

# Control Systems

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**Abstract**—The objective of this manual is to introduce control system design at an elementary level.

Download python codes using

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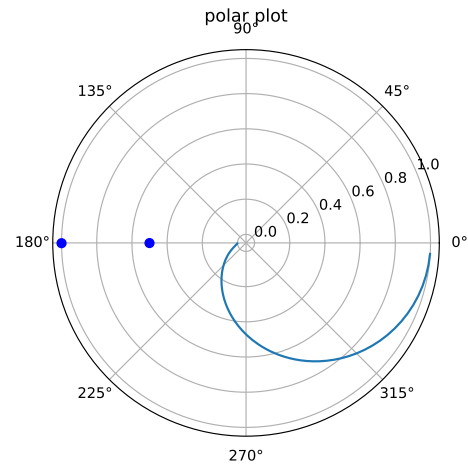


Fig. 1.1.1

svn co <https://github.com/gadepall/school/trunk/control/ketan/codes>

## 1 FREQUENCY RESPONSE ANALYSIS

### 1.1 Polar Plot

1.1.1. Sketch the Polar Plot for

$$G(s) = \frac{1}{(1+s)(1+2s)} \quad (1.1.1)$$

**Solution:** The following code generates Fig. 1.1.1

codes/ee18btech11012.py

The polar plot is to the right of  $(-1, 0)$ . Hence the closed loop system is stable.

1.1.2. Sketch the polar plot of

$$G(s) = \frac{1}{(s^2)(s+1)(s+2)}. \quad (1.1.2)$$

**Solution:** Substituting  $s = j\omega$  in (1.1.2),

Now the magnitude will be

$$r = |G(j\omega)| = \frac{1}{(\omega^2)(\sqrt{1+\omega^2})(\sqrt{1+4\omega^2})} \quad (1.1.3)$$

$$\theta = \angle G(j\omega) = -\tan^{-1}(0) - \tan^{-1}(\omega) - \tan^{-1}(2\omega) \quad (1.1.4)$$

$$= 180^\circ - \tan^{-1}(\omega) - \tan^{-1}(2\omega) \quad (1.1.5)$$

The polar plot is the  $(r, \theta)$  plot for  $\omega \in (0, \infty)$ . The following python code generates the polar plot in Fig. 1.1.2

```
codes/ee18btech11028.py
```

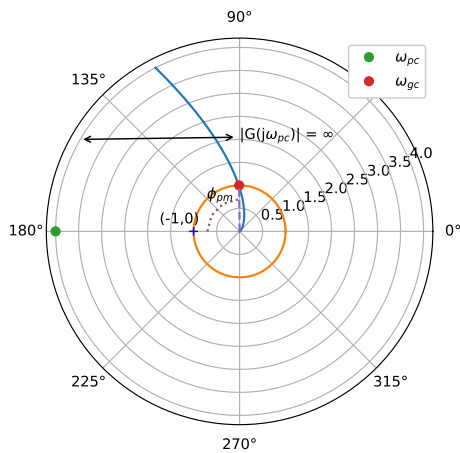


Fig. 1.1.2

The location of  $(-1, 0)$  with respect to the polar plot provides information regarding the stability of the system.

- If  $(-1, 0)$  is not enclosed, then it is stable.
- If  $(-1, 0)$  is enclosed by polar plot then it is unstable.
- If  $(-1, 0)$  is on the polar plot then it is marginally stable

In Fig. 1.1.2, the point  $(-1, 0)$  is enclosed by the polar plot, which implies system is not stable. The polar plot also provides info on the GM and PM, which can then be used for determining the stability of the system.

- If the  $GM > 1 \cap PM > 0$ , then the control system is **stable**.
- If the  $GM = 1 \cap PM = 0$ , then the control system is **marginally stable**.
- If the  $GM < 1 \cup PM < 0$ , then the control system is **unstable**.

Therefore, our system is unstable  $\because GM < 1 \cap PM < 0$ .

1.1.3. Sketch the Polar Plot of

$$G(s) = \frac{1}{s(1+s^2)} \quad (1.1.6)$$

**Solution:** From (1.1.6),

$$G(j\omega) = \frac{1}{j\omega(1-\omega^2)} \quad (1.1.7)$$

$$|G(j\omega)| = \frac{1}{|\omega(1-\omega^2)|} \quad (1.1.8)$$

$$\angle G(j\omega) = \begin{cases} \frac{\pi}{2} & \omega > 1 \\ -\frac{\pi}{2} & 0 < \omega < 1 \end{cases} \quad (1.1.9)$$

The corresponding polar plot is generated in Fig. 1.1.3 using

```
codes/ee18btech11023.py
```

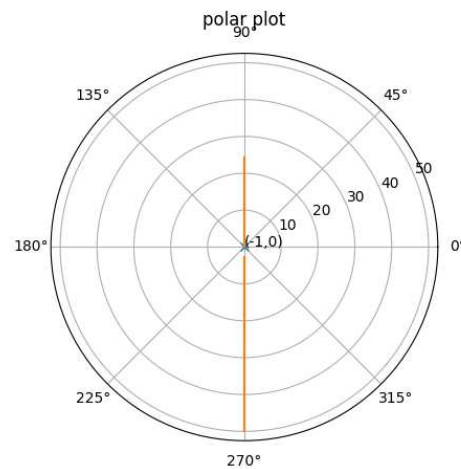


Fig. 1.1.3

In Fig. 1.1.3,  $(-1, 0)$  is exactly on the polar plot. Hence, the system is marginally stable.

1.1.4. Sketch the Polar Plot of

$$G(s) = \frac{(1 + \frac{s}{29})(1 + 0.0025s)}{(s^3)(1 + 0.005s)(1 + 0.001s)} \quad (1.1.10)$$

**Solution:** The following code generates the polar plot in Fig. 2.5.1

```
codes/ee18btech11029.py
```

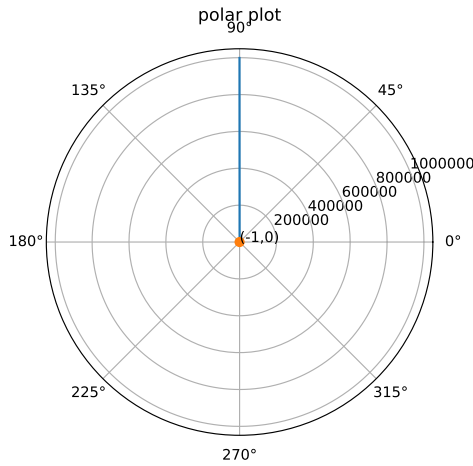


Fig. 1.1.4

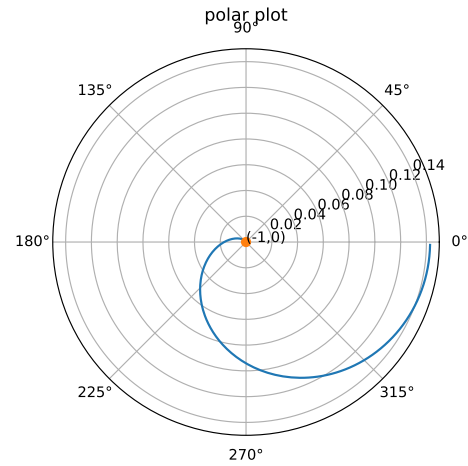


Fig. 1.1.5

- The polar plots use open loop transfer function to determine the stability and hence reference point is shifted to  $(-1, 0)$
- If  $(-1, 0)$  is left of the polar plot or  $(-1, 0)$  is not enclosed, then it is stable
- If  $(-1, 0)$  is on right side of the polar plot or  $(-1, 0)$  is enclosed by polar plot then it is unstable.
- If  $(-1, 0)$  is on the polar plot then it is marginally stable

In Fig. 2.5.1,  $(-1, 0)$  is on the polar plot so the system is marginally stable.

1.1.5. Plot the polar plot of

$$G(s) = \frac{1}{(s+1)(s+2)(s+3)}. \quad (1.1.11)$$

#### Solution:

The following python code generates the polar plot in Fig. 1.1.5

```
codes/ee18btech11033.py
```

$\therefore (-1, 0)$  is on the right side of the polar plot, the system is unstable.

1.1.6. Plot the polar plot of

$$G(s) = \frac{100(s+5)}{s(s+3)(s^2+4)}. \quad (1.1.12)$$

**Solution:** The following python code generates the polar plot in Fig. 1.1.6

```
codes/ee18btech11042.py
```

Since  $(-1, 0)$  is on the polar plot, the above system is marginally stable.

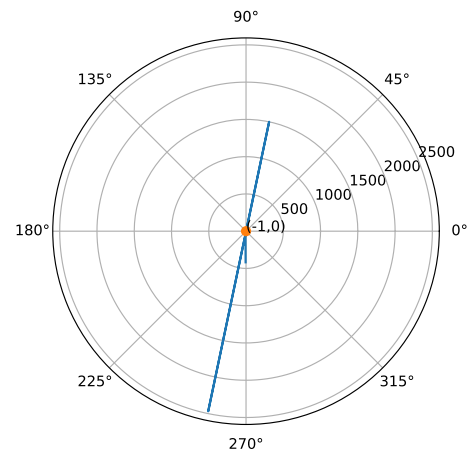


Fig. 1.1.6

## 1.2 Direct and Inverse Polar Plot

Sketch the direct polar plot for a unity feedback system with open loop transfer function

$$G(s) = \frac{1}{s(1+s)^2} \quad (1.2.1)$$

**Solution:** The polar plot is obtained by plotting  $(r, \phi)$

$$r = |H(j\omega)||G(j\omega)| \quad (1.2.2)$$

$$\phi = \angle H(j\omega)G(j\omega), 0 < \omega < \infty \quad (1.2.3)$$

The following code plots the polar plot in Fig. 1.2.1

```
codes/ee18btech11002/polarplot.py
```

Sketch the inverse polar plot for (1.2.1)



Fig. 1.2.1: Polar Plot

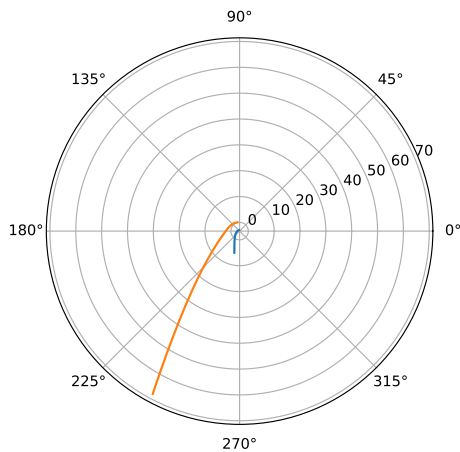


Fig. 1.2.2: Inverse Polar Plot

**Solution:** The above code plots the polar plot in Fig. 1.2.2 by plotting  $(\frac{1}{r}, -\phi)$

### 1.3 Bode Plot

1.3.1. Sketch the Bode Magnitude and Phase plot for the following system. Also compute the gain margin and the phase margin.

$$G(s) = \frac{10}{s(1 + 0.5s)(1 + .01s)} \quad (1.3.1)$$

**Solution:** The Bode magnitude and phase plot are available in Fig. 1.3.1 and generated by

codes/ee18btech11048.py

The pole-zero locations are available in Table 1.3.1.

