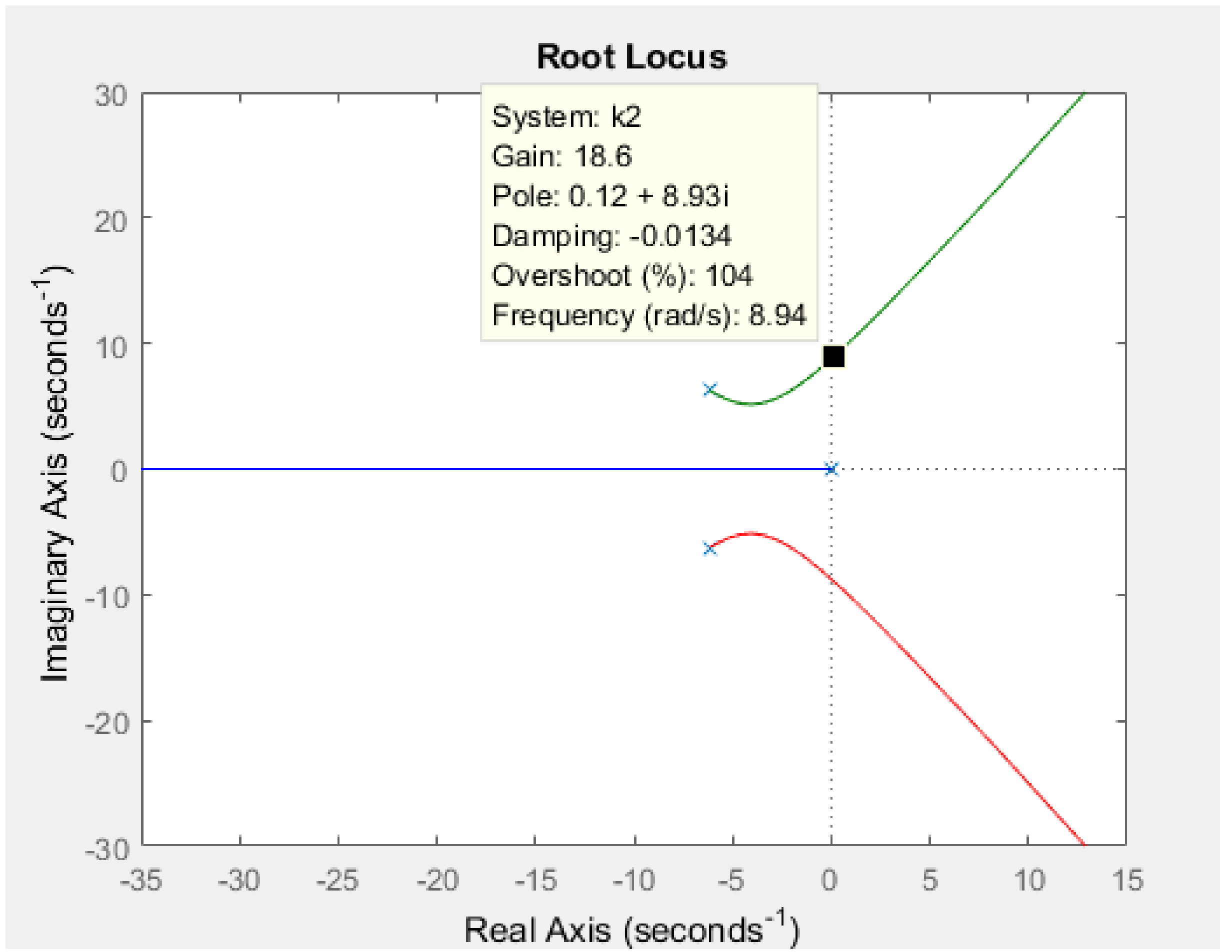



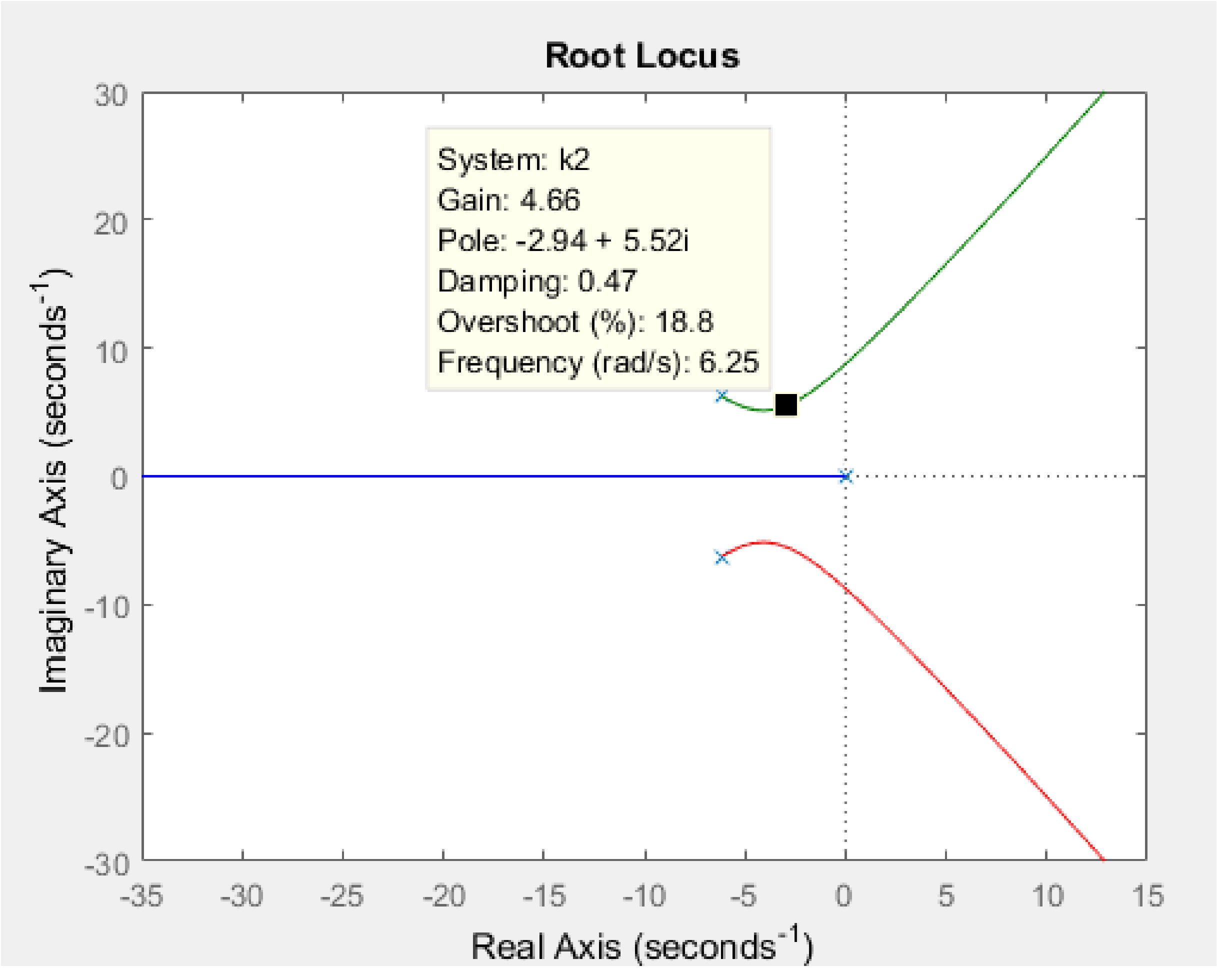

Inner loop gain at damping of about 0.7 (Gain 0.234)


$\phi_{ref}$
$\frac{53.82}{s^2+12.3s+76.82}$
$\frac{1}{s}$
$\phi_{output}$

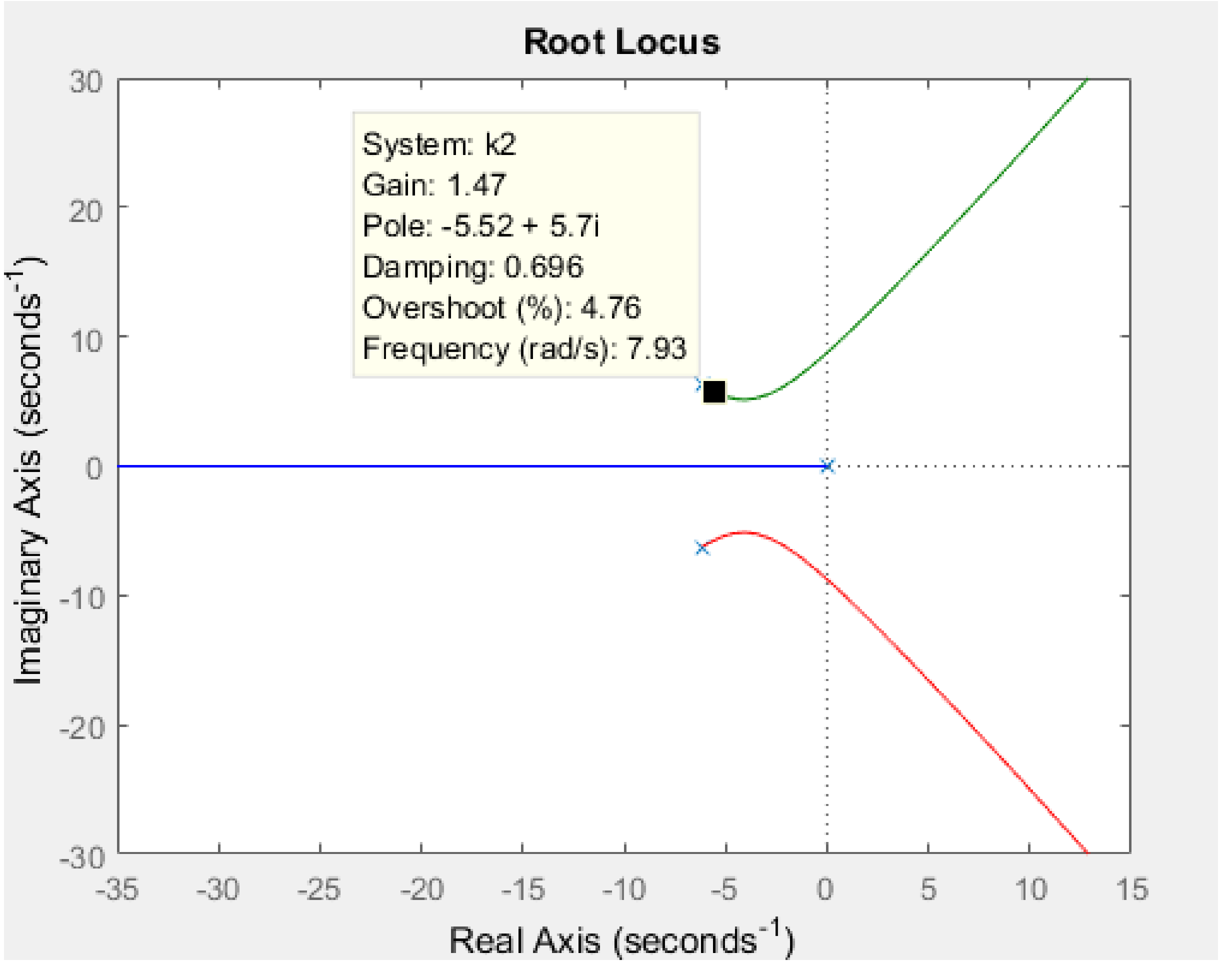

Root Locus
Imaginary Axis (seconds$^{-1}$)
Real Axis (seconds$^{-1}$)
30
20
10
0
-10
-20
-30
-35
-30
-25
-20
-15
-10
-5
0
5
10
15

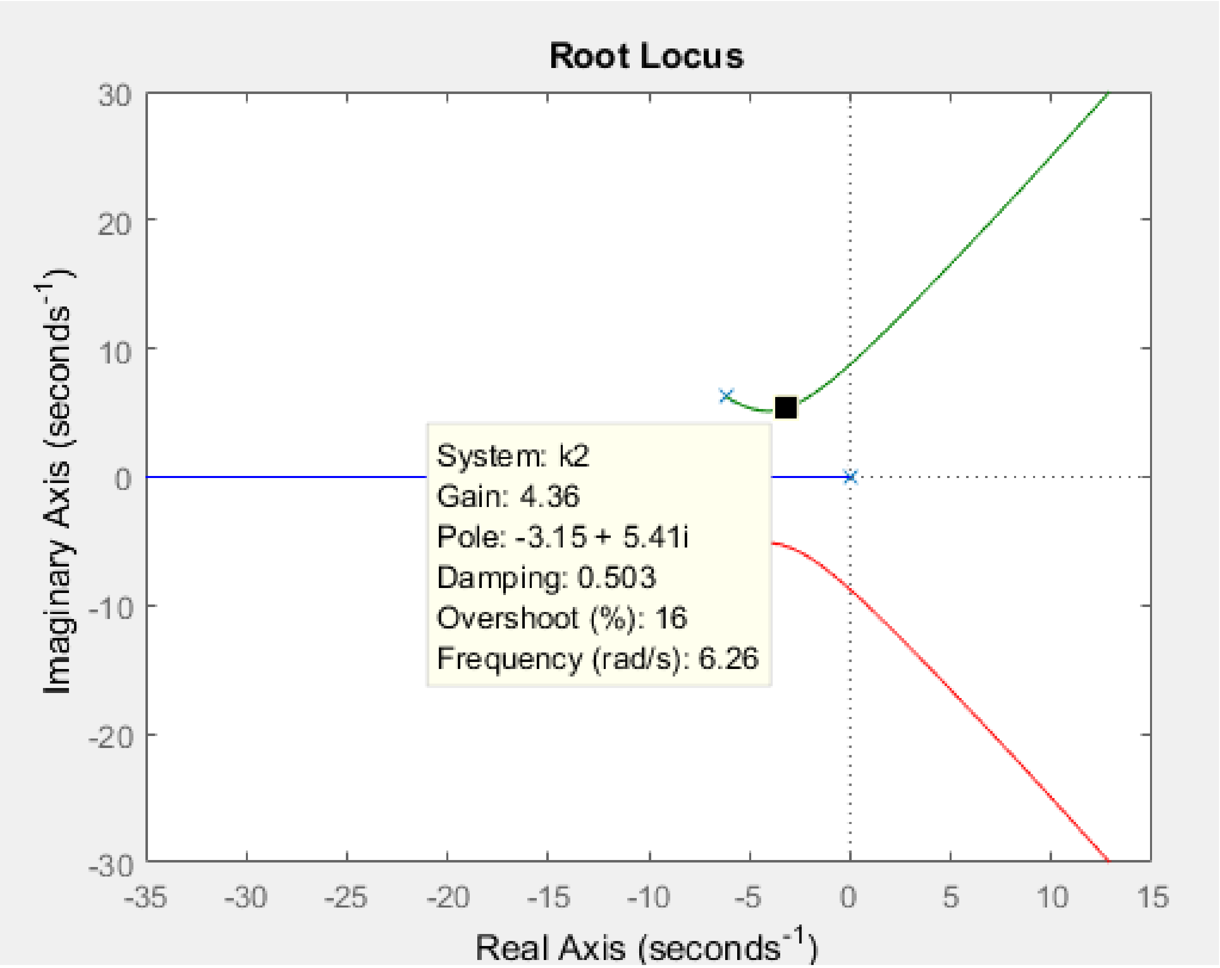

$\phi_{ref}$
$\frac{53.82}{s^2+12.3s+76.82}$
$\frac{1}{s}$
$\phi_{output}$


Root Locus
System: k2
Gain: 18.6
Pole: 0.12 + 8.93i
Damping: -0.0134
Overshoot (%): 104
Frequency (rad/s): 8.94
Imaginary Axis (seconds$^{-1}$)
Real Axis (seconds$^{-1}$)
30
20
10
0
-10
-20
-30
-35
-30
-25
-20
-15
-10
-5
0
5
10
15

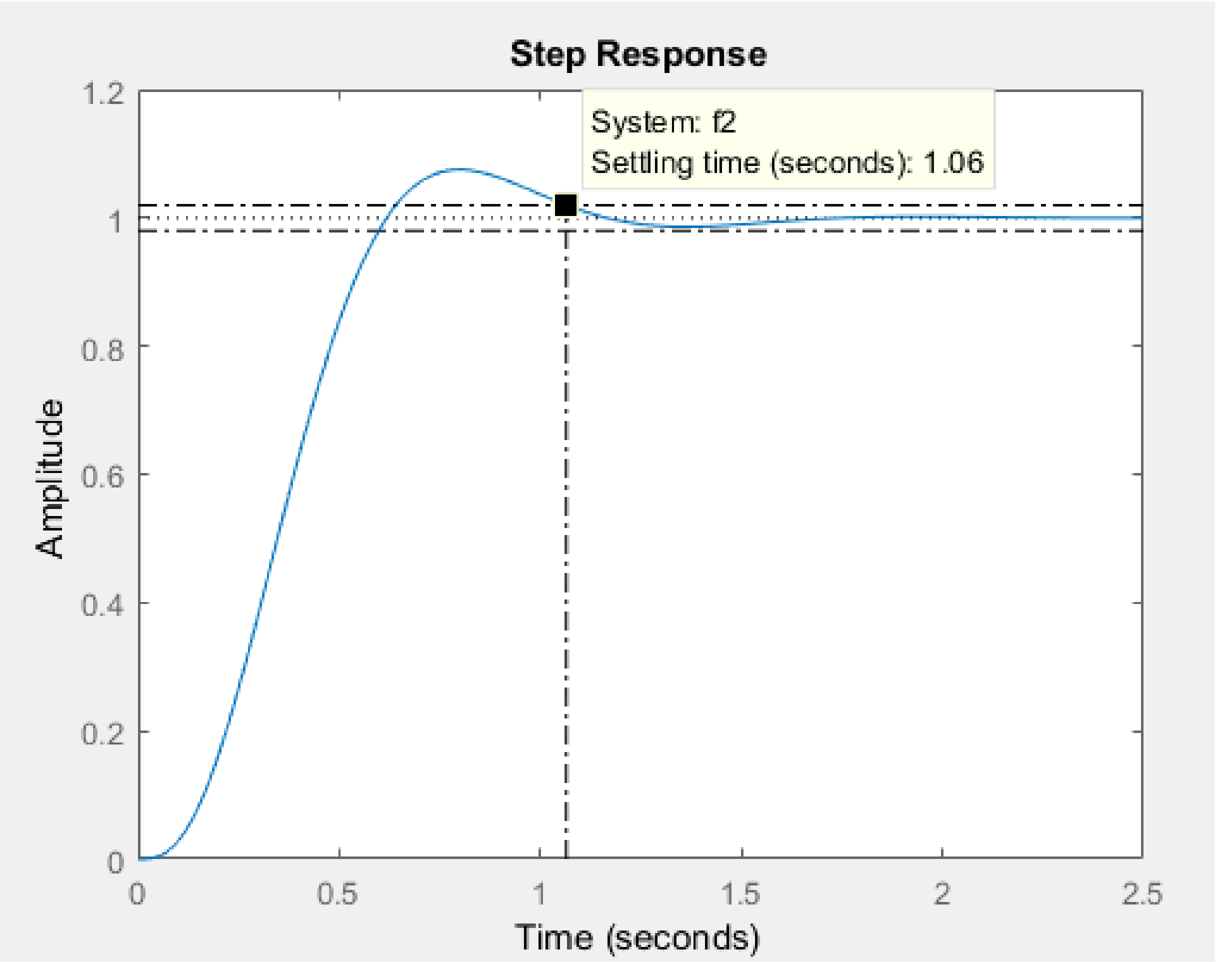


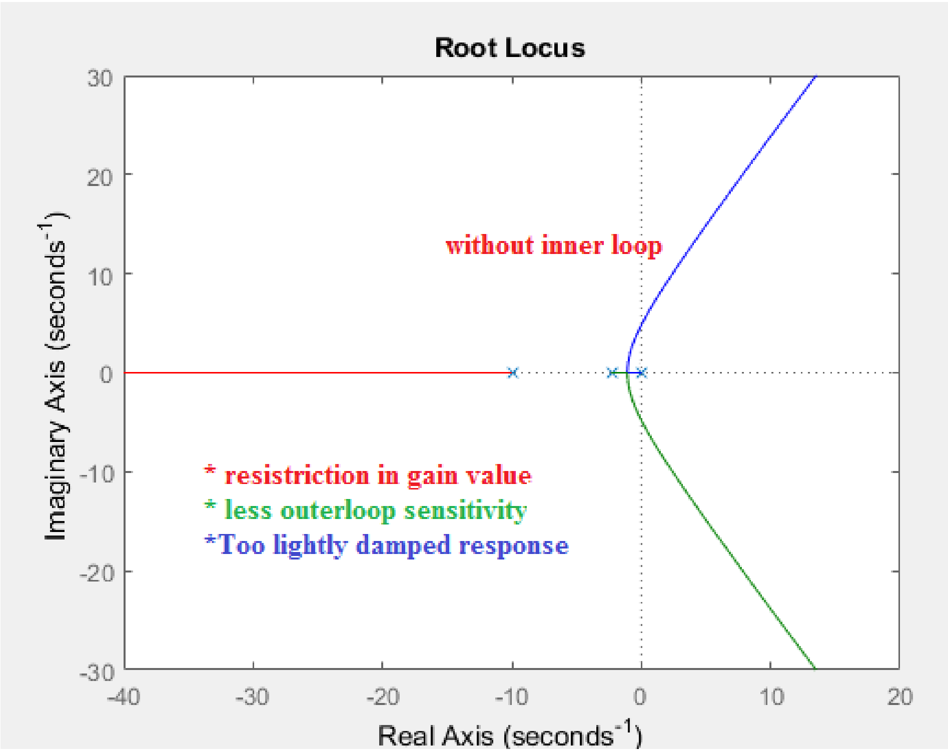
Root Locus
System: k2
Gain: 4.66
Pole: -2.94 + 5.52i
Damping: 0.47
Overshoot (%): 18.8
Frequency (rad/s): 6.25
30
20
10
0
-10
-20
-30
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
Imaginary Axis (seconds$^{-1}$)
Real Axis (seconds$^{-1}$)


Root Locus
System: k2
Gain: 1.47
Pole: -5.52 + 5.7i
Damping: 0.696
Overshoot (%): 4.76
Frequency (rad/s): 7.93
Imaginary Axis (seconds-1)
Real Axis (seconds-1)
30
20
10
0
-10
-20
-30
-35
-30
-25
-20
-15
-10
-5
0
5
10
15




Select damping of about 0.5 for outer loop to get desired response


Step Response
System: f2
Settling time (seconds): 1.06
Amplitude
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1.5
2
2.5
Time (seconds)



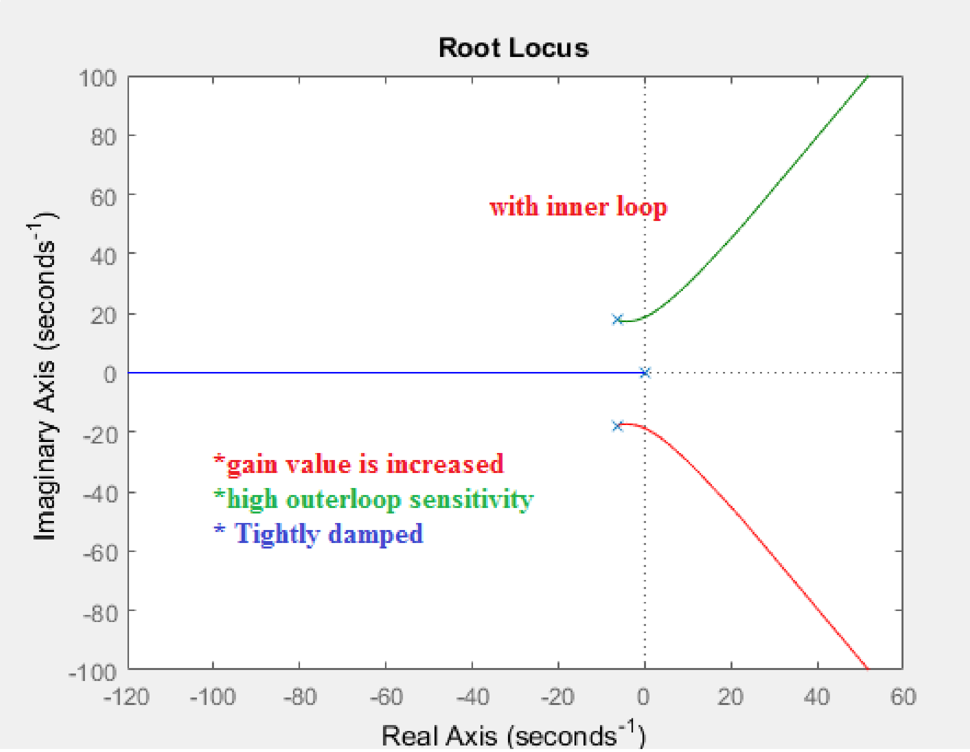
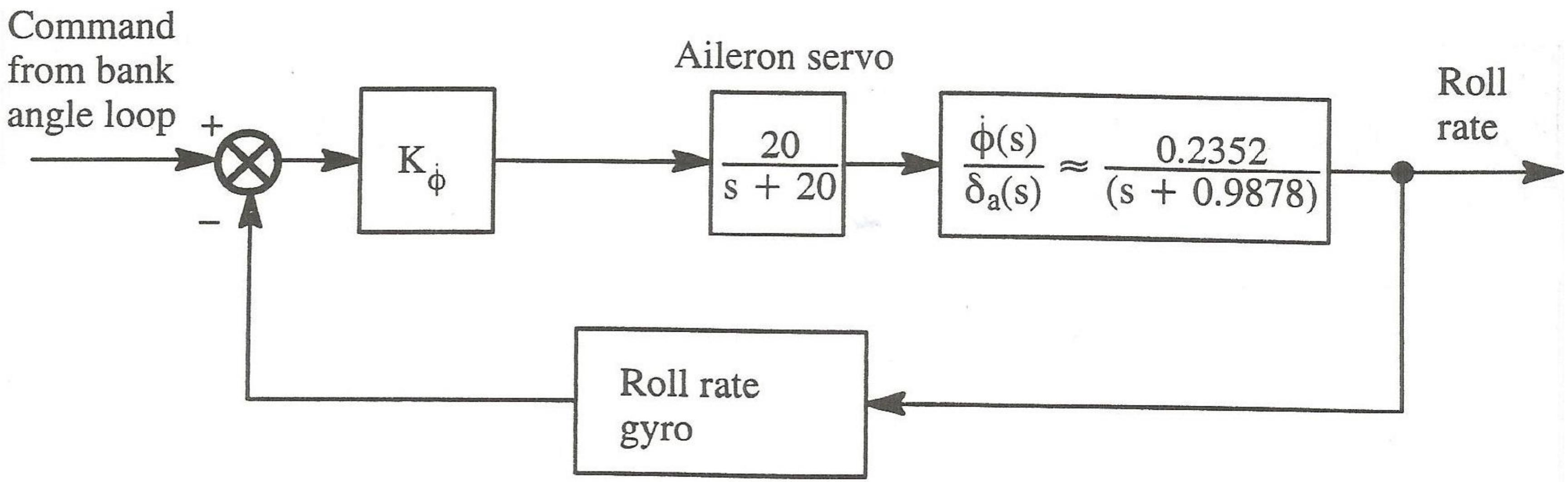