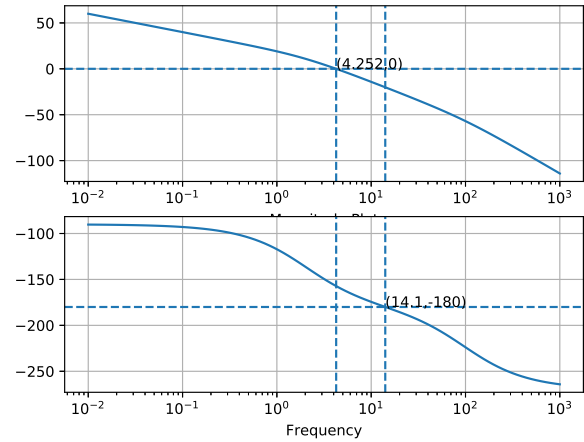


Fig. 1.3.1: Graphs

Zeros	Poles
-	0
	-2
	-100

TABLE 1.3.1: Zeros and Poles

The *Gain* and *Phase* of (1.3.2) are

$$|G(j\omega)| = \frac{100}{\omega \sqrt{(0.5\omega)^2 + 1} \sqrt{(0.01\omega)^2 + 1}} \quad (1.3.2)$$

$$\angle G(j\omega) = \tan^{-1}(0) - \tan^{-1}\left(\frac{\omega}{0}\right) - \tan^{-1}\left(\frac{\omega}{2}\right) - \tan^{-1}\left(\frac{\omega}{100}\right) \quad (1.3.3)$$

Hence,

$$|G(j\omega_{gc})| = 1 \quad (1.3.4)$$

$$\Rightarrow \omega_{gc} = 4.25 \quad (1.3.5)$$

$$\angle G(j\omega_{gc}) = -157.2 \quad (1.3.6)$$

$$\Rightarrow PM = 22.8 \quad (1.3.7)$$

Similarly,

$$\angle G(j\omega_{pc}) = -180^\circ \quad (1.3.8)$$

$$\Rightarrow \omega_{pc} = 14.1 \quad (1.3.9)$$

$$\Rightarrow -|G(j\omega_{pc})| = -20.2dB \quad (1.3.10)$$

$$\Rightarrow GM = 20.2dB \quad (1.3.11)$$

1.3.2. Plot the Bode magnitude and phase plots for

the following system

$$G(s) = \frac{75(1 + 0.2s)}{s(s^2 + 16s + 100)} \quad (1.3.12) \quad 1.3.3.$$

Also compute gain margin and phase margin .

**Solution:** From (1.3.12), we have

$$G(j\omega) = \frac{75(1 + 0.2j\omega)}{j\omega((j\omega)^2 + 16j\omega + 100)} \quad (1.3.13)$$

poles = 0 , -8-6j , -8+6j

zeros = -5

Gain and phase plots are shown in Fig. 1.3.2



Fig. 1.3.2: a

The following code plots Fig. 1.3.2

codes/ee18btech11049.py

Solving

$$\begin{aligned} |G(j\omega)| &= \frac{75 \sqrt{\omega^2 + 25}}{\omega \sqrt{(\omega + 6)^2 + 64} \sqrt{(\omega - 6)^2 + 64}} \\ &= 1, \end{aligned} \quad (1.3.14)$$

or from Fig. 1.3.2, the gain crossover frequency

$$\Rightarrow \omega_{gc} = 0.757 \quad (1.3.15)$$

$$\angle G(j\omega_{gc}) = -88.3 \quad (1.3.16)$$

$$\Rightarrow PM = 91.7 \quad (1.3.17)$$

**Solution:** From Fig. 1.3.2 ,we can say that phase never crosses  $-180^\circ$  . So , the gain margin is *infinite*. Which means we can add

any gain, and the equivalent closed loop system never becomes unstable.

Plot the Bode magnitude and phase plots for the following system

$$G(s) = \frac{Ks^2}{(1 + 0.2s)(1 + 0.02s)} \quad (1.3.18)$$

Also compute gain margin and phase margin .

**Solution:** Substituting  $s = j\omega$  in (3.6.1.1) and assuming  $K = 1$ ,

$$G(j\omega) = \frac{(j\omega)^2}{(1 + 0.2j\omega)(1 + 0.02j\omega)} \quad (1.3.19)$$

The corner frequencies are

$$\omega_{c1} = 1/0.2 = 5 \quad (1.3.20)$$

$$\omega_{c2} = 1/0.02 = 50 \quad (1.3.21)$$

$$\begin{aligned} 20 \log |G(j\omega)| &= 20 \log |(j\omega)^2| \\ &- 20 \log |(1 + 0.2j\omega)| - 20 \log |(1 + 0.02j\omega)| \end{aligned} \quad (1.3.22)$$

The various values of  $G(j\omega)$  are available in Table 3.6.1, in the increasing order of their corner frequencies also slope contributed by each term and the change in slope at the corner frequency. The phase

TERM	Corner Freq	Slope	Slope change
$(j\omega)^2$	--	+40	--
$\frac{1}{1+j0.2}$	$\omega_{c1} = \frac{1}{0.2}$	-20	40-20=20
$\frac{1}{1+j0.02}$	$\omega_{c2} = \frac{1}{0.02}$	-20	20-20=0

TABLE 1.3.2: Magnitude

$$\begin{aligned} \phi = \angle G(j\omega) &= 180^\circ \\ &- \tan^{-1}(0.2\omega) - \tan^{-1}(0.02\omega) \end{aligned} \quad (1.3.23)$$

The phase angle of  $G(j\omega)$  are calculated for various value of  $\omega$  in Table 1.3.3. The magnitude and phase plot are generated in Fig. 1.3.3 using the following python code

codes/es17btech11002.py

$\therefore$  the gain crossover frequency is 2 and the corresponding gain At  $\omega = 2$  is 13dB,

$$20 \log K = -13db \quad (1.3.24)$$

$$\Rightarrow K = 0.65 \quad (1.3.25)$$

$\omega$	$\tan^{-1}(0.2\omega)$	$\tan^{-1}(0.02\omega)$	$\phi = \angle G(j\omega)$
0.5	5.7	0.6	174
1	11.3	1.1	168
2	21.8	2.3	156
5	45	5.7	130
10	63.4	11.3	106
50	84.3	45	50

TABLE 1.3.3: Phase

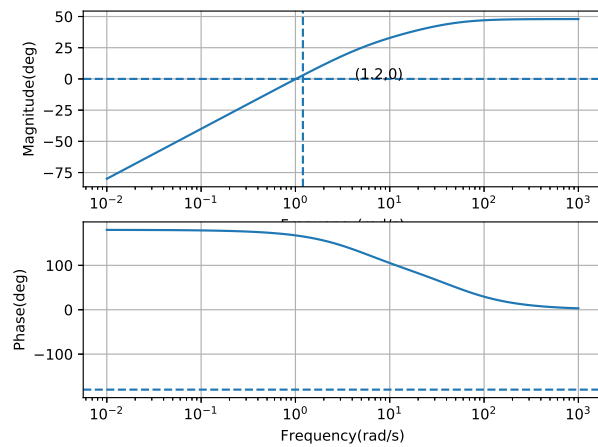


Fig. 1.3.3: Graphs

Solving (1.3.19) or from Fig. 1.3.3, the gain crossover frequency,

$$\omega_{gc} = 1.2 \quad (1.3.26)$$

$$\Rightarrow PM = 344.8 \quad (1.3.27)$$

From Fig. 1.3.3, we can say that phase never crosses  $-180^\circ$ . So, the gain margin is *infinite*. Which means we can add any gain, and the equivalent closed loop system never goes unstable.

1.3.4. Sketch the Bode magnitude and phase plots for

$$G(s) = \frac{(1 + 0.2s)(1 + 0.025s)}{s^3(1 + 0.005s)(1 + 0.001s)} \quad (1.3.28)$$

Also compute the gain margin and phase margin.

**Solution:**

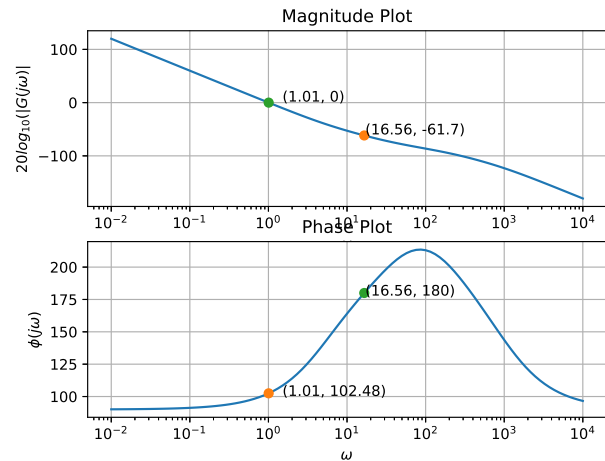


Fig. 1.3.4: Bode plot

From fig. 1.3.4,

$$\omega_{gc} = 16.55, \text{ Gain Margin} = -61.7\text{dB} \quad (1.3.29)$$

$$\omega_{pc} = 1, \text{ Phase Margin} = -77.52^\circ \quad (1.3.30)$$

The program for plotting bode plot and finding phase margin and gain margin -

codes/ee18btech11039.py

1.3.5. Plot the Bode magnitude and phase plots for the following system

$$G(s) = \frac{50(s + 3)(s + 5)}{s(s + 2)(s + 4)(s + 6)} \quad (1.3.31)$$

The magnitude and phase plot are as follows: Fig1.3.5

The python code to obtain the graphs and results:

codes/ee18btech11031.py

*Gain and Phase of Transfer Function*

$$G(j\omega) = \frac{50(j\omega + 3)(j\omega + 5)}{j\omega(j\omega + 2)(j\omega + 4)(j\omega + 6)} \quad (1.3.32)$$

Gain:

$$\frac{100 \sqrt{(\omega)^2 + 9} \sqrt{(\omega)^2 + 25}}{\omega \sqrt{(\omega)^2 + 4} \sqrt{(\omega)^2 + 16} \sqrt{(\omega)^2 + 36}} \quad (1.3.33)$$