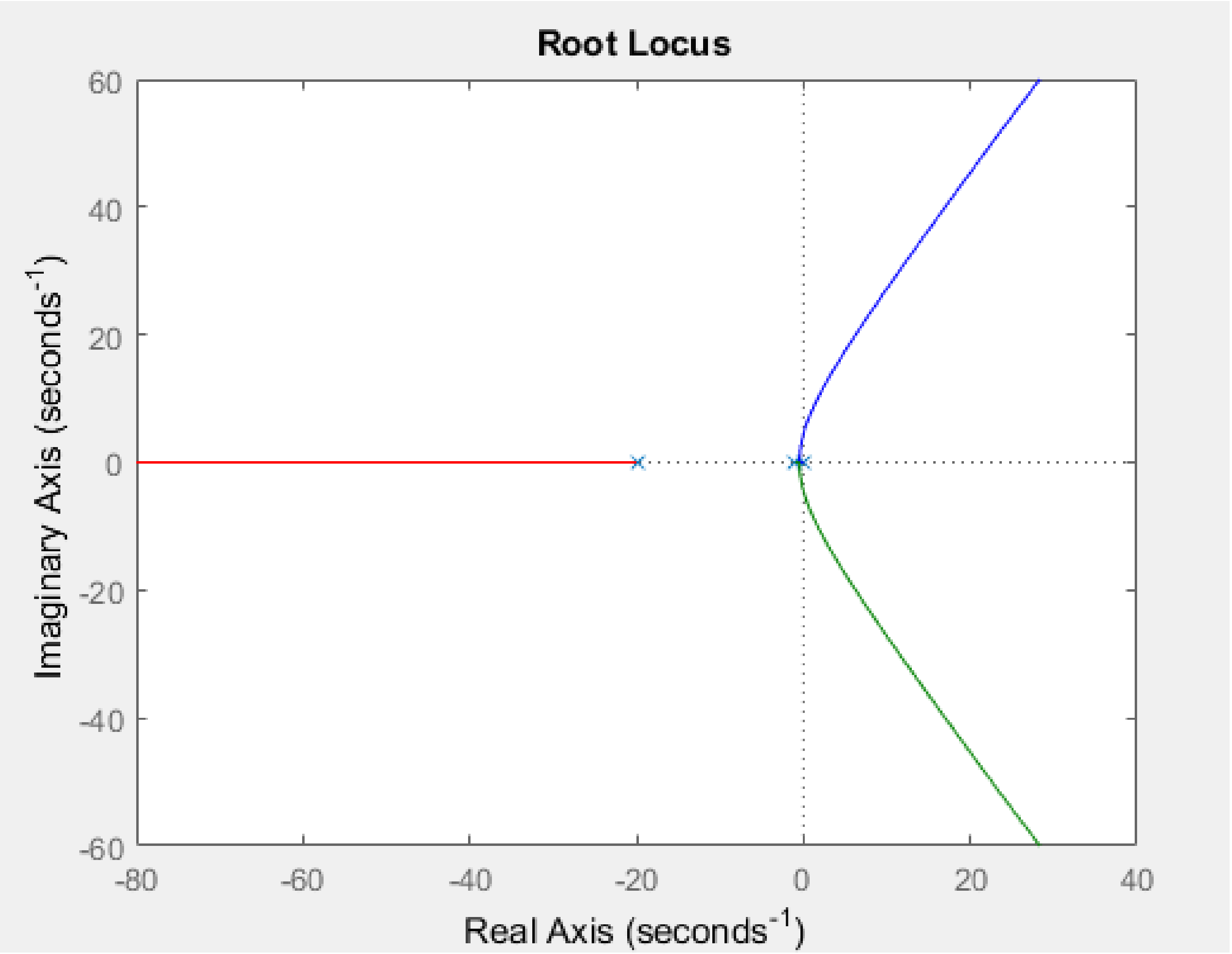

Figure.1 a comparison of bank angle hold without inner loop

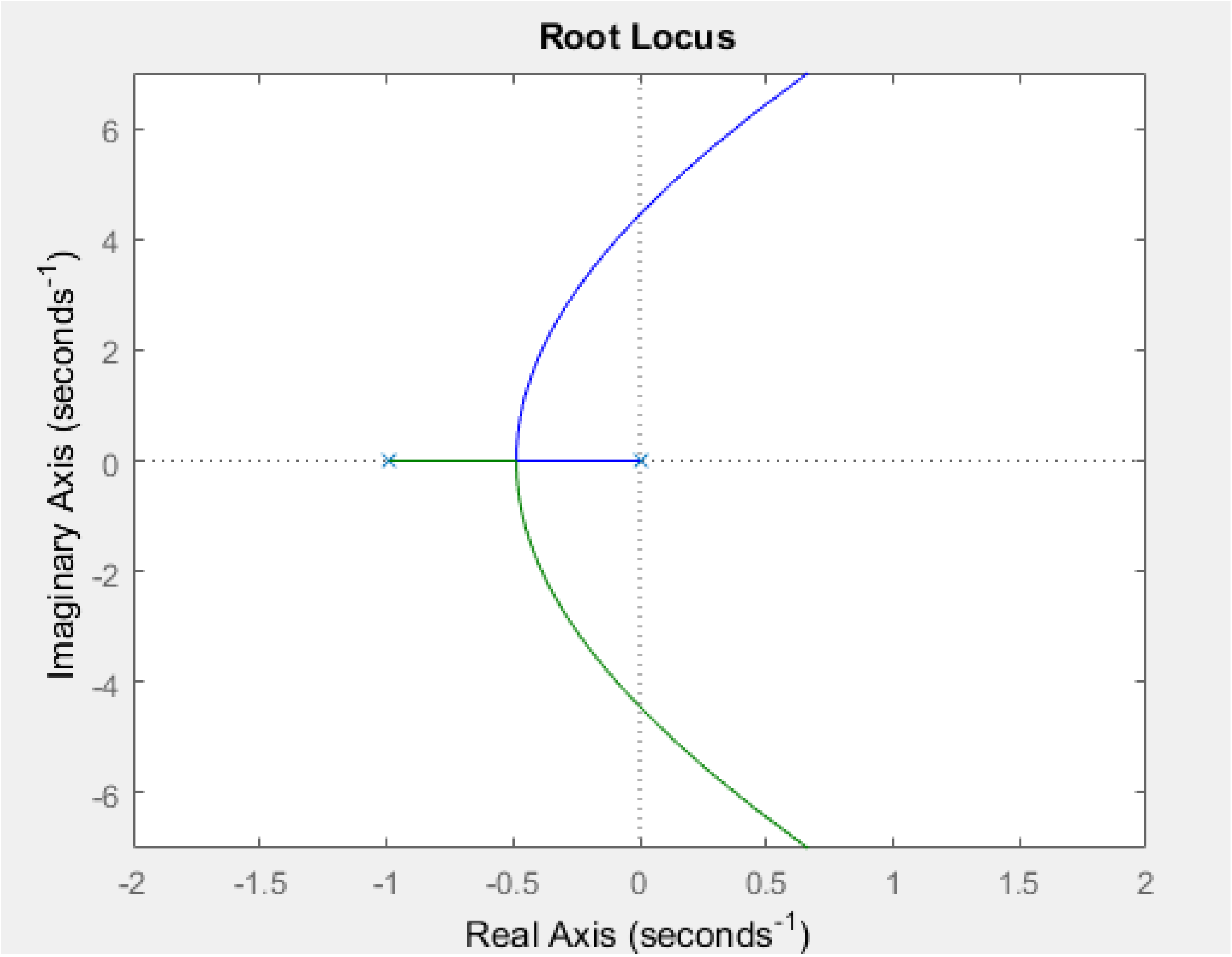
Figure.1 b comparison of bank angle hold with inner loop

# Case II

- The following aircraft transfer function has already very good roll damping characteristic.
- Further adding roll rate feed back may leads to decreasing the gain value of the outer loop compared to its inner loop.
- It is noted that in figure 2 and figure 3 the gain value without rate feedback is high when compare to rate feedback.
- In general, the rate feedback is mainly used to improve the gain sensitivity and improve less damping value.
- If a aircraft having very good roll damping characteristic don’t use the roll rate feedback.
- The following case is just for reference study.


Command
from bank
angle loop
+
−
$K_{\dot\phi}$
Aileron servo
$\frac{20}{s + 20}$
$\frac{\dot\phi(s)}{\delta_a(s)} \approx \frac{0.2352}{(s + 0.9878)}$
Roll
rate
Roll rate
gyro


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


Root Locus
Imaginary Axis (seconds$^{-1}$)
Real Axis (seconds$^{-1}$)
6
4
2
0
-2
-4
-6
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

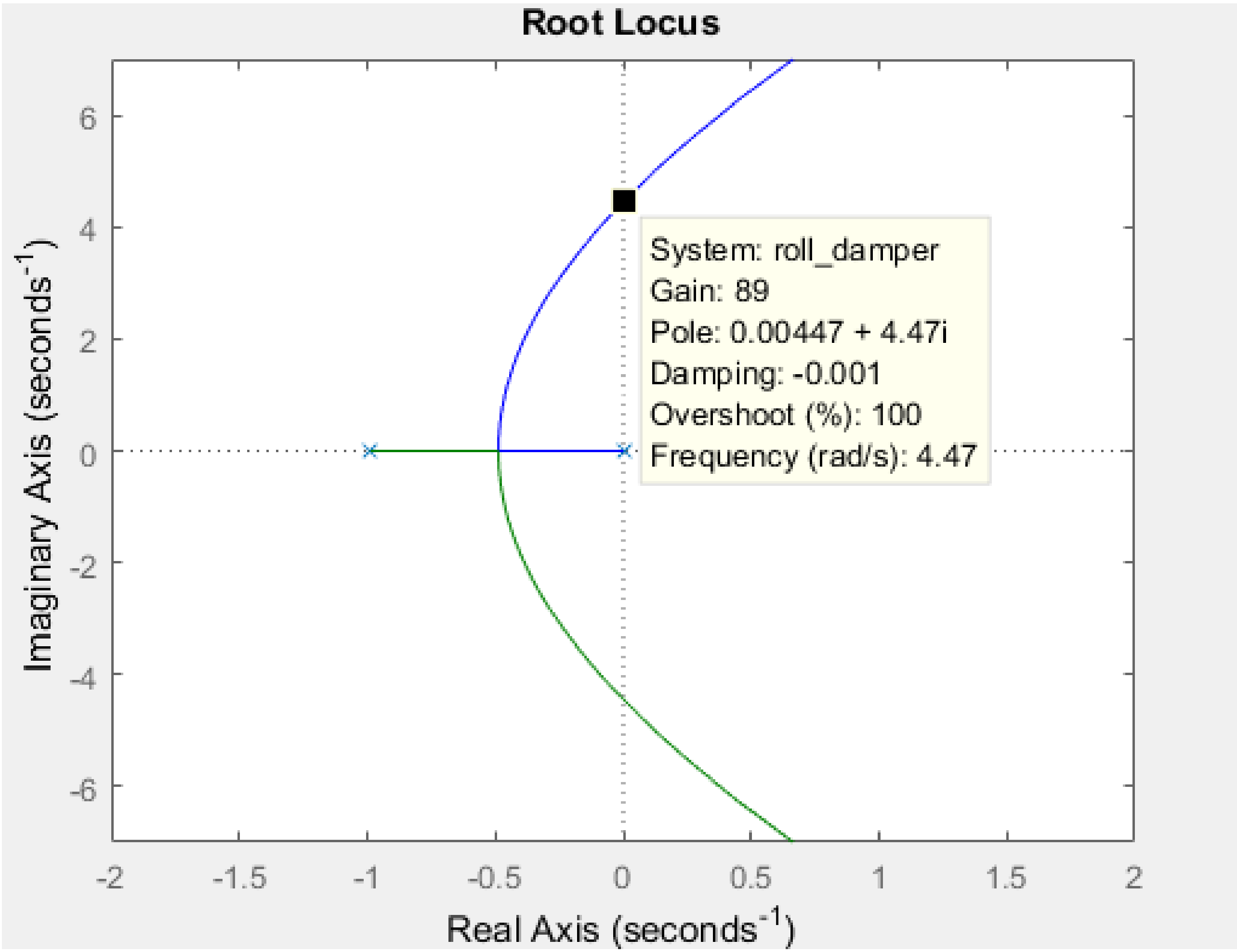
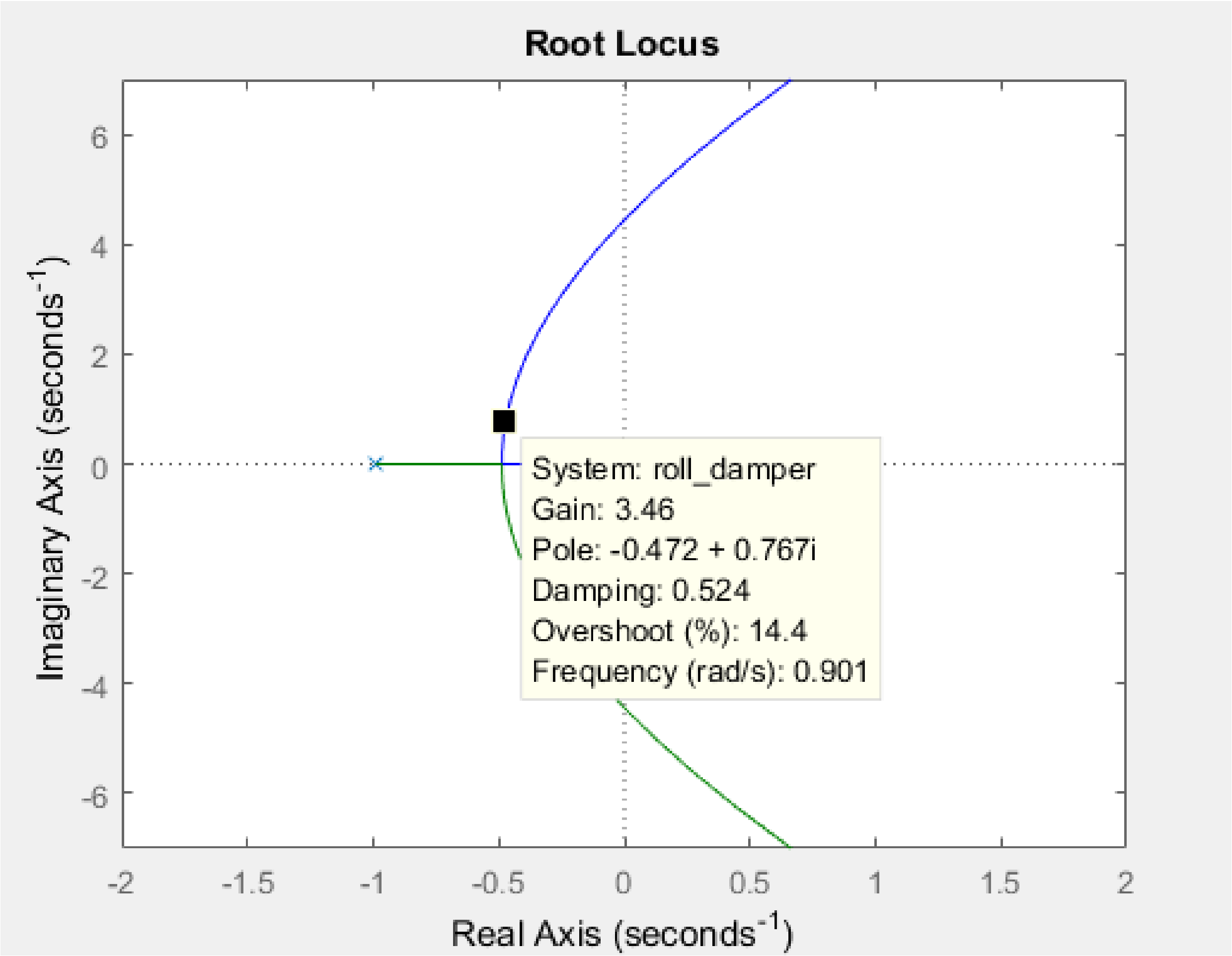
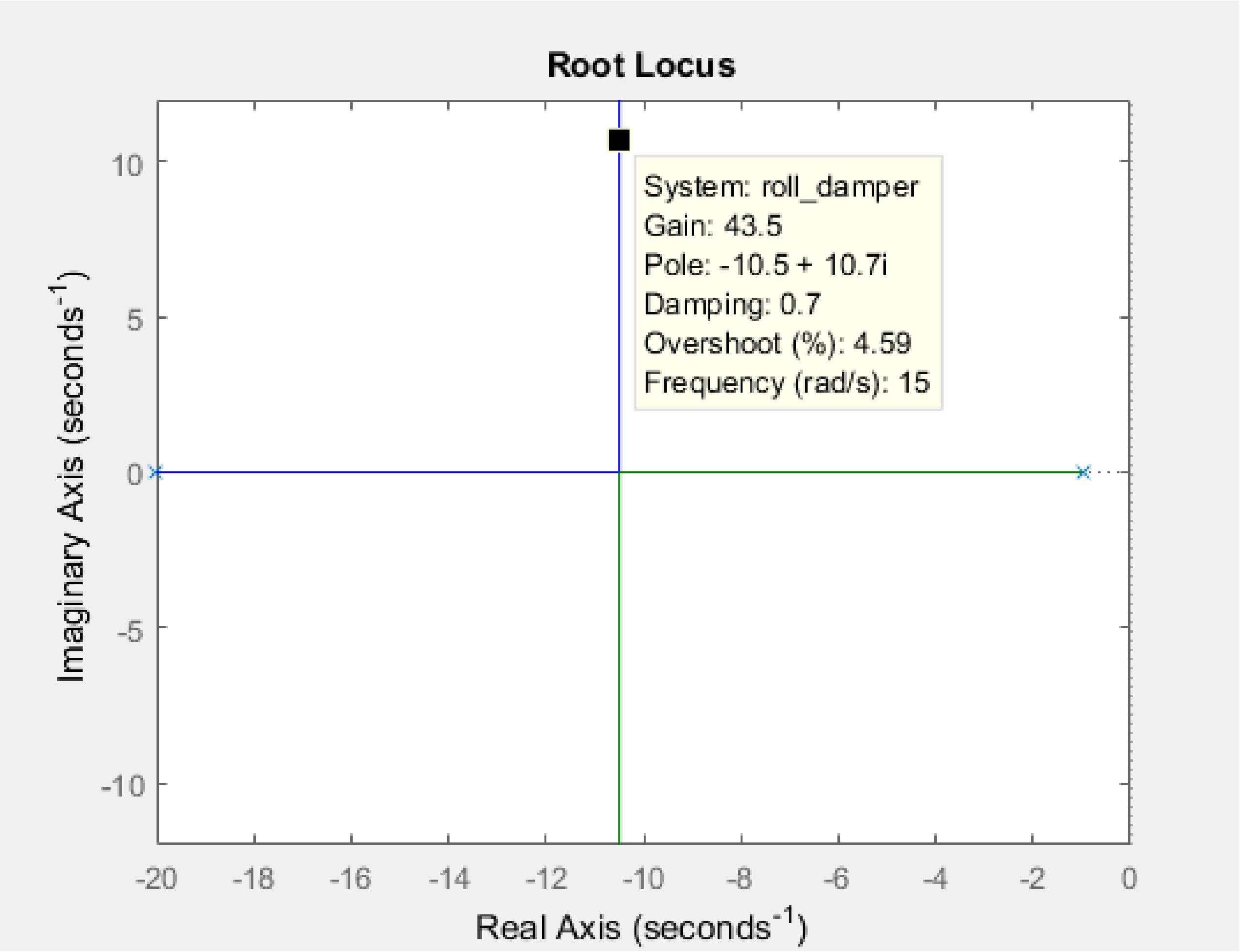
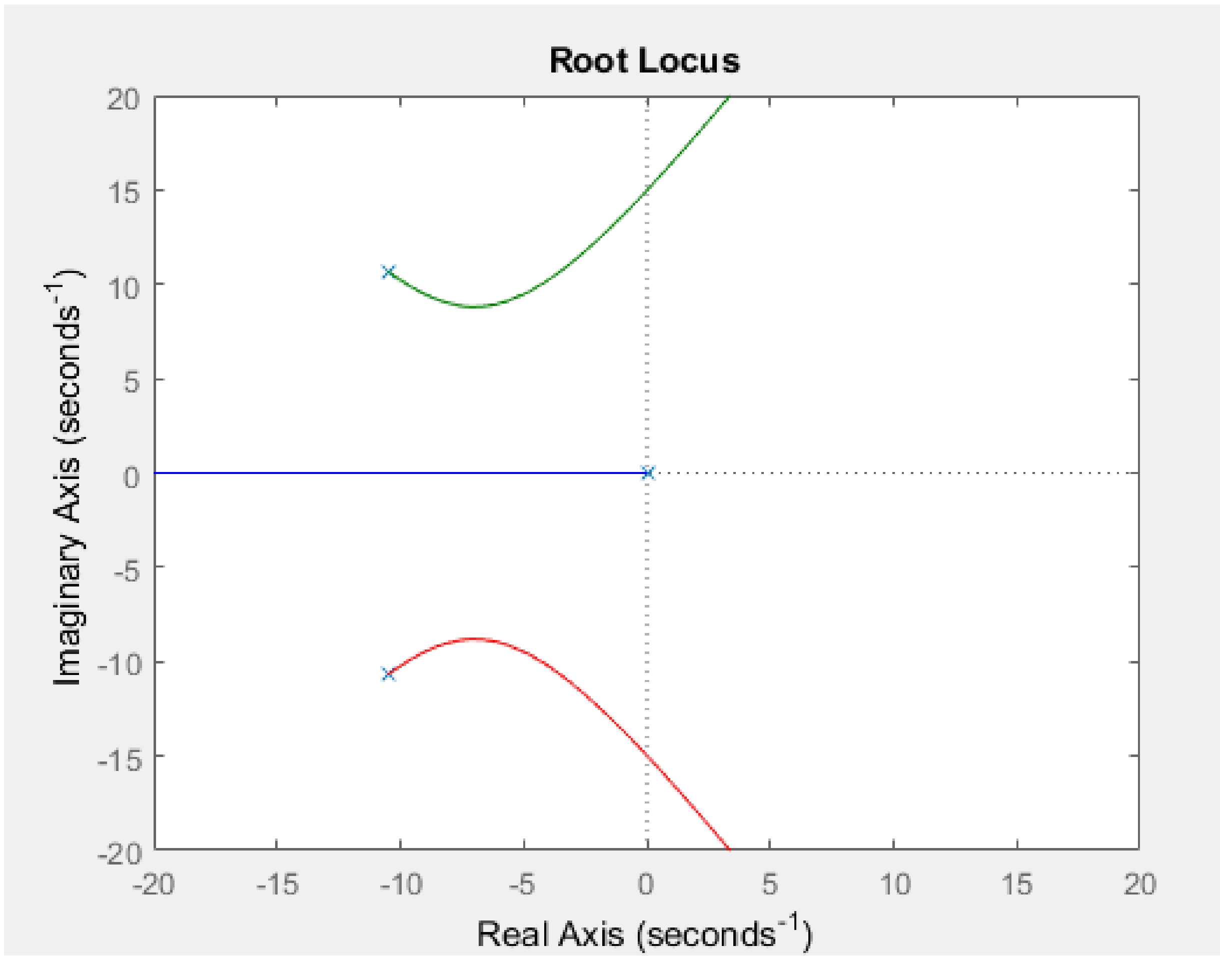



Figure 2 Gain value of 89


Root Locus
System: roll_damper
Gain: 3.46
Pole: -0.472 + 0.767i
Damping: 0.524
Overshoot (%): 14.4
Frequency (rad/s): 0.901
Imaginary Axis (seconds^-1)
Real Axis (seconds^-1)
6
4
2
0
-2
-4
-6
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2