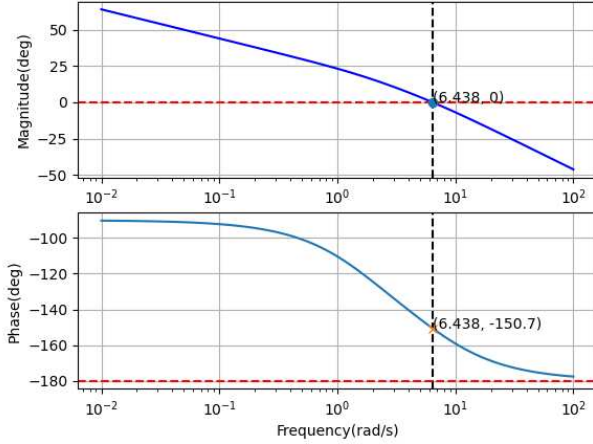


Fig. 1.3.5: Graphs

Phase:

$$\tan^{-1}(0) + \tan^{-1}\left(\frac{\omega}{3}\right) + \tan^{-1}\left(\frac{\omega}{5}\right) - \tan^{-1}\left(\frac{\omega}{0}\right) - \tan^{-1}\left(\frac{\omega}{2}\right) - \tan^{-1}\left(\frac{\omega}{4}\right) - \tan^{-1}\left(\frac{\omega}{6}\right) \quad (1.3.34)$$

$$PM = \angle G(j\omega_{gc}) + 180^\circ \quad (1.3.35)$$

$$\omega_{gc} = \text{Gain Crossover Frequency} \quad (1.3.36)$$

$$\text{At } \omega_{gc} |G(s)| = 1 \quad (1.3.37)$$

**Solution:**

$$\frac{100 \sqrt{(\omega_{gc})^2 + 9} \sqrt{(\omega_{gc})^2 + 25}}{\omega_{gc} \sqrt{(\omega_{gc})^2 + 4} \sqrt{(\omega_{gc})^2 + 16} \sqrt{(\omega_{gc})^2 + 36}} = 1 \quad (1.3.38)$$

Solving Eq. (1.3.38) or from Fig 1.3.5 :

$$\Rightarrow \omega_{gc} = 6.438 \quad (1.3.39)$$

$$\angle G(j\omega_{gc}) = -150.725 \quad (1.3.40)$$

$$\Rightarrow PM = 29.275 \quad (1.3.41)$$

$$GM = 0 - G(j\omega_{pc})db \quad (1.3.42)$$

$$\omega_{pc} = \text{Phase Crossover Frequency} \quad (1.3.43)$$

$$\text{At } \omega_{pc}, \angle G(s) = -180^\circ \quad (1.3.44)$$

From Fig 1.3.5, we can say that phase never crosses  $-180^\circ$ . So, the gain margin is *infinite*

and from the equation: 1.3.44,  $\omega_{pc}$  is non-existent.

1.3.6. Sketch the bode magnitude and phase plots for the closed loop (negative feedback) system given by:

$$G(s) = \frac{100(s+2)(s+4)}{s^2-3s+10} \quad (1.3.45)$$

$$H(s) = \frac{1}{s} \quad (1.3.46)$$

**Solution:** The system can be represented as:

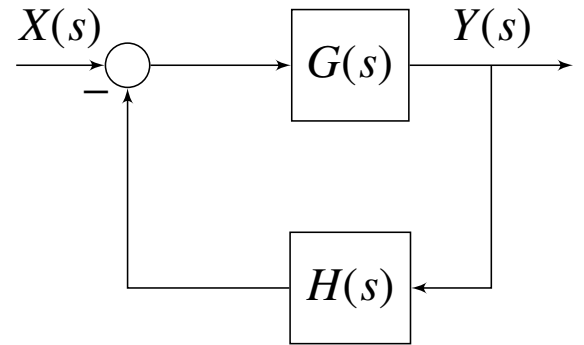


Fig. 1.3.6: Block diagram for the system

The closed loop transfer function of the system is given by:

$$G_m(s) = \frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s) \cdot H(s)} \quad (1.3.47)$$

$$= \frac{100s(s+2)(s+4)}{s^3 + 97s^2 + 610s + 800} \quad (1.3.48)$$

Evaluate at  $s = j\omega$ :

$$G_m(j\omega) = \frac{100j\omega(j\omega+2)(j\omega+4)}{(j\omega)^3 + 97(j\omega)^2 + 610(j\omega) + 800} \quad (1.3.49)$$

$$= \frac{-600\omega^2 + j(800\omega - 100\omega^3)}{800 - 97\omega^2 + j(610\omega - \omega^3)} \quad (1.3.50)$$

From (1.3.50):

$$|G_m(j\omega)| = \frac{\sqrt{(600\omega^2)^2 + (800\omega - 100\omega^3)^2}}{\sqrt{(800 - 97\omega^2)^2 + (610\omega - \omega^3)^2}} \quad (1.3.51)$$

$$\angle G_m(j\omega) = \tan^{-1}\left(\frac{\omega^2 - 8}{6\omega}\right) - \tan^{-1}\left(\frac{610\omega - \omega^3}{800 - 97\omega^2}\right) \quad (1.3.52)$$

The following code plots the bode magnitude and phase plots in Fig. 1.3.7:

```
codes/ee18btech11045/
ee18btech11045_bode1.py
```

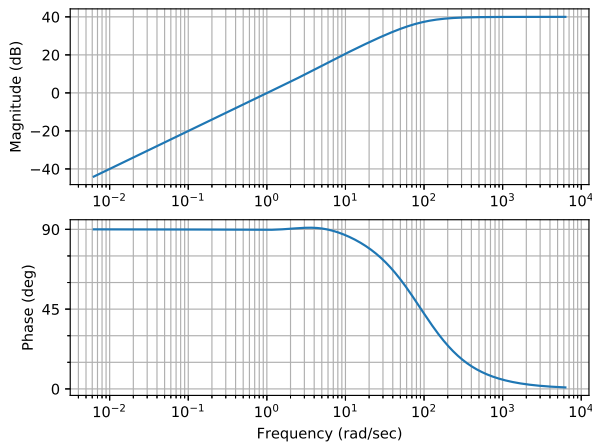


Fig. 1.3.7: Bode plot for  $G_m(j\omega)$

$$G(j\omega)H(j\omega) = \left(\frac{100(j\omega + 2)(j\omega + 4)}{(j\omega)^2 - 3j\omega + 10}\right)\left(\frac{1}{j\omega}\right) \quad (1.3.53)$$

$$= \frac{100(-\omega^2 + 8 + j6\omega)}{3\omega^2 + j(10\omega - \omega^3)} \quad (1.3.54)$$

Using (1.3.54)

$$|G(j\omega)H(j\omega)| = \frac{100\sqrt{(8 - \omega^2)^2 + (6\omega)^2}}{\sqrt{(3\omega^2)^2 + (10\omega - \omega^3)^2}} \quad (1.3.55)$$

$$\angle G(j\omega)H(j\omega) = \tan^{-1}\left(\frac{6\omega}{8 - \omega^2}\right) - \tan^{-1}\left(\frac{10 - \omega^2}{3\omega}\right) \quad (1.3.56)$$

At the phase crossover frequency  $\omega_{pc}$ :

$$|\angle G(j\omega)H(j\omega)| = 180 \quad (1.3.57)$$

$$\Rightarrow \tan^{-1}\left(\frac{6\omega_{pc}}{8 - \omega_{pc}^2}\right) - \tan^{-1}\left(\frac{10 - \omega_{pc}^2}{3\omega_{pc}}\right) = 180 \quad (1.3.58)$$

Solving the above equation:

$$\frac{6\omega_{pc}}{8 - \omega_{pc}^2} = \frac{10 - \omega_{pc}^2}{3\omega_{pc}} \quad (1.3.59)$$

$$\Rightarrow \omega_{pc} = 5.8 \text{ rad/sec} \quad (1.3.60)$$

$$|G(j\omega)H(j\omega)|_{\omega=\omega_{pc}} = 28.1 \text{ dB} \quad (1.3.61)$$

Gain Margin  $GM$  :

$$GM = 0 - |G(j\omega)H(j\omega)|_{\omega=\omega_{pc}} \text{ dB} \quad (1.3.62)$$

$$= -28.1 \text{ dB} \quad (1.3.63)$$

At the gain crossover frequency  $\omega_{gc}$ :

$$|G(j\omega)H(j\omega)|_{\omega=\omega_{gc}} = 1 \quad (1.3.64)$$

From (1.3.55),

$$10^4 \left( (8 - \omega^2)^2 + (6\omega)^2 \right) = 9\omega^4 + (10\omega - \omega^3)^2 \quad (1.3.65)$$

$$\Rightarrow \omega_{gc} = 100.15 \text{ rad/sec} \quad (1.3.66)$$

Substitute  $\omega_{gc}$  in (1.3.56):

$$\angle G(j\omega)H(j\omega)_{\omega=\omega_{gc}} = 265^\circ \quad (1.3.67)$$

Phase Margin  $PM$ :

$$PM = 180^\circ - \angle G(j\omega)H(j\omega)_{\omega=\omega_{gc}} \quad (1.3.68)$$

$$= 180^\circ - 265^\circ = -85^\circ \quad (1.3.69)$$

The following code is used to verify the gain and phase margins:

```
codes/ee18btech11045/
ee18btech11045_bode2.py
```

As both the Gain Margin (GM) and Phase Margin (PM) are found to be negative, the system is unstable.



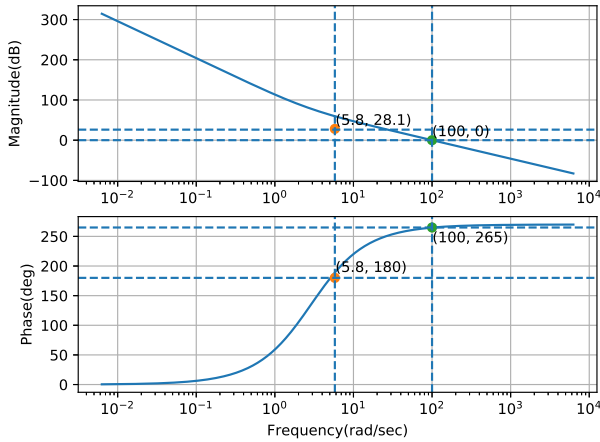


Fig. 1.3.8: Bode plot for  $G(j\omega)H(j\omega)$

### 1.4 Transient Response from Bode Plot

1.4.1. Consider the following transfer functions as open-loop transfer functions in two different unity feedback(negative) systems.

$$G(s) = \frac{50(s+3)(s+5)}{s(s+2)(s+4)(s+6)} \quad (1.4.1.1)$$

$$G(s) = \frac{75(1+0.2s)}{s(s^2+16s+100)} \quad (1.4.1.2)$$

Estimate transient response of these systems from their respective bode plots.