Inner loop gain at damping of about 0.7



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

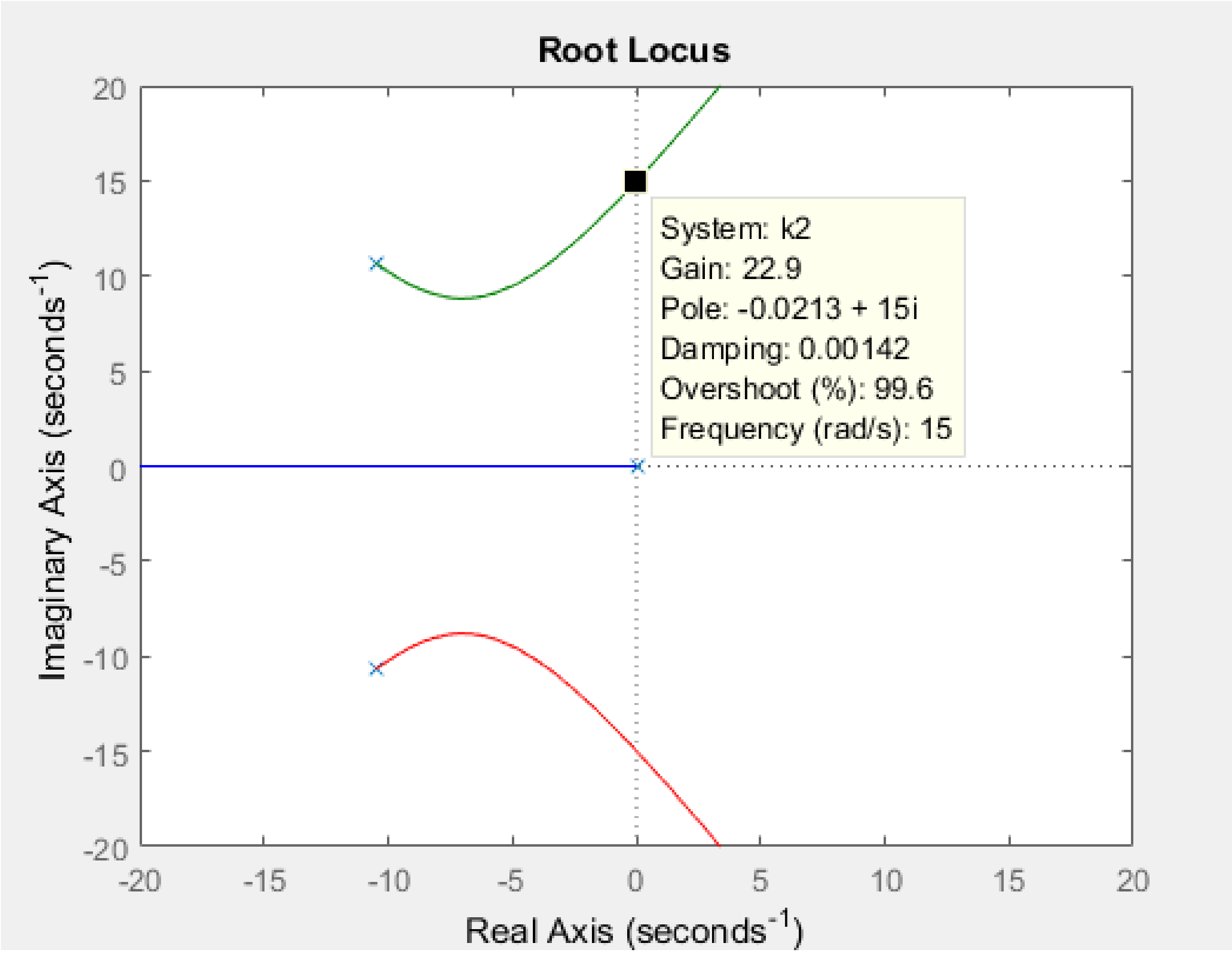
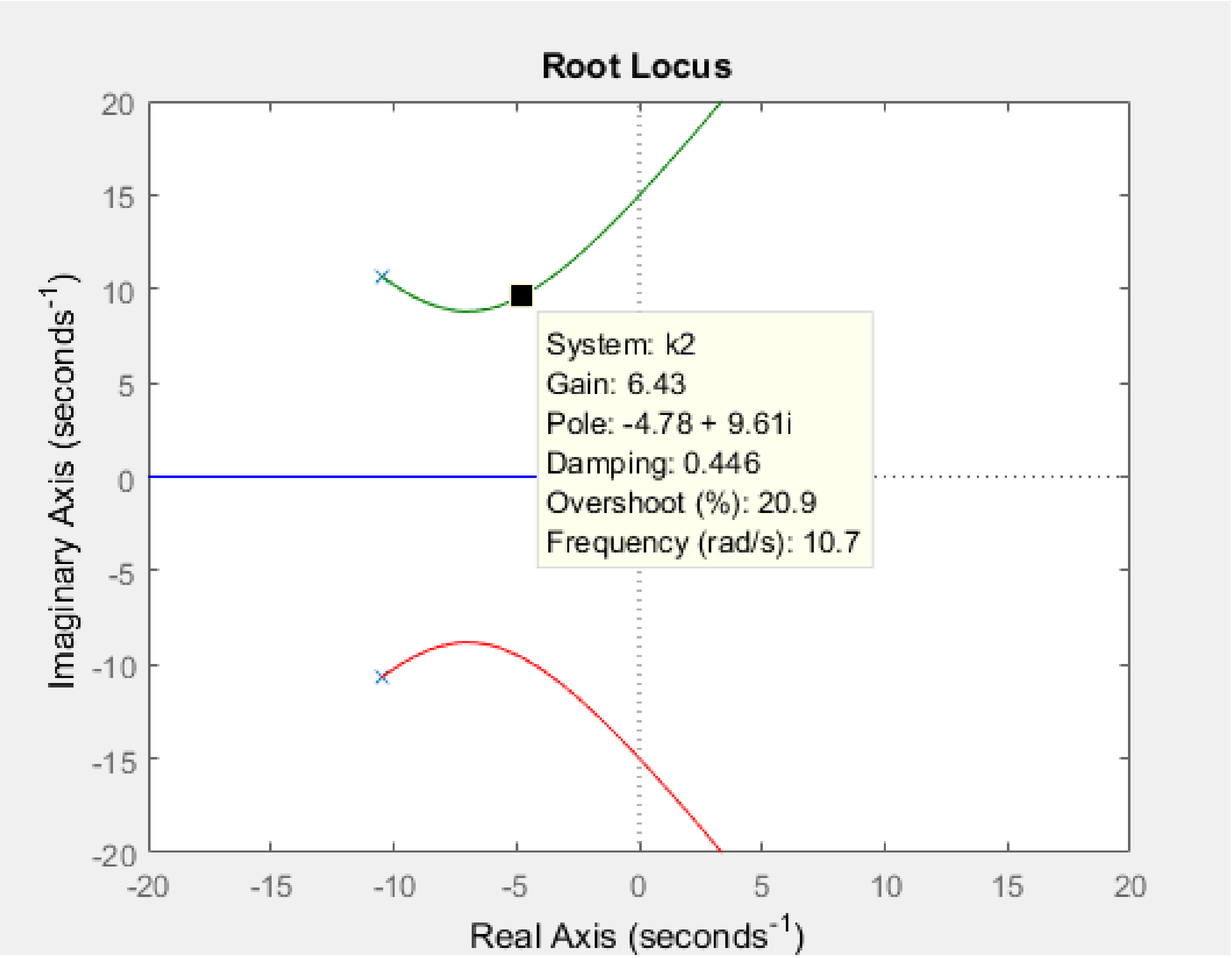
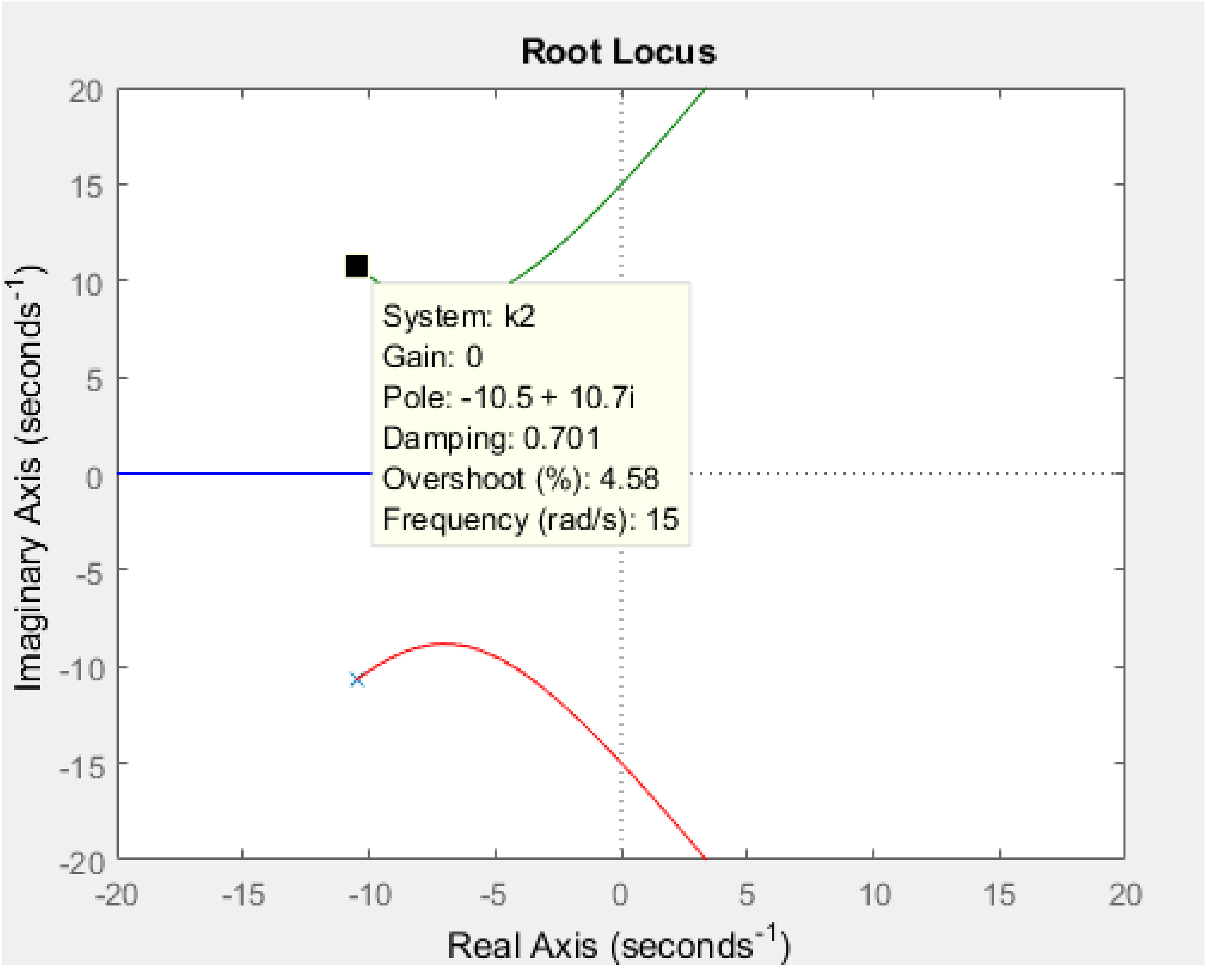



Figure 3. Gain value of 22.9 (note gain value is decreasing instead of increasing


Root Locus
System: k2
Gain: 6.43
Pole: -4.78 + 9.61i
Damping: 0.446
Overshoot (%): 20.9
Frequency (rad/s): 10.7
Imaginary Axis (seconds-1)
Real Axis (seconds-1)
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20


Root Locus
Imaginary Axis (seconds^-1)
Real Axis (seconds^-1)
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20
System: k2
Gain: 0
Pole: -10.5 + 10.7i
Damping: 0.701
Overshoot (%): 4.58
Frequency (rad/s): 15

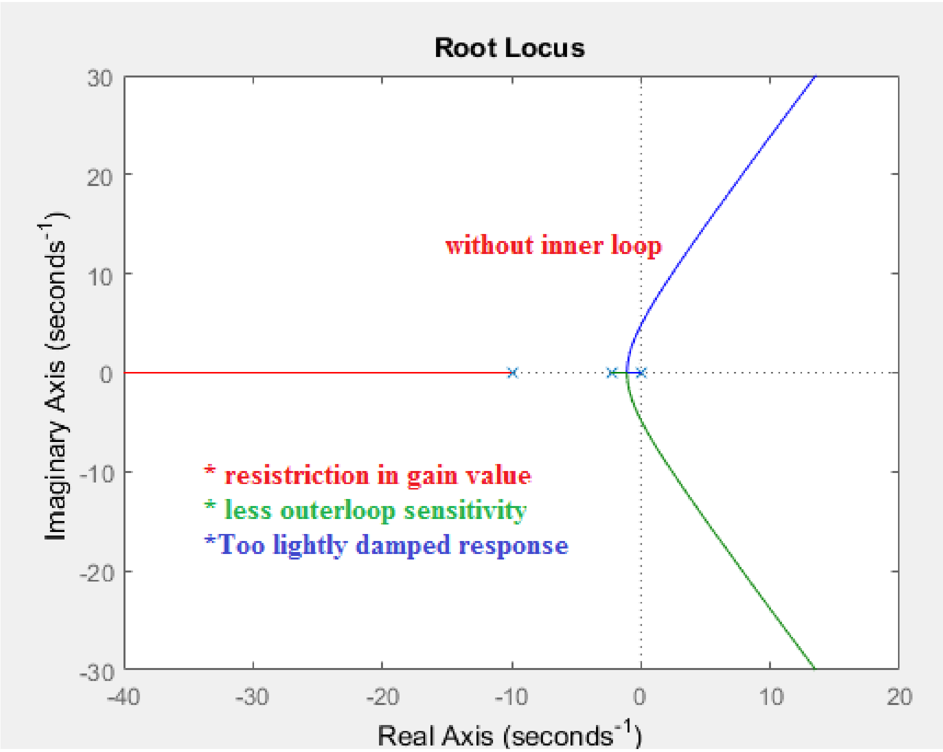



Figure.1 a comparison of bank angle hold without inner loop

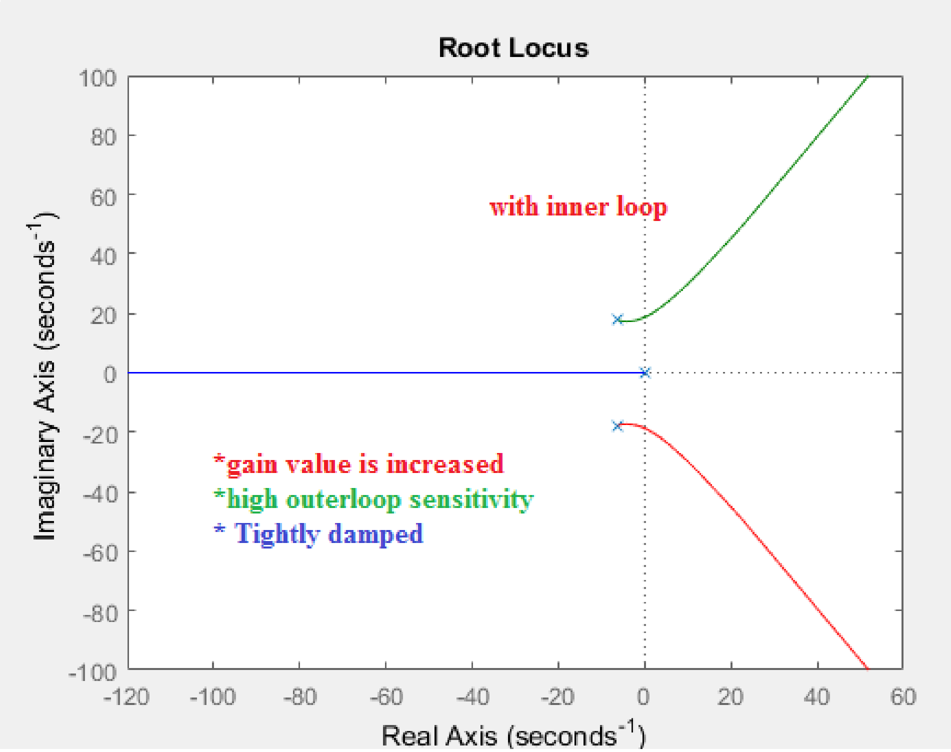



Figure.1 b comparison of bank angle hold with inner loop

# Yaw Damper and its importance

- Yaw damper will tends to appose any yaw rate away from the reference input.
- In a steady and level flight the reference yaw rate input is normally zero.
- However, if a pilot want to do roll maneuver (Constant bank angle turn ) a non-zero yaw rate is desired. Else the yaw damper will tend to "fight " a pilot who is try to setup a constant bank angle turn.
- The above problem has been overcome by two methods
  - Feed Computed yaw rate to the yaw damper (reference)input
  - Use a washout circuit in the feedback path.

- In the case of computed yaw rate, a compute signal from the equation is feed to the reference input.

$$R = \dot{\psi}_1 \cos\theta_1 \cos\phi_1$$

- The yaw damper will try to eliminate any yaw rate above or below the value given in the above equation. This is referred as "Computed yaw rate" input.

- From the equation it is evident that, these components are mandatory to measure the computed yaw rate

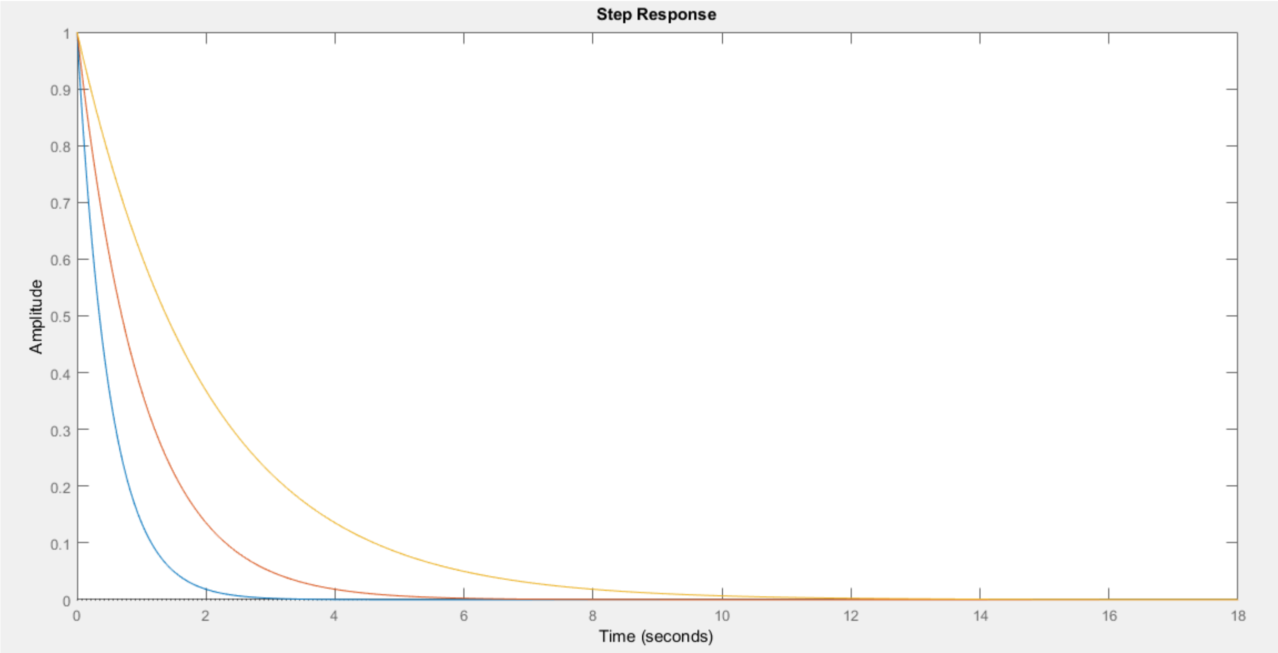
  - A gyro to measure pitch angle
  - A gyro to measure bank angle
  - A gyro to measure the heading
  - A computer to multiply the above values.