**Solution:**

a) The dominant pole approximation is used to characterize higher order systems because it is difficult to characterize and analyse systems with order greater than 3.

b) Consider a transfer function.

$$H(s) = K \frac{\alpha\beta}{(s+\alpha)(s+\beta)} \quad (1.4.1.3)$$

It has two poles  $-\alpha$  and  $-\beta$ . If the magnitude of  $\beta$  is very large compared to  $\alpha$  (typically if  $\frac{|\beta|}{|\alpha|} > 5$ ) we can approximate for the transfer function assuming  $s$  is sufficiently small compared to  $\beta$  as follows.

$$H(s) = K_2 \left( \frac{1}{s+\alpha} \right) \quad (1.4.1.4)$$

Note that the value of  $H(0)$  should be unchanged for the exact and approximate transfer functions. This is necessary to ensure

that the final value of the step response is unchanged.

$$\lim_{t \rightarrow \infty} y(t) = \lim_{s \rightarrow 0} sY(s) \quad (1.4.1.5)$$

$$\lim_{t \rightarrow \infty} y(t) = \lim_{s \rightarrow 0} sU(s)H(s) = H(0) \quad (1.4.1.6)$$

In order to achieve this we adjust the gain value of the approximated transfer function by equating  $H(0)$  values.

$$\Rightarrow H(s) = K \frac{\alpha}{(s+\alpha)} \quad (1.4.1.7)$$

- c) In terms of poles, the pole closer to the origin is considered as the dominating pole. As considered above, the magnitude of  $\alpha$  is small therefore the time constant  $\frac{1}{\alpha}$  will be high and reaches equilibrium slowly and vice versa in case of  $\beta$ . Therefore, this approximation assumes that the slowest part of the system dominates the response. The faster parts of the system are ignored.
- d) Complex poles along with real poles : In this case the dominant pole(s) can be determined by comparing only the real parts. If the real part of the complex conjugate poles is greater in magnitude than the real pole, the two complex conjugate poles are the dominant poles.
- e) If the transfer function has zeros along with poles, we have to consider the fact that pole and zero cancel out each other if their respective magnitudes are comparable.

1.4.2. Find the closed loop transfer function of a negative unity feedback system given open loop transfer function  $G(s)$ .

**Solution:**

$$T(s) = \frac{G(s)}{1+G(s)} \quad (1.4.2.1)$$

1.4.3. Find the approximate transfer function for the open loop transfer function.

$$G(s) = \frac{50(s+3)(s+5)}{s(s+2)(s+4)(s+6)} \quad (1.4.3.1)$$

**Solution:** Using equation (1.4.2.1)

$$T(s) = \frac{50(s^2+8s+15)}{s^4+12s^3+94s^2+448s+750} \quad (1.4.3.2)$$

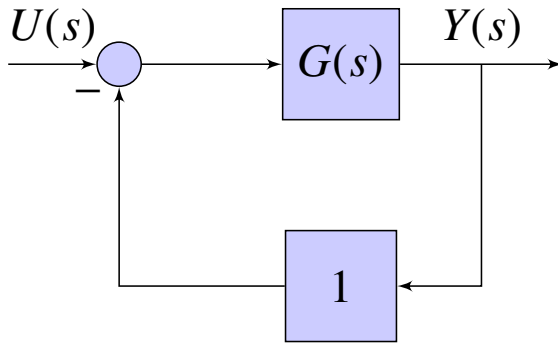


Fig. 1.4.1

The following code gives the poles and zeros of the transfer function.

```
codes/ee18btech11047/ee18btech11047_1.py
```

Poles	Zeros
$p_1 = -5.14$	$z_1 = -5$
$p_2 = -3.09$	$z_2 = -3$
$p_3 = -1.87 + 6.60j$	
$p_4 = -1.87 - 6.60j$	

TABLE 1.4.1

The real poles ( $p_1, p_2$ ) and zeros ( $z_1, z_2$ ) cancel out each other as mentioned above. So, we are left with the two conjugate poles. The approximated transfer function is

$$T_1(s) = \frac{K_1}{(s - p_3)(s - p_4)} \quad (1.4.3.3)$$

$$T(0) = T_1(0) \quad (1.4.3.4)$$

$$\Rightarrow K_1 = p_3 p_4 \quad (1.4.3.5)$$

$$T_1(s) = \frac{47.09}{s^2 + 3.74s + 47.09} \quad (1.4.3.6)$$

1.4.4. Estimate the transient response of the obtained second order system using the respective bode plot.

**Solution:** The following code generates the bode plot for open loop transfer function.

```
codes/ee18btech11047/ee18btech11047_2.py
```

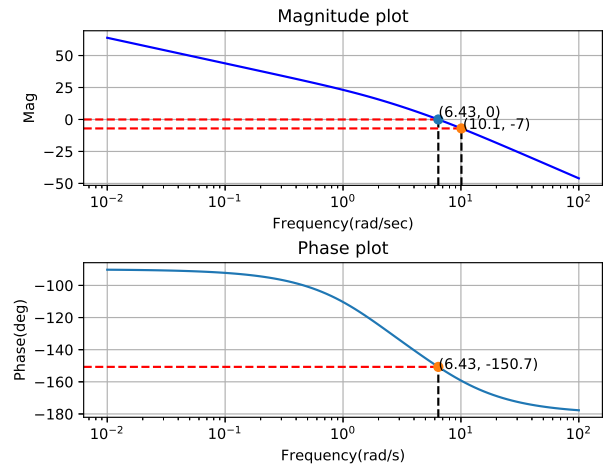


Fig. 1.4.2: 1

The phase margin is

$$\phi_M = 180^\circ - 150.7^\circ \Rightarrow \phi_M = 29.3^\circ \quad (1.4.4.1)$$

The closed-loop bandwidth,  $\omega_{BW}$  (-3 dB frequency), equals the frequency at which the open-loop magnitude response is around -7 dB.

$$\omega_{BW} = 10.1 \text{ rad/sec} \quad (1.4.4.2)$$

**Damping ratio:** Substitute  $\phi_M$  value from equation (1.4.4.1)

$$\phi_M = \tan^{-1} \left( \frac{2\zeta}{\sqrt{-2\zeta^2 + \sqrt{1 + 4\zeta^2}}} \right) \quad (1.4.4.3)$$

$$\Rightarrow \zeta = 0.34 \quad (1.4.4.4)$$

**Settling time:** Substitute  $\omega_{BW}$  value from equation (1.4.4.2) and  $\zeta$

$$T_s = \frac{4}{\omega_{BW}\zeta} \sqrt{(1 - 2\zeta^2) + \sqrt{4\zeta^4 - 4\zeta^2 + 2}} \quad (1.4.4.5)$$

$$\Rightarrow T_s = 1.65 \text{ sec} \quad (1.4.4.6)$$

**Peak time:**

$$T_p = \frac{\pi\zeta T_s}{4\sqrt{1 - \zeta^2}} \quad (1.4.4.7)$$

$$\Rightarrow T_p = 0.325 \text{ sec} \quad (1.4.4.8)$$

**Percent overshoot:**

$$\%OS = 100e^{-\left(\frac{\zeta\pi}{\sqrt{1-\zeta^2}}\right)} \quad (1.4.4.9)$$

$$\Rightarrow \%OS = 35.1\% \quad (1.4.4.10)$$

Note that the answers will be approximate due to the dominant pole approximation. The following code generates the step response of the system.

codes/ee18btech11047/ee18btech11047\_3.py

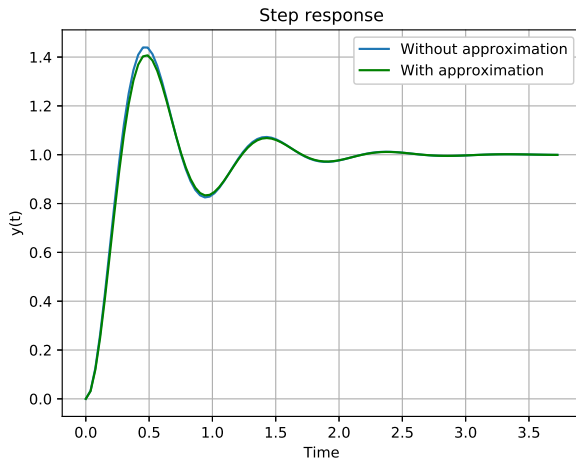


Fig. 1.4.3: 2

1.4.5. Find the approximate transfer function for the open loop transfer function

$$G(s) = \frac{75(1 + 0.2s)}{s(s^2 + 16s + 100)} \quad (1.4.5.1)$$

**Solution:** Using equation (1.4.2.1)

$$T(s) = \frac{75(1 + 0.2s)}{s^3 + 16s^2 + 115s + 75} \quad (1.4.5.2)$$

The following code gives the poles and zeros of the transfer function.

codes/ee18btech11047/ee18btech11047\_4.py

Poles	Zeros
$p_1 = -0.72$	$z_1 = -5$
$p_2 = -7.64 + 6.75j$	
$p_3 = -7.63 - 6.75j$	

TABLE 1.4.2

The real part of the complex conjugate poles is comparable with the zero  $z_1$  of the transfer

function. So, they cancel out each other. The approximated transfer function is of first order.

$$T_2(s) = \frac{K_2}{(s - p_1)} \quad (1.4.5.3)$$

$$T(0) = T_2(s) \quad (1.4.5.4)$$

$$\Rightarrow K_2 = p_1 \quad (1.4.5.5)$$

$$T_2(s) = \frac{0.72}{s + 0.72} \quad (1.4.5.6)$$

1.4.6. Estimate the transient response of the obtained first order system.

**Solution: Time constant:** The time constant is the time taken by the step response to rise to 63% of its final value.

$$T = \frac{1}{|pole|} \quad (1.4.6.1)$$

$$T = \frac{1}{0.72} = 1.388 \text{ sec} \quad (1.4.6.2)$$

**Rise time:** Rise time is the time for the waveform to go from 0.1 to 0.9 of its final value.

$$T_r = \frac{2.2}{|pole|} \quad (1.4.6.3)$$

$$T_r = \frac{2.2}{0.72} = 3.05 \text{ sec} \quad (1.4.6.4)$$

**Settling time:** Settling time is defined as the time for the response to reach and stay within, 2% of its final value.

$$T_s = \frac{4}{|pole|} \quad (1.4.6.5)$$

$$T_s = \frac{4}{0.72} = 5.55 \text{ sec} \quad (1.4.6.6)$$

The following code plots the step response of the system.

codes/ee18btech11047/ee18btech11047\_5.py

### 1.5 Parameter Estimation from Bode Plot

Obtain the transfer function from the frequency response data given below. **Solution:** The following code generates the plot for the given data.