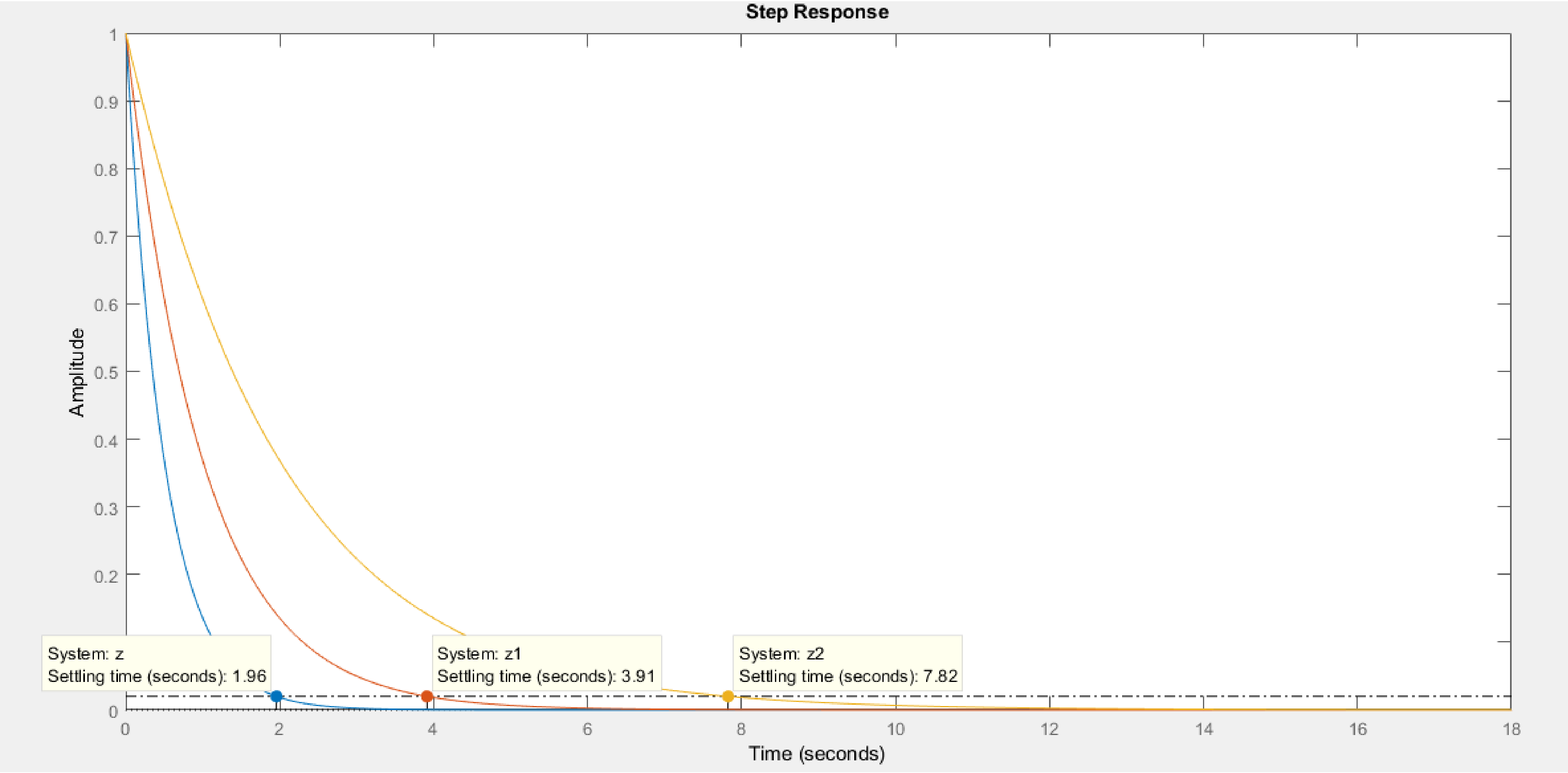
- If any one of the sensor is not available, a low cost option is the use of "wash out circuit".

$$H_{washout} = \frac{\tau s}{\tau s + 1}$$

*Where $\tau$ is a washout time constant*

- The time domain response of a washout circuit is shown in the figure. It is seen that a washout circuit drives a given input to zero at pace determined by the magnitude of time constant.




Step Response
Amplitude
Time (seconds)
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12
14
16
18
System: z
Settling time (seconds): 1.96
System: z1
Settling time (seconds): 3.91
System: z2
Settling time (seconds): 7.82

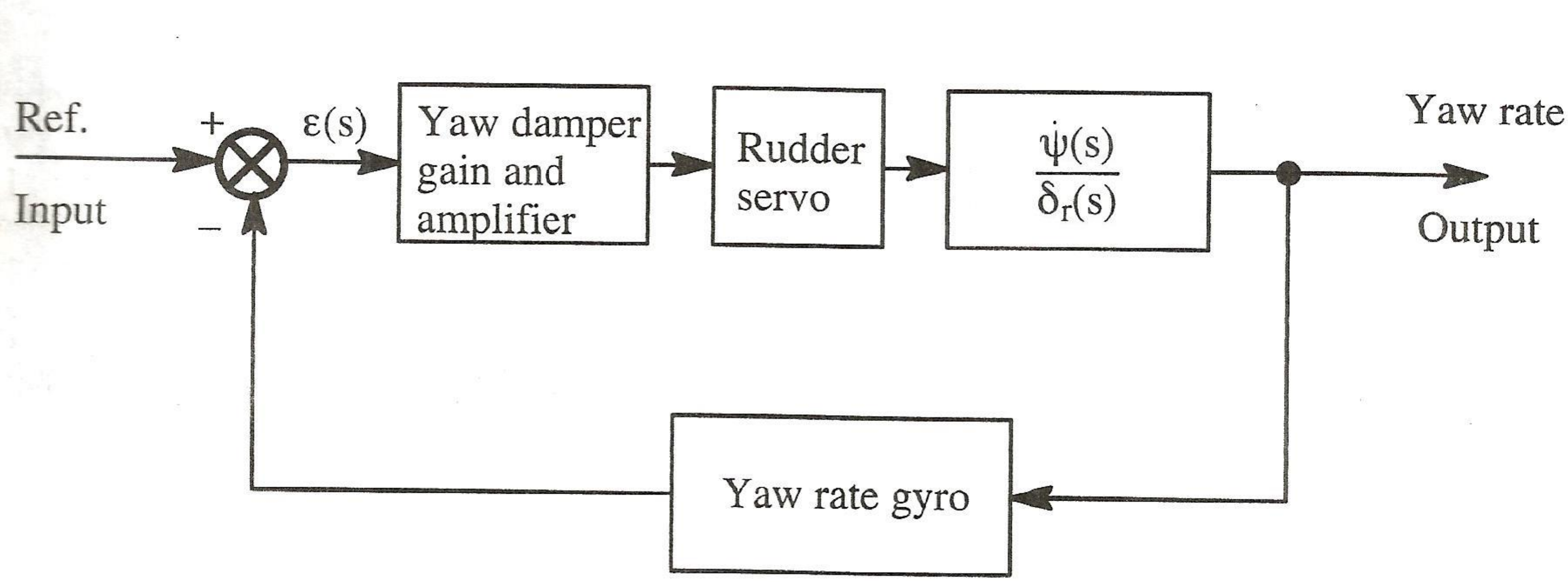
- During a turn, the washout circuit will stop "fighting" the yaw rate in any significant manner after a little time more than seconds elapsed.

- Clearly if $\tau$ is very small, the yaw damper will not work at all. If $\tau$ is very large, the yaw damper will fight the pilot in the setting up turn.

- A compromise is required. Typical of such compromise is

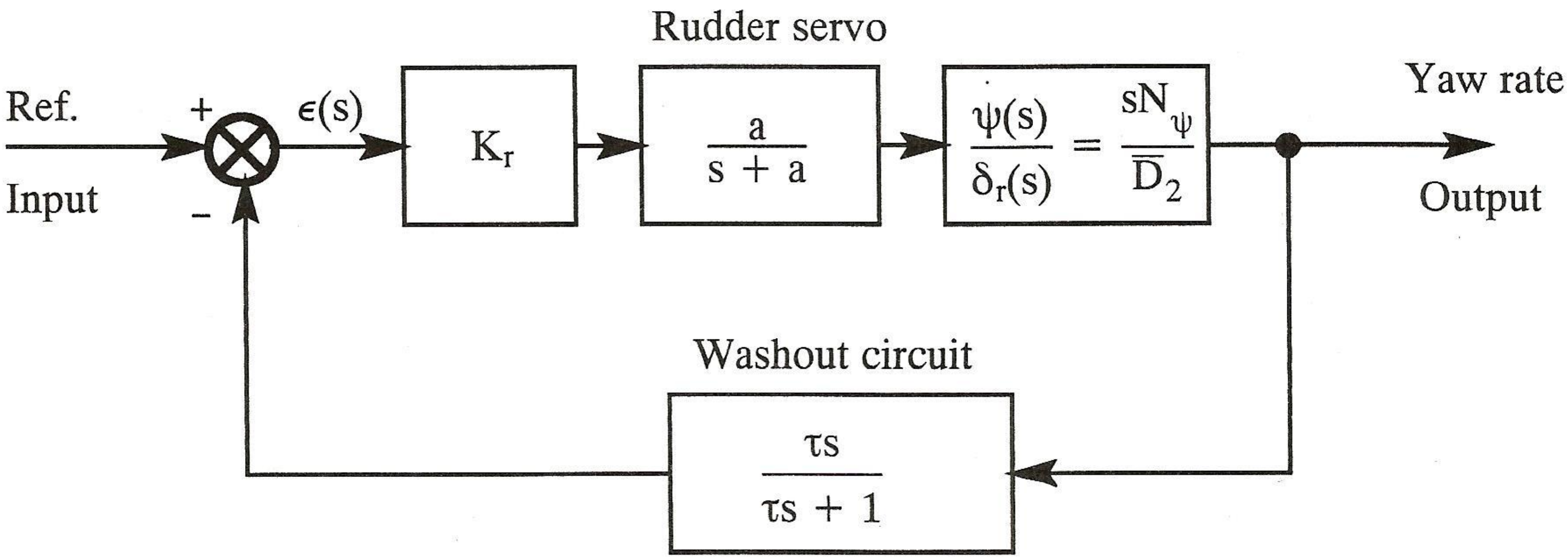
$$\tau = 4 \sec$$

# Yaw

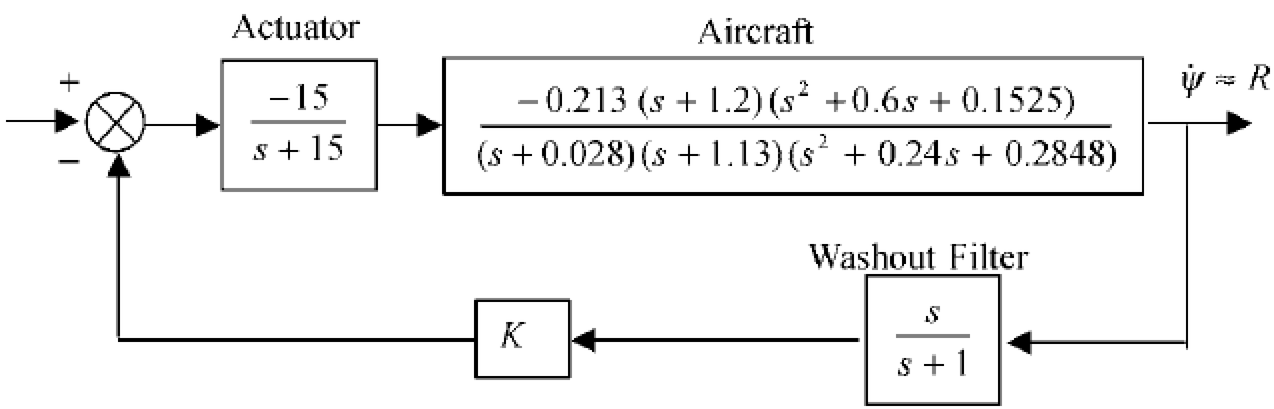


Ref.
Input
+
−
ε(s)
Yaw damper gain and amplifier
Rudder servo
ψ̇(s) / δr(s)
Yaw rate
Output
Yaw rate gyro

# Yaw damper with washout circuit



$$\frac{\dot{\psi}}{\delta_r} = -\frac{0.213(s+1.2)(s^2+0.6s+0.1525)}{(s+0.028)(s+1.13)(s^2+0.24s+0.2848)}$$



# What's the need of yaw damper?

- A yaw damper is primarily used to improve Dutch roll characteristics of an aircraft. Good Dutch roll characteristics are essential to tight tracking tasks such as
- Air-to-Air refueling.
- Formation flying.
- Approach (landing).
- Air-to-Air tracking.
- Air-to-ground tracking.