codes/ee18btech11006/ee18btech11006\_1.py

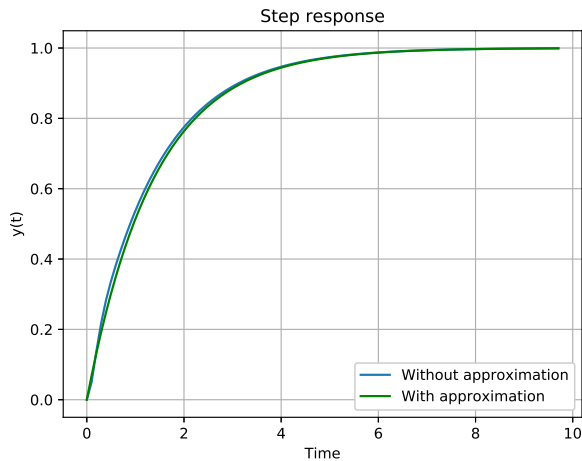


Fig. 1.4.4

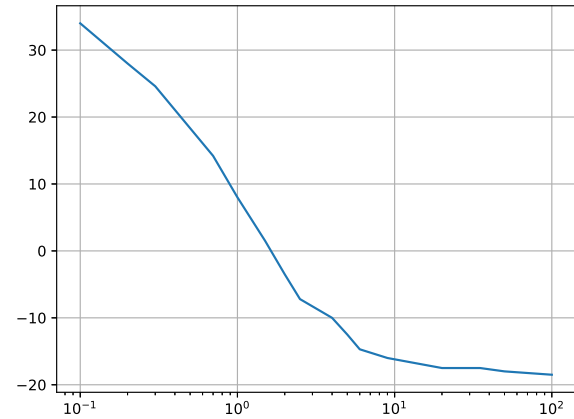


Fig. 1.5.1: 1

Freq(rad/sec)	Mag(dB)
0.1	34
0.2	28
0.3	24.6
0.7	14.2
1.0	8
1.5	1.5
2.0	-3.5
2.5	-7.2
4.0	-10
5.0	-10
6.0	-14.7
9.0	-16.0
20	-17.5
35	-17.5
50	-18
100	-18.5

TABLE 1.5.1

Consider the Transfer function

$$H(s) = \frac{k(s + z_1)(s + z_2)}{(s + p_1)(s + p_2)} \quad (1.5.1)$$

Let's draw the magnitude bode plot.

$$20\log_{10}|H(s)| = 20\log_{10}|s + z_1| + 20\log_{10}|s + z_2| - 20\log_{10}|s + p_1| - 20\log_{10}|s + p_2| + 20\log_{10}k \quad (1.5.2)$$

Now, for the given set of points finding slopes

corresponding to every two points and identifying the points at which the slope change occurs by 20dB would give us the poles and zeros respectively. The slope initially is -20dB/decade i.e. pole at 0.1. We can observe that the slope decreases approximately by 20dB/dec at the point 0.7 and increases further by 20dB/dec at 2.5 and 6 giving a slope of almost 0 later on.

$$Poles = 0.1, 0.7 \quad (1.5.3)$$

$$Zeros = 2.5, 6 \quad (1.5.4)$$

Lets plot the magnitude bode plot considering these poles and zeros. The following code generates the plot for the transfer function

$$H(s) = \frac{(s + 2.5)(s + 6)}{(s + 0.1)(s + 0.7)} \quad (1.5.5)$$

```
codes/ee18btech11006/ee18btech11006_2.py
```

Now the gain,

$$K = \frac{H(\omega)(given)}{H(\omega)(calculated)} \quad (1.5.6)$$

This value would vary for different frequencies. Considering the average value,  $K = 0.1778$ . The following code generates the plot for the transfer function

$$H(s) = \frac{0.1778(s + 2.5)(s + 6)}{(s + 0.1)(s + 0.7)} \quad (1.5.7)$$

```
codes/ee18btech11006/ee18btech11006_3.py
```

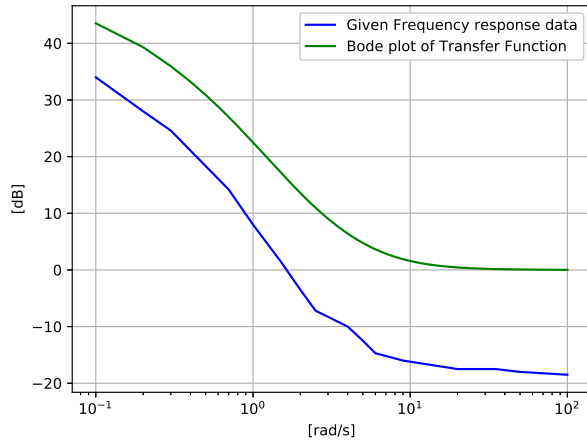


Fig. 1.5.2: 2

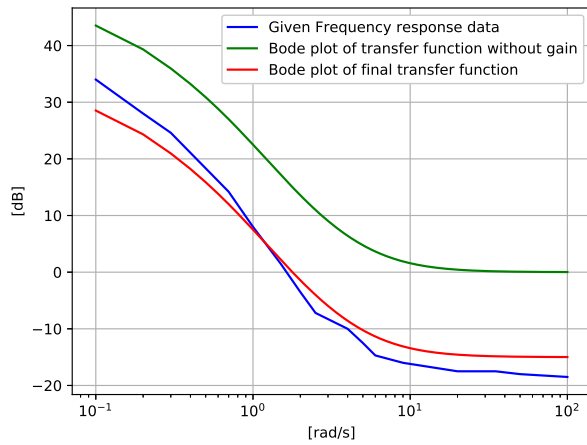


Fig. 1.5.3: 3

Thus, our Transfer function is

$$H(s) = \frac{0.1778(s + 2.5)(s + 6)}{(s + 0.1)(s + 0.7)} \quad (1.5.8)$$

## 2 STABILITY IN FREQUENCY DOMAIN

### 2.1 Nyquist Criterion

2.1.1. Using Nyquist Criterion, find out whether this system is stable or not.

$$G(s) = \frac{50}{s(s + 3)(s + 6)} \quad (2.1.1.1)$$

$$H(s) = 1. \quad (2.1.1.2)$$

Nyquist Stability:

$$N = Z - P \quad (2.1.1.3)$$

where Z is number of unstable poles of closed loop transfer function, P is number of unstable poles of open loop transfer function. and N is number of clockwise encirclement of  $-1 + j0$ .  
Closed Loop Transfer Function:

$$T(s) = \frac{50}{s^3 + 9s^2 + 18s + 50} \quad (2.1.1.4)$$

$$Z = 0, P = 0 \quad (2.1.1.5)$$

$$N = 0 \quad (2.1.1.6)$$

Thus, system is stable, which can be verified from Nyquist Plot in Fig 2.1.1

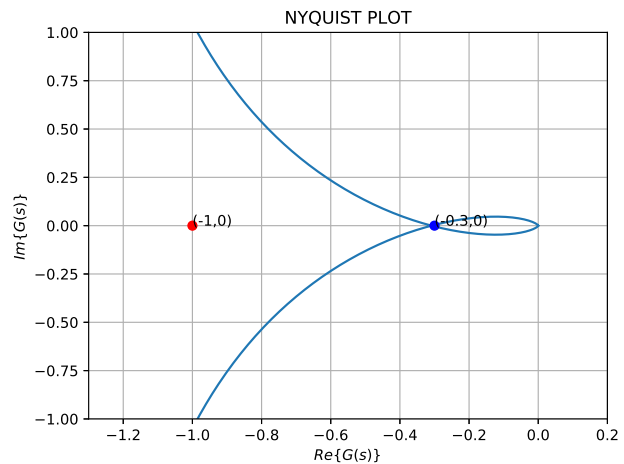


Fig. 2.1.1

The following code generates Fig 2.1.1

```
codes/ee18btech11050_1.py
```

2.1.2. Using Nyquist criterion find the range of K for which closed loop system is stable.

$$G(s) = \frac{K}{s(s + 6)} \quad (2.1.2.1)$$

$$H(s) = \frac{1}{s + 9} \quad (2.1.2.2)$$

**Solution:** The system flow can be described as,

$$G_1(s) = \frac{1}{s(s + 6)}. \quad (2.1.2.3)$$

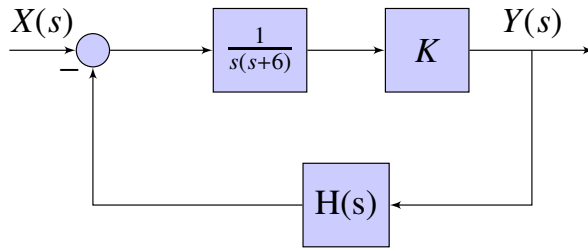


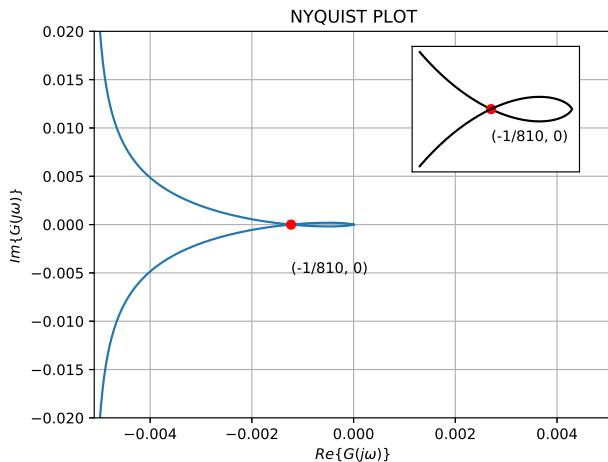
Fig. 2.1.2

For Nyquist plot,

$$\text{Im}\{G_1(j\omega)H(j\omega)\} = \frac{-(54 - \omega^2)}{(\omega)(\omega^2 + 56)(\omega^2 + 81)} \quad (2.1.2.4)$$

$$\text{Re}\{G_1(j\omega)H(j\omega)\} = \frac{-15\omega}{(\omega)(\omega^2 + 56)(\omega^2 + 81)} \quad (2.1.2.5)$$

From (2.2.1.4) and (2.2.1.5)

Fig. 2.1.3: Nyquist plot for  $G_1(s)H(s)$ 

### Nyquist Stability Criterion:

$$N = Z - P \quad (2.1.2.6)$$

where  $Z$  is # unstable poles of closed loop transfer function,  $P$  is # unstable poles of open loop transfer function and  $N$  is # clockwise encirclement of  $(-1/K, 0)$ .