Air-to-Air refueling

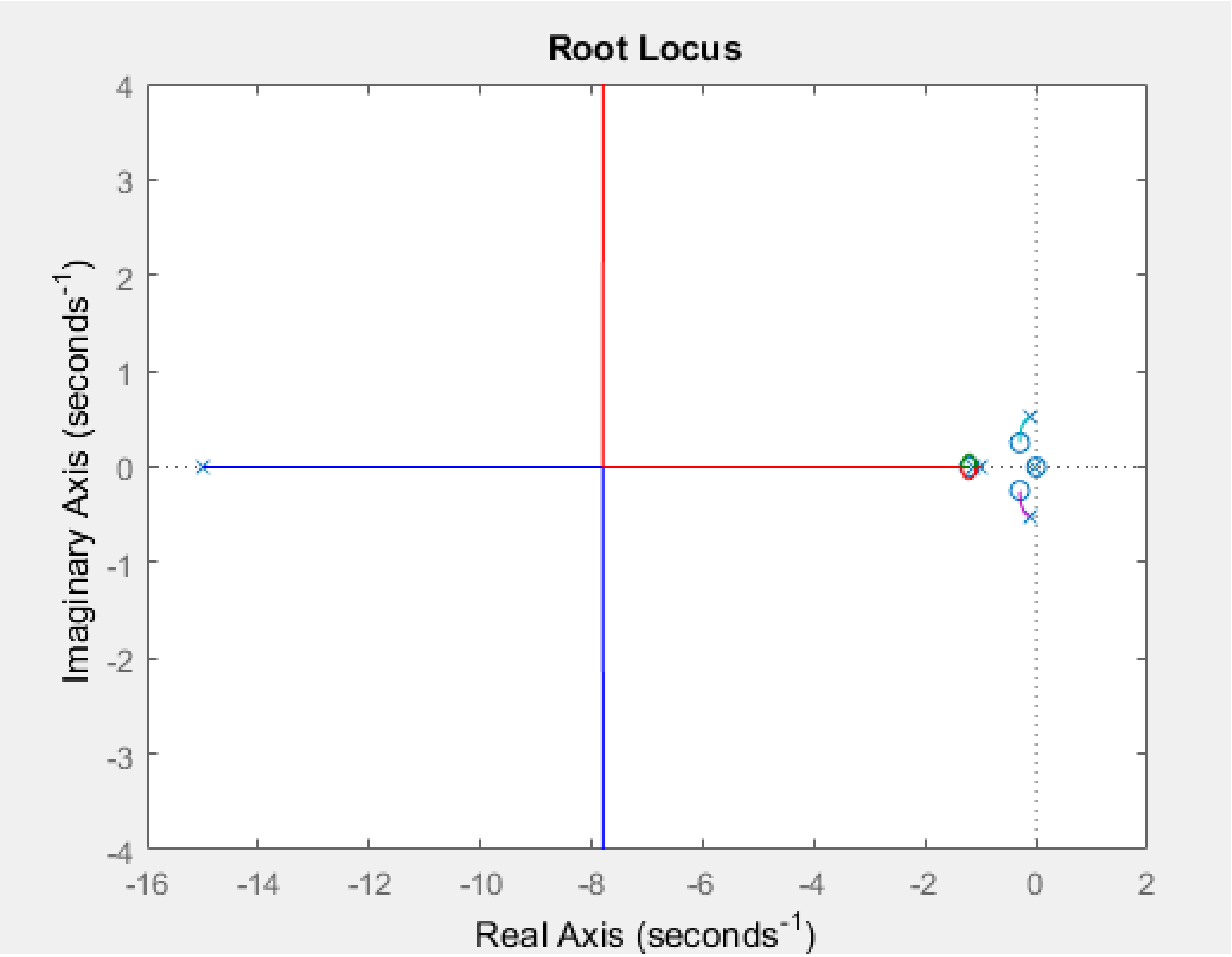
Formation flying

Air-to-Air tracking

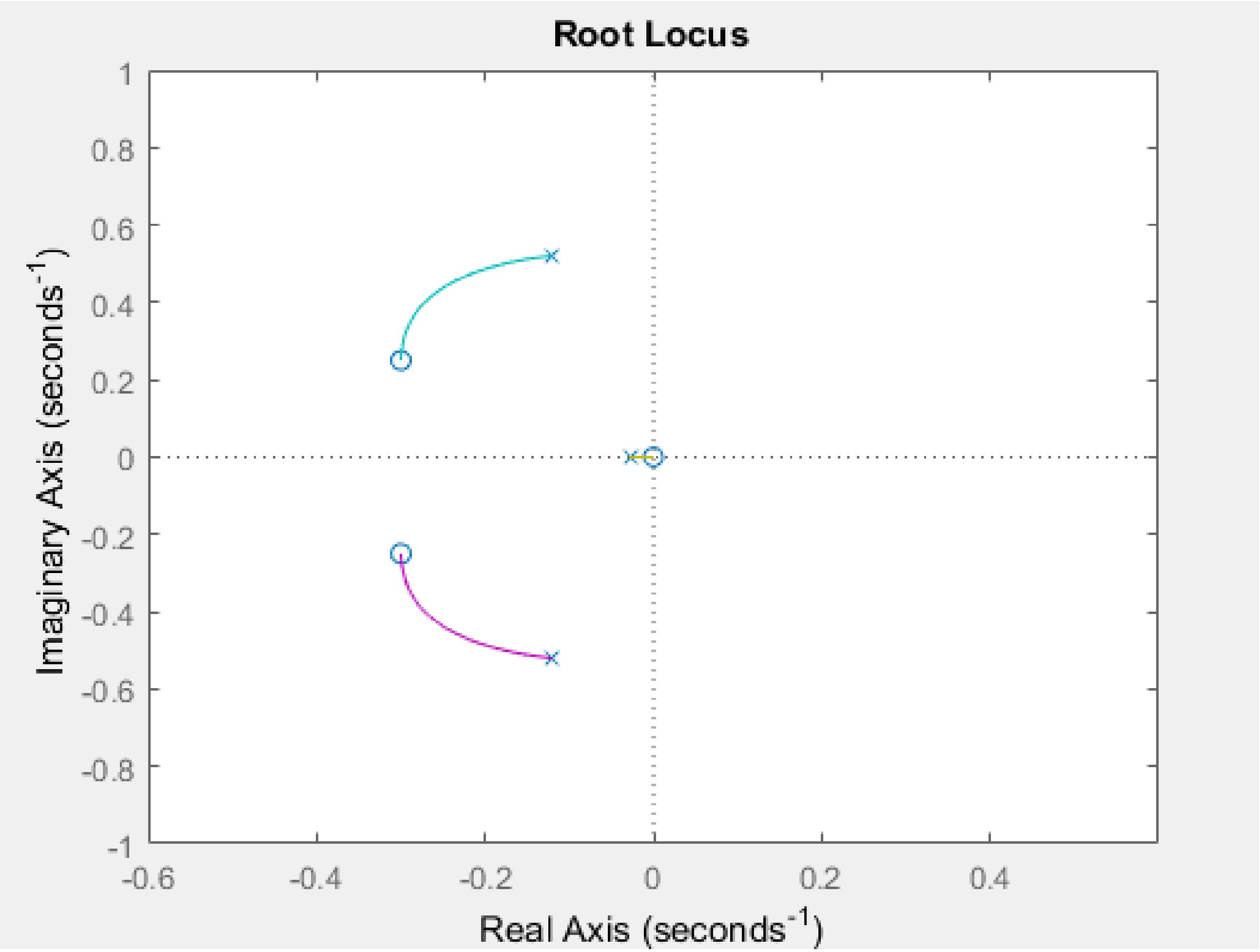
Air-to-ground tracking( weapon delivery)

Aircraft landing

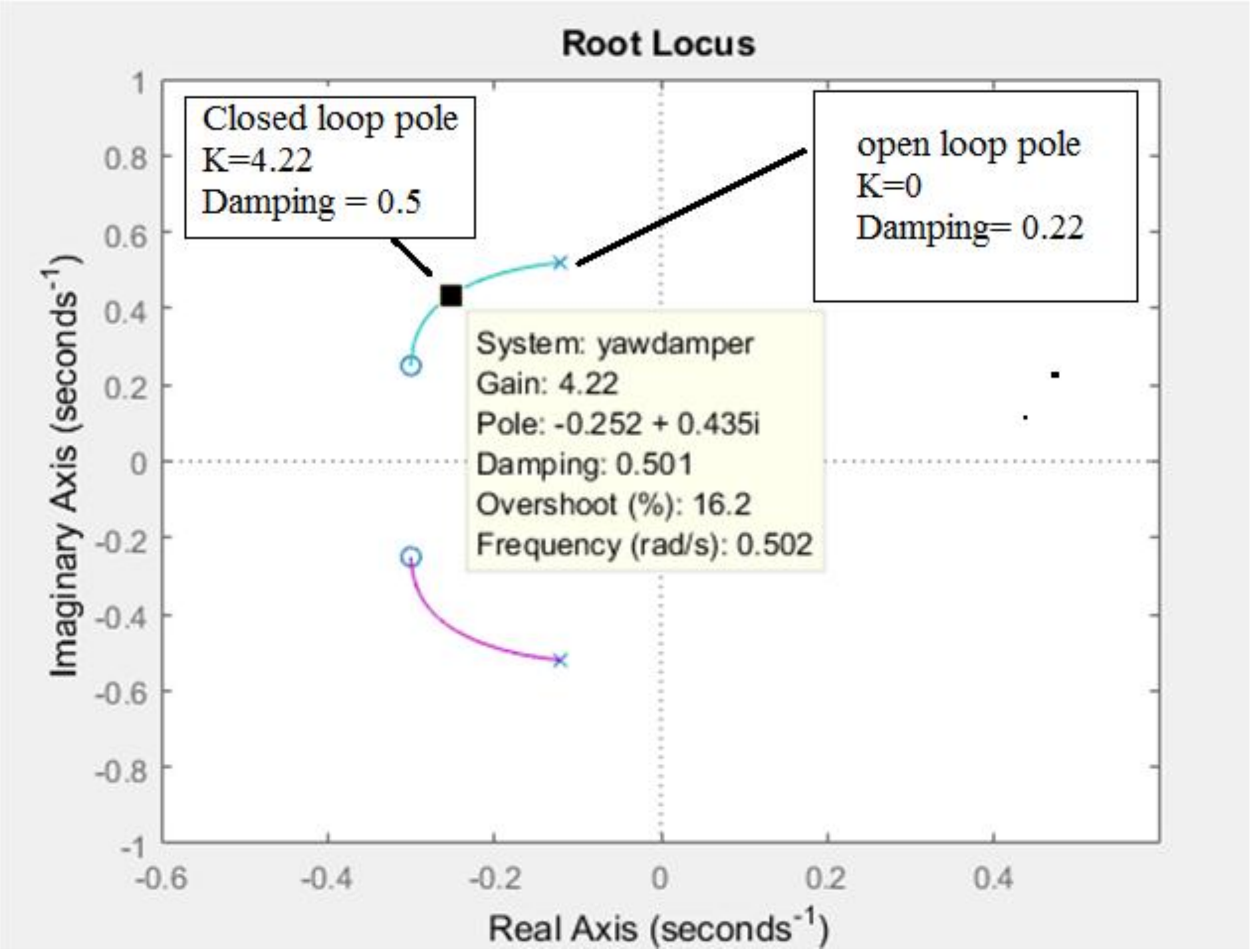
# Yaw damper root locus plot focusing on Dutch roll roots