For stable system,

$$Z = 0 \quad (2.1.2.7)$$

From (2.2.1.2) and (2.2.1.3),

$$P = 0 \quad (2.1.2.8)$$

$$\Rightarrow N = 0 \quad (2.1.2.9)$$

Since, there is a zero at origin, an infinite radius half circle will enclose the right hand side of end points of the Nyquist plot. So for (2.2.1.9),

$$\Rightarrow \frac{-1}{K} < \frac{-1}{810} \Rightarrow K < 810 \quad (2.1.2.10)$$

And also,

$$K > 0 \quad (2.1.2.11)$$

$$\Rightarrow 0 < K < 810 \quad (2.1.2.12)$$

The following python code generates Fig. 2.2.2

codes/ee18btech11028\_1.py

2.1.3. Using Nyquist criterion, find out whether the system below is stable or not

$$G(s) = \frac{41}{s^2(s+3)} \quad (2.1.3.1)$$

$$H(s) = (s+4) \quad (2.1.3.2)$$

**Solution:** According to the Nyquist criteria the number of unstable closed-loop poles ( $Z$ ) is equal to the number of unstable open-loop poles ( $P$ ) plus the number of clockwise encirclements ( $N$ ) of the point  $(-1, j0)$  of the Nyquist plot of  $G(s)H(s)$ , i.e

$$Z = N + P \quad (2.1.3.3)$$

Open loop transfer function :

$$G(s)H(s) = \frac{41(s+4)}{s^2(s+3)} \quad (2.1.3.4)$$

Closed loop transfer function:

$$T(s) = \frac{G(s)}{1 + G(s)H(s)} = \frac{41}{s^3 + 3s^2 + 41s + 164} \quad (2.1.3.5)$$

In Fig.2.1.4 it can be seen that there is a clockwise encirclement around  $(-1+0j)$ . As the open loop transfer function has zero pole of multiplicity 2, therefore it should be assumed

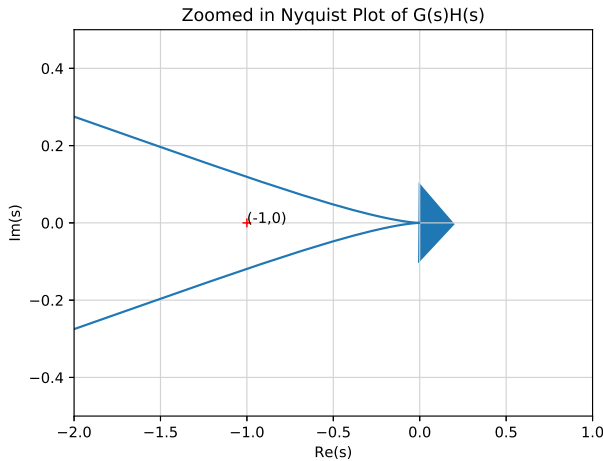


Fig. 2.1.4

that the phasor travels 2 times clock-wise along a semicircle of infinite radius.

$$N=2, P=0$$

$$\Rightarrow Z = 2 \quad (2.1.3.6)$$

Therefore, The system  $T(s)$  is unstable as it has two poles on the right side of the  $s$  plane. The following code generates the nyquist plot

codes/ee18btech11041.py

2.1.4. Using Nyquist criterion, find out whether the following is stable or not.

$$G(s) = \frac{100(s+5)}{s(s^2+4)(s+3)} \quad (2.1.4.1)$$

$$H(s) = 1 \quad (2.1.4.2)$$

**Solution:** Open loop transfer function (oltf):

$$G(s)H(s) = \frac{100(s+5)}{s(s^2+4)(s+3)} \quad (2.1.4.3)$$

Closed loop transfer function (cltf):

$$\frac{G(s)}{1 + G(s)H(s)} \quad (2.1.4.4)$$

Nyquist Stability Criterion can be expressed as:

$$Z = N + P \quad (2.1.4.5)$$

where:

- $Z$  = zeros of  $1 + G(s)H(s)$  in RHS of  $s$ -plane
- $N$  = number of encirclement of critical point  $1+0j$  in the clockwise direction.

- $P$  = poles of  $G(s)H(s)$  in RHS of  $s$ -plane.
- The pole-zero plot of equation (2.1.4.3) is fig. (2.1.5) which gives  $P = 0$ .

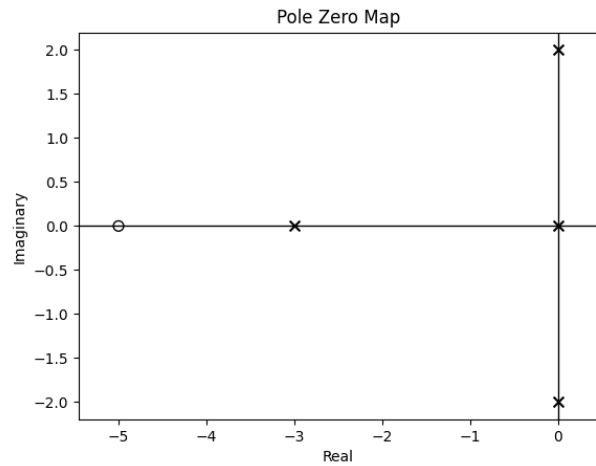


Fig. 2.1.5

- Since the multiplicity of zero pole is 1 (fig.2.1.5), it should be assumed that the phasor travels one time clockwise along a semicircle of infinite radius.
- Same applies for poles at  $2j$  and  $-2j$ .
- Fig. (2.1.6) shows a schematic, the dotted lines are infinite radii semi-circles.

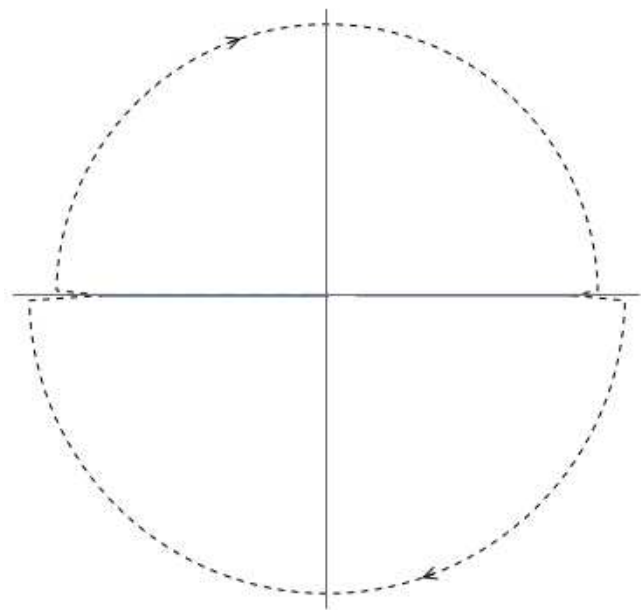


Fig. 2.1.6

- The point  $-1+0j$  is not encircled by the nyquist plot (fig. 2.1.8).

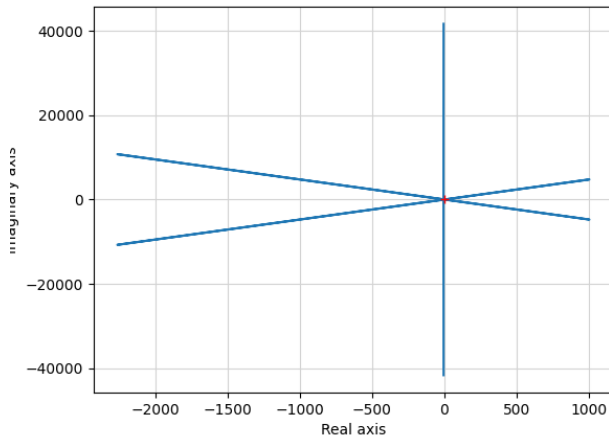
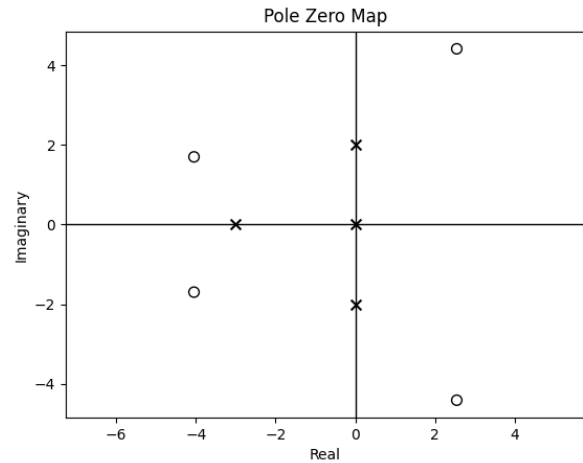
Fig. 2.1.7: Nyquist plot of  $G(s)H(s)$ 

Fig. 2.1.9

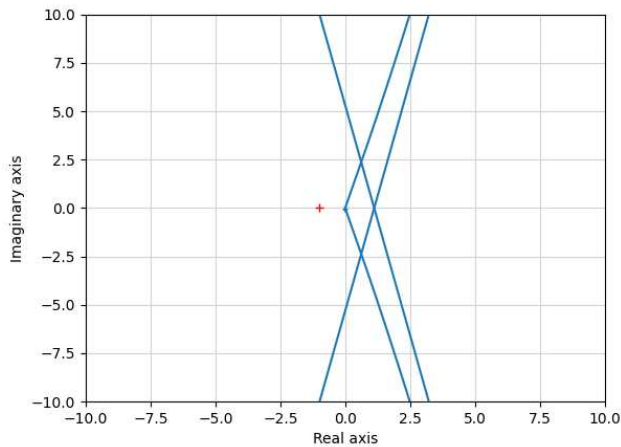


Fig. 2.1.8: Zoomed in

**no poles on RHS** of  $s$ -plane.

The following code plots the pole zero plot and the nyquist plot.

```
codes/ee18btech11025.py
```

2.1.5. Using Nyquist criterion, find out whether the system below is stable or not.

$$G(s) = \frac{20}{s(s+1)}, H(s) = \frac{s+3}{s+4} \quad (2.1.5.1)$$

**Solution:** The following python code generates the Nyquist plot in Fig.2.1.10.

```
codes/ee18btech11011.py
```

From the nyquist plot (fig. 2.1.8),  $-1+0j$  is not encircled by the plot. So from above points, the only clockwise encirclement is considered due to the mentioned poles (zero,  $2j$  and  $-2j$ ) with multiplicity of 1.

Therefore,  **$N=2$**

Substituting values of  $P = 0$  and  $N = 2$  in equation (2.1.4.5):

$$\Rightarrow Z = 2 \quad (2.1.4.6)$$

This is verified using pole zero plot of  $1+G(s)H(s)$  (fig. 2.1.9). Two zeroes on RHS of  $s$ -plane i.e.  $Z=2$ .

Since  $Z \neq 0$ , **the closed loop system is unstable.**

**The open loop system is stable** as there are

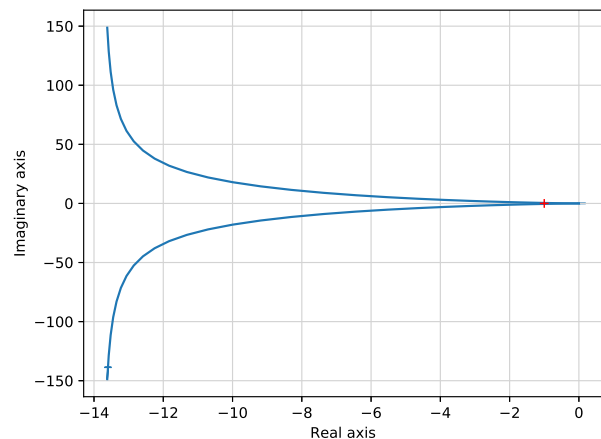


Fig. 2.1.10: Nyquist Plot



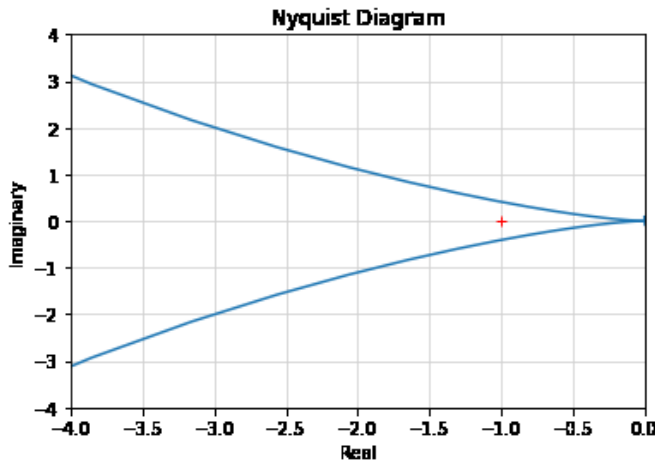


Fig. 2.1.11: Zoomed image

The closed loop system the transfer function will be =

$$\frac{G(s)}{1 + G(s)H(s)} \quad (2.1.5.2)$$

$$\Rightarrow G(s)H(s) = \frac{20(s+3)}{s(s+1)(s+4)} \quad (2.1.5.3)$$

So it has 3 open-loop poles 0, -1 and -4, therefore  $P=0$ . Further we know that  $N = Z - P$ , now we know  $Z = \text{Poles of } \frac{G(s)}{1+G(s)H(s)}$  in right half of  $s$  plane. To find the poles we can use the following Routh Hurwitz python code. Using this we get  $Z = 0$ .

```
codes/ee18btech11011_1.py
```

$$P = 0, Z = 0 \quad (2.1.5.4)$$

$$\Rightarrow N = 0 \quad (2.1.5.5)$$

This can also be seen from the Fig. 2.1.10 that the encirclement is counter-clockwise not clockwise. Hence the system is stable.

2.1.6. Using Nyquist criterion, find out the range of  $K$  for which the closed loop system will be stable.

$$G(s) = \frac{K(s+2)(s+4)}{s^2-3s+10}; H(s) = \frac{1}{s} \quad (2.1.6.1)$$

**Solution:** The system flow can be described by Fig. 2.1.12 From (2.1.6.1),

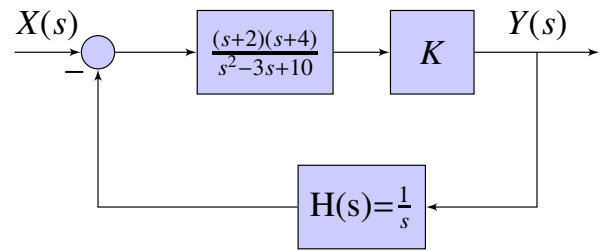


Fig. 2.1.12

$$G(s)H(s) = \frac{K(s+2)(s+4)}{s(s^2-3s+10)} \quad (2.1.6.2)$$

$$G(j\omega)H(j\omega) = \frac{K(j\omega+2)(j\omega+4)}{j\omega((10-\omega^2)-3j\omega)} \quad (2.1.6.3)$$

$$\text{Re}\{G(j\omega)H(j\omega)\} = \frac{K(84\omega^2 - 9\omega^4)}{\omega^6 - 11\omega^4 + 100\omega^2} \quad (2.1.6.4)$$

$$\text{Im}\{G(j\omega)H(j\omega)\} = \frac{K(-\omega^5 + 36\omega^3 - 80\omega)}{\omega^6 - 11\omega^4 + 100\omega^2} \quad (2.1.6.5)$$

The Nyquist plot is a graph of  $\text{Re}\{G(j\omega)H(j\omega)\}$  vs  $\text{Im}\{G(j\omega)H(j\omega)\}$ . Let's take  $K=1$  and draw the nyquist plot.

The following python code generates the Nyquist plot in Fig. 2.1.13

```
codes/ee18btech11016.py
```

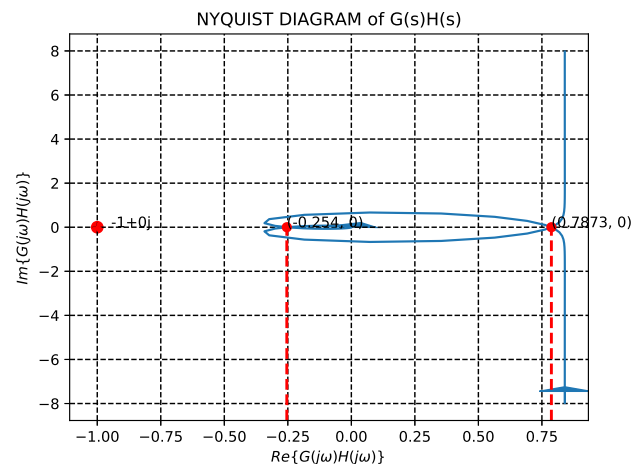


Fig. 2.1.13

Note that this nyquist plot is plotted when  $K=1$ .

## 2.2 Nyquist Criterion

**Nyquist criterion**-For the stable system :

$$Z = P + N = 0, \quad (2.1.6.6)$$

Variable	Description
Z	Poles of $\frac{G(s)}{1+G(s)H(s)}$ in right half of s plane
N	No of encirclements of $G(s)H(s)$ about $-1+j0$ in the Nyquist plot
P	Poles of $G(s)H(s)$ in right half of s plane

TABLE 2.1.1

Since from the equation (2.1.6.2),  $P = 2$  as the number of poles on right hand side of s-plane is equal to 2 .So, for Z to be equal to 0 ,we have to choose the range of K such that N should be equal to -2.

If we consider the Nyquist plot with K term i.e. of equation (2.1.6.2) , then it will cut x-axis at  $x = -0.254K$  ,  $x = 0$  and at  $x = 0.7873K$  (as we have nyquist graph at  $K=1$ , now we just need to multiply the intersected coordinates on x-axis by K).

So, we have to make sure that  $(-1 + j0)$  should be included in between  $x = -0.254K$  to  $x = 0$ , because then only  $N = -2$  (as the no. of encirclements are 2 in anticlockwise direction in this case so  $N=-2$ )

$$-0.254K < -1 < 0 \quad (2.1.6.7)$$

So,

$$K > \frac{1}{0.254} \quad (2.1.6.8)$$

i.e.

$$K > 3.937 \quad (2.1.6.9)$$

Hence  $K > 3.937$  ensures that the system is stable as no. of poles on the right hand side of s-plane (in this case) is 0.

2.2.1. Using Nyquist criterion find the range of K for which closed loop system is stable.

$$G(s) = \frac{K}{s(s+6)} \quad (2.2.1.1)$$

$$H(s) = \frac{1}{s+9} \quad (2.2.1.2)$$

**Solution:** The system flow can be described as,

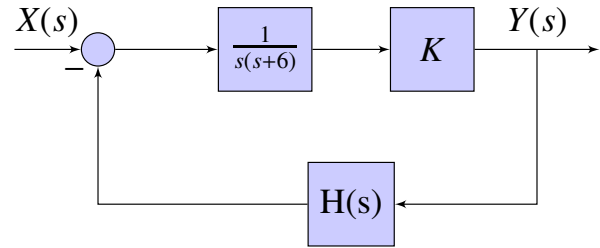


Fig. 2.2.1

$$G_1(s) = \frac{1}{s(s+6)}. \quad (2.2.1.3)$$

For Nyquist plot,

$$\text{Im} \{G_1(j\omega)H(j\omega)\} = \frac{-(54 - \omega^2)}{(\omega)(\omega^2 + 56)(\omega^2 + 81)} \quad (2.2.1.4)$$

$$\text{Re} \{G_1(j\omega)H(j\omega)\} = \frac{-15\omega}{(\omega)(\omega^2 + 56)(\omega^2 + 81)} \quad (2.2.1.5)$$

From (2.2.1.4) and (2.2.1.5)

**Nyquist Stability Criterion:**

$$N = Z - P \quad (2.2.1.6)$$

where Z is # unstable poles of closed loop transfer function, P is # unstable poles of open loop transfer function and N is # clockwise encirclement of  $(-1/K, 0)$ .

For stable system,

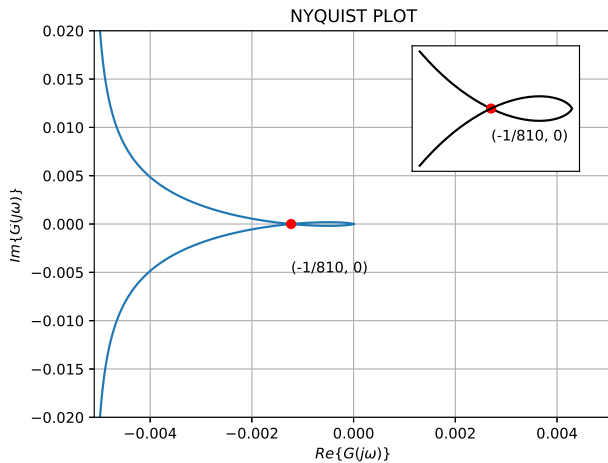
$$Z = 0 \quad (2.2.1.7)$$

From (2.2.1.2) and (2.2.1.3),

$$P = 0 \quad (2.2.1.8)$$

$$\Rightarrow N = 0 \quad (2.2.1.9)$$

Since, there is a zero at origin, an infinite radius

Fig. 2.2.2: Nyquist plot for  $G_1(s)H(s)$ 

half circle will enclose the right hand side of end points of the Nyquist plot. So for (2.2.1.9),

$$\Rightarrow \frac{-1}{K} < \frac{-1}{810} \Rightarrow K < 810 \quad (2.2.1.10)$$

And also,

$$K > 0 \quad (2.2.1.11)$$

$$\Rightarrow 0 < K < 810 \quad (2.2.1.12)$$

The following python code generates Fig. 2.2.2

```
codes/ee18btech11028_1.py
```

2.2.2. Using Nyquist criterion, find out the range of  $K$  for which the closed loop system will be stable.

$$G(s) = \frac{K}{(s+1)(s+3)}$$

$$H(s) = \frac{1}{(s+5)(s+7)} \quad (2.2.2.1)$$

The system flow can be described by Fig. 2.2.3 From (2.2.2.1),

$$L(s) = G(s)H(s)$$

$$= \frac{K}{(s+1)(s+3)(s+5)(s+7)} \quad (2.2.2.2)$$

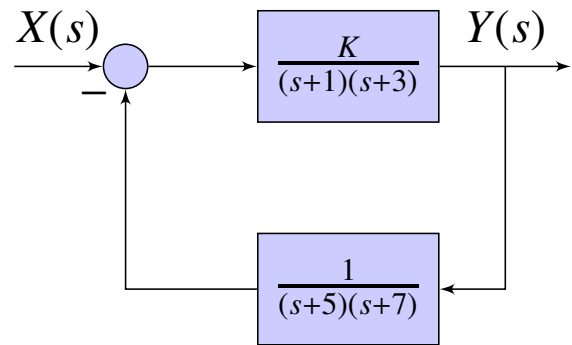


Fig. 2.2.3

$$L(j\omega) = G(j\omega)H(j\omega)$$

$$= \frac{K}{(j\omega + 1)(j\omega + 3)(j\omega + 5)(j\omega + 7)} \quad (2.2.2.3)$$

The Nyquist plot is a graph of  $\text{Re}\{L(j\omega)\}$  vs  $\text{Im}\{L(j\omega)\}$ . Let's take  $K=1$  and draw the nyquist plot.