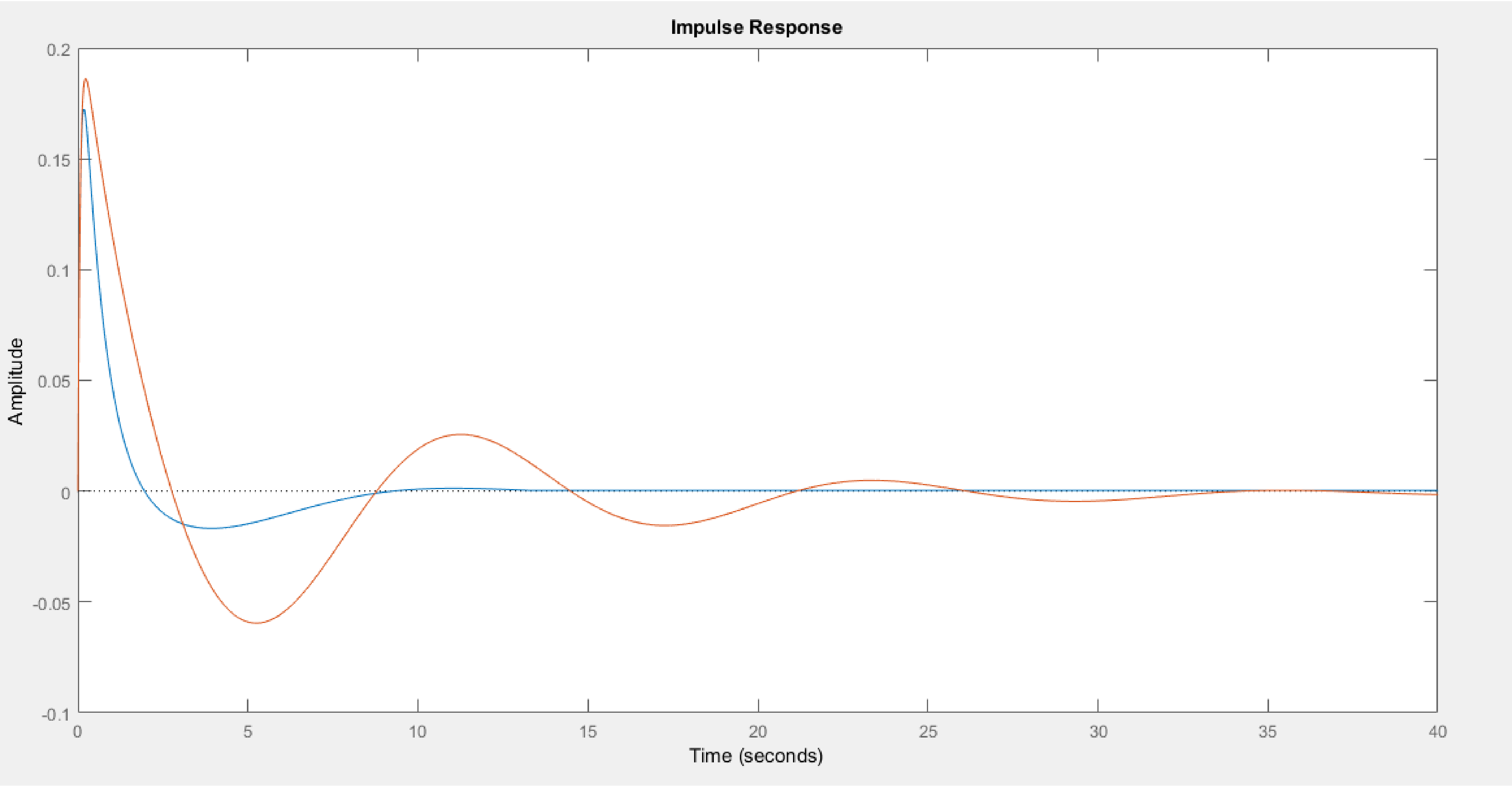


# Yaw damper root locus plot focusing on Dutch roll roots

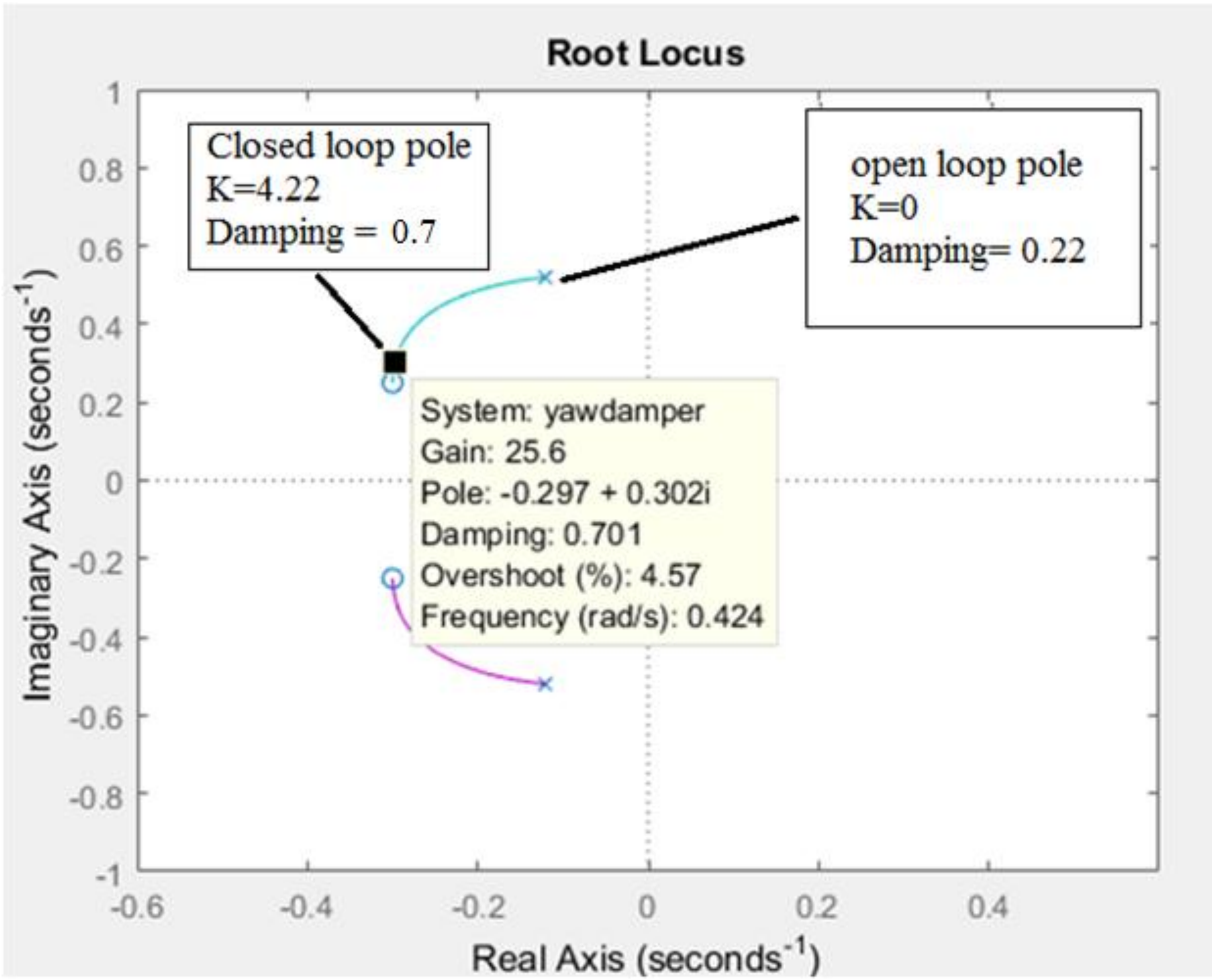


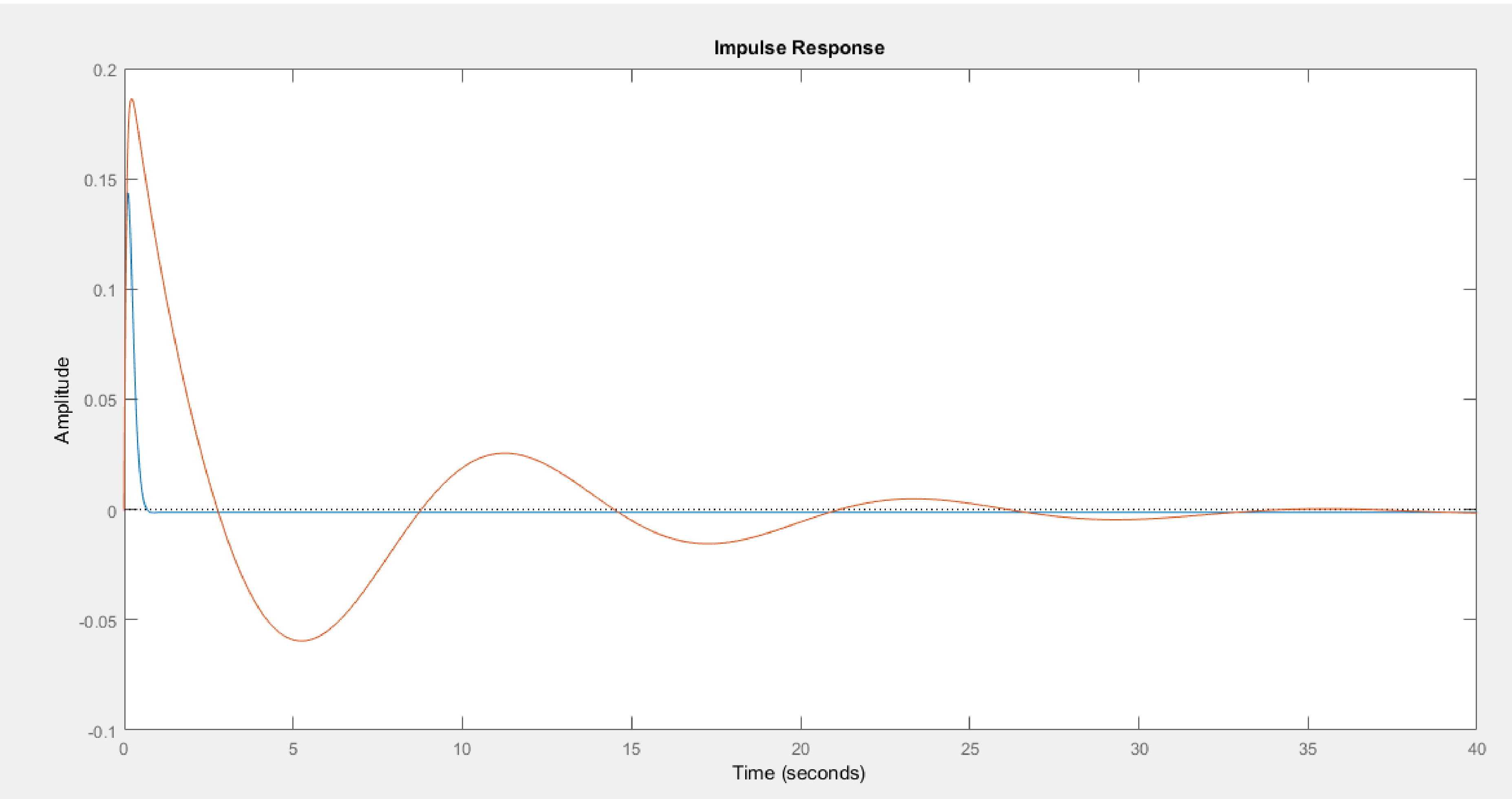
# Yaw damper root locus plot focusing on Dutch roll roots –damping of 0.5



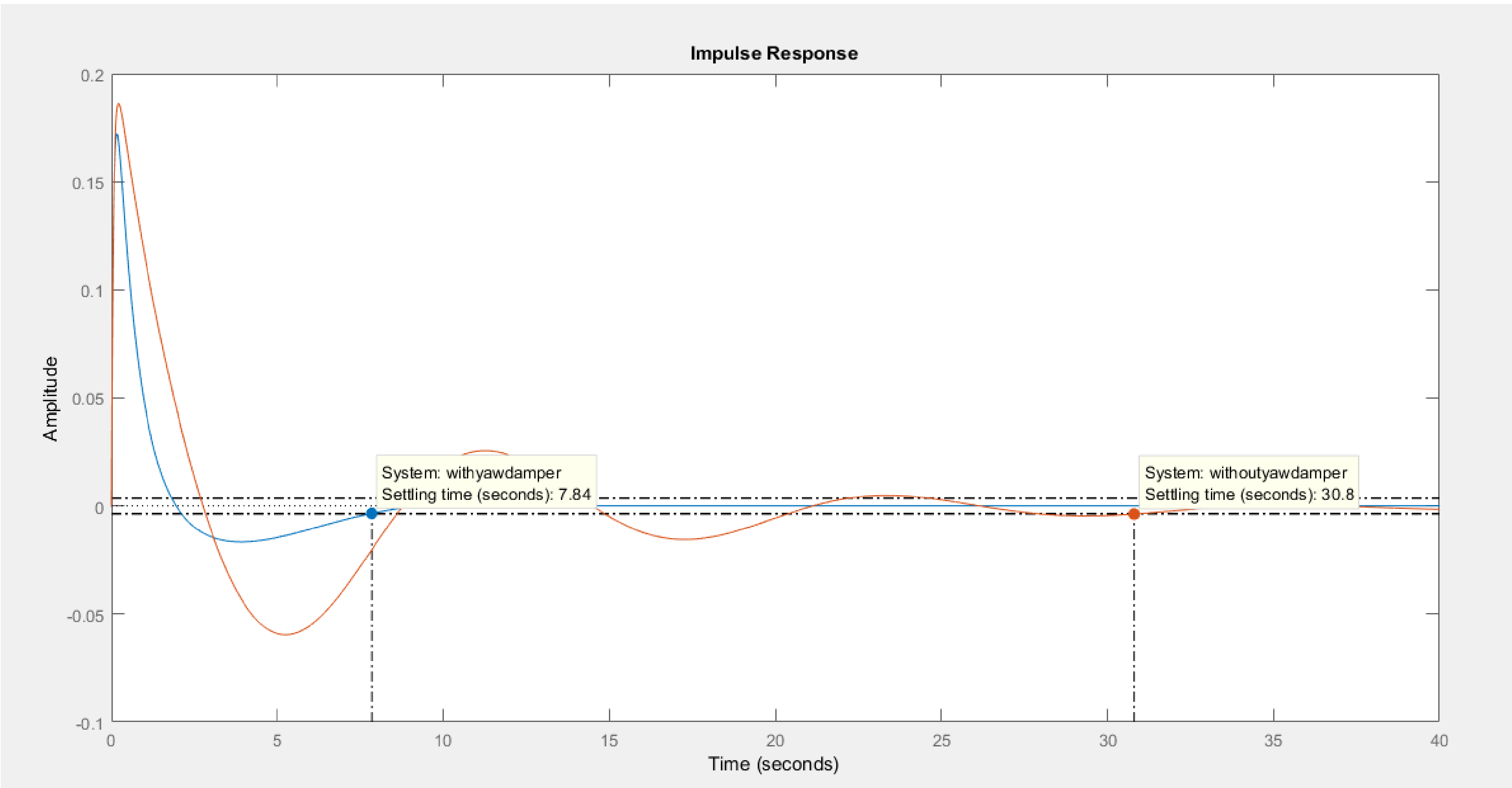


Impulse Response
Amplitude
Time (seconds)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30
35
40


Root Locus
Closed loop pole
K=4.22
Damping = 0.7
open loop pole
K=0
Damping= 0.22
System: yawdamper
Gain: 25.6
Pole: -0.297 + 0.302i
Damping: 0.701
Overshoot (%): 4.57
Frequency (rad/s): 0.424
Imaginary Axis (seconds-1)
Real Axis (seconds-1)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.6
-0.4
-0.2
0
0.2
0.4



Impulse Response
Amplitude
Time (seconds)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30
35
40


Impulse Response
Amplitude
Time (seconds)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
5
10
15
20
25
30
35
40
System: withyawdamper
Settling time (seconds): 7.84
System: withoutyawdamper
Settling time (seconds): 30.8

- To make the yaw damper more effective throughout the aircraft flight envelope, the gain, K, may be scheduled with dynamic pressure or other flight parameters.

- In addition, selection of the washout filter time constant will affect the value of the gain needed to obtain the desired stability characteristics.

# Yaw Damper


Stand alone yaw damper

- With passenger comfort its primary function, the Yaw Damper is an independent subsystem compatible with any autopilot system.
- It enhances directional stability by eliminating short-term yaw oscillations.
- It may assures exact coordination in all turns and maneuvers through the use of an exclusive rate gyro and electrolytic potentiometer (skid sensor), thus reducing pilot workload.
- Mostly yaw dampers are considered stand-alone systems unless they are approved as part of the autopilot system.
- Some of the yaw damper systems have the capability to be inter-connected to the autopilot systems to provide full three axis control when the autopilot is engaged and disengagement of the yaw damper when the autopilot master disconnect is used.


BENDIXKING®
KAP 140
HDG
AP
VS
A
R
M
ALT
1,500
FT
ARM
BARO
UP
DN
AP
HDG
NAV
APR
REV
ALT


PLEASE DO NOT GRAB HERE!
PLEASE DO NOT GRAB HERE!
PLEASE DO NOT TOUCH SCREENS
PLEASE DO NOT TOUCH SCREENS


AP
HDG
TRIM DN
ATT
NAV
EXT
ALT
APR
TST
GS
REV
YD
FD
TRIM UP


ON
HDG
NAV
APR
REV
DN
OFF
TST
FD
YD
ALT
UP
CENTURY
2000


CO-DETECTOR
Portable Peace of Mind
WARNING
WARNING
LORAN APPROVED FOR VFR ONLY
MIXTURE

Thank you