The following python code generates the Nyquist plot.

```
/codes/es17btech11015.py
```

The Fig. 2.2.4 shows the Nyquist plot for  $K = 1$

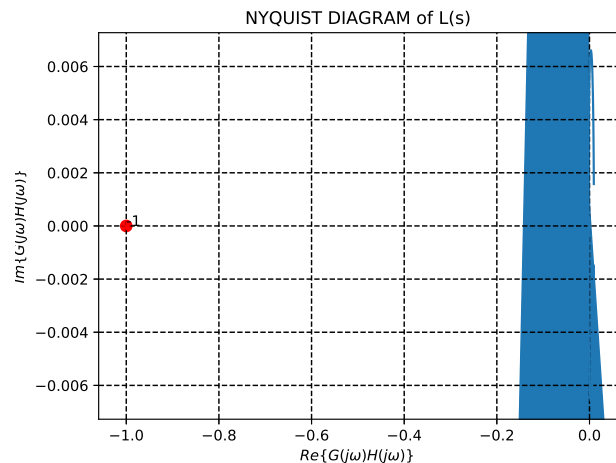


Fig. 2.2.4

**Nyquist criterion**-For the stable system :

$$Z = P + N = 0, \quad (2.2.2.4)$$

where,

$Z$  = Poles of  $\frac{G(s)}{1+G(s)H(s)}$  in right half of  $s$  plane

P = Poles of  $G(s)H(s)$  in right half of s plane

N = No. of encirclements of  $G(s)H(s)$  about -1 in the Nyquist plot

Since from the equation (2.2.2.2),  $P = 0$

So, for Z to be equal to 0, we have to choose the range of K such that N is equal to 0. From the figure 2.2.4, we can observe that the plot is not cutting the x-axis. If we consider the Nyquist plot with K term even then the plot won't cut the x-axis.

So,  $N = 0$  irrespective of K.

Therefore, the system is stable for

$$-\infty < K < \infty \quad (2.2.2.5)$$

### 2.3 M and N Circles

2.3.1. What are Constant M and N circles and how can we determine closed loop frequency response using M and N circles?

**Solution:** M circles are called constant magnitude Loci and N circles are called as constant phase angle Loci. These are helpful in determining the closed-loop frequency response of unity negative feedback systems.

**Constant-Magnitude Loci (M-circle):** Let  $G(j\omega)$  be complex quantity it can be written as

$$G(j\omega) = X + jY \quad (2.3.1.1)$$

where X, Y are real quantities. Let M be magnitude of closed loop transfer function.

$$M = \left| \frac{X + jY}{1 + X + jY} \right| \quad (2.3.1.2)$$

$$M^2 = \frac{X^2 + Y^2}{(1 + X)^2 + Y^2} \quad (2.3.1.3)$$

Hence,

$$X^2(1 - M^2) - 2M^2X - M^2 + (1 - M^2)Y^2 = 0 \quad (2.3.1.4)$$

If  $M = 1$ , then from Equation (2.3.1.4), we obtain  $X = -\frac{1}{2}$ . This is the equation of a straight line parallel to the Y axis and passing through the point  $(-\frac{1}{2}, 0)$ .

If  $M \neq 1$  Equation (2.3.1.4) can be written as

$$X^2 + \frac{2M^2}{M^2 - 1}X + \frac{M^2}{M^2 - 1} + Y^2 = 0 \quad (2.3.1.5)$$

Simplifying,

$$\left(X + \frac{M^2}{M^2 - 1}\right)^2 + Y^2 = \frac{M^2}{(M^2 - 1)^2} \quad (2.3.1.6)$$

Equation (2.3.1.6) is the equation of a circle with center  $(-\frac{M^2}{M^2 - 1}, 0)$  and radius  $|\frac{M}{M^2 - 1}|$

Thus the intersection of Nyquist plot with M circle at a frequency( $\omega$ ) results as the magnitude of closed loop transfer function as M at frequency ( $\omega$ )

**Constant-Phase-Angle Loci (N Circles):**

Finding Phase angle  $\alpha$  from (2.3.1.3) we get,

$$\alpha = \tan^{-1}\left(\frac{Y}{X}\right) - \tan^{-1}\left(\frac{Y}{1 + X}\right) \quad (2.3.1.7)$$

$$\text{Let } \tan \alpha = N \quad (2.3.1.8)$$

$$N = \tan\left(\tan^{-1}\left(\frac{Y}{X}\right) - \tan^{-1}\left(\frac{Y}{1 + X}\right)\right) \quad (2.3.1.9)$$

Simplifying,

$$N = \frac{Y}{X^2 + X + Y^2} \quad (2.3.1.10)$$

Further Simplifying..

$$\left(X + \frac{1}{2}\right)^2 + \left(Y - \frac{1}{2N}\right)^2 = \frac{1}{4} + \frac{1}{(2N)^2} \quad (2.3.1.11)$$

Equation (2.3.1.11) is the equation of a circle with center at  $(-\frac{1}{2}, \frac{1}{2N})$  and radius  $\sqrt{\frac{1}{4} + \frac{1}{(2N)^2}}$

Thus the intersection of Nyquist plot with N circle at a frequency( $\omega$ ) results as the phase of closed loop transfer function as  $\tan^{-1}(N)$  at frequency ( $\omega$ )

For unity Feedback system given below, obtain closed loop frequency response using constant M and N circles.

$$G(s) = \frac{50(s + 3)}{s(s + 2)(s + 4)} \quad (2.3.1.12)$$

**Solution:** The following code plots Fig. 2.3.1

codes/ee18btech11017\_code1.py

The following code finds intersection of M

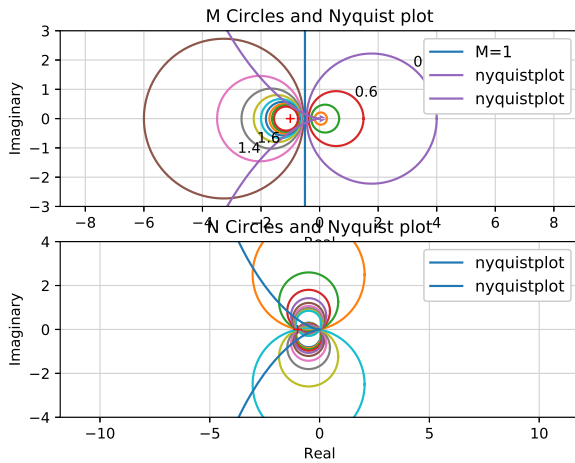


Fig. 2.3.1

and N circles with Nyquist plot at different frequencies

codes/ee18btech11017\_code2.py

The points M and frequencies are listed in Table 2.3.1

M in dB	M	$\omega$
5.15	1.81	5.08
7.64	2.41	6.34
6.48	2.11	7.58
-0.81	0.91	9.86
-10.17	0.31	14.33
-40	0.01	57.91

TABLE 2.3.1

The points M and frequencies are listed in Table 2.3.2

$\alpha$	N	$\omega$
-38.65	-0.80	5.42
-66.50	-2.30	6.40
-78.60	-5.00	6.72
-101.50	4.90	7.32
-158.19	0.4	11.68
-174.28	0.1	46.01

TABLE 2.3.2

The constant N locus for given value of  $\alpha$  is not the entire circle but only an arc. This

is because tangent of angle remains same if  $+180^\circ$  or  $-180^\circ$  is added to the angle.

The following code plots Fig. 2.3.2

codes/ee18btech11017\_code3.py

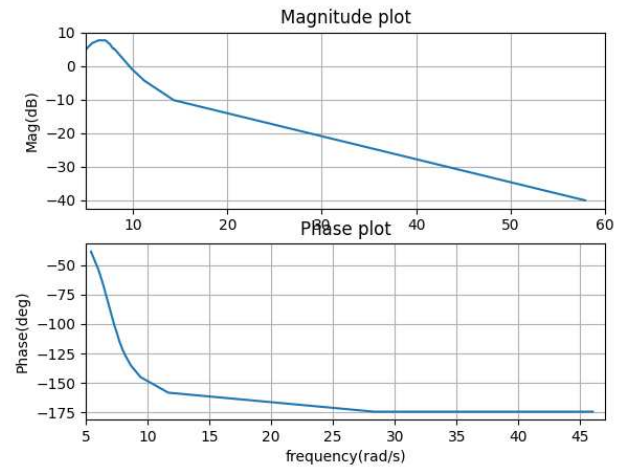


Fig. 2.3.2

The following code plots Fig. 2.3.3

codes/ee18btech11017\_code4.py

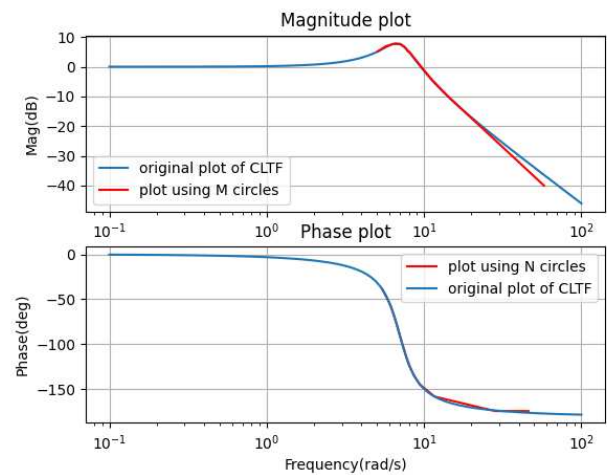


Fig. 2.3.3

## 2.4 Nyquist and Routh-Hurwitz

2.4.1. Find the range of k such that given characteristic equation

$$s(s^3 + 2s^2 + s + 1) + k(s^2 + s + 1) = 0 \quad (2.4.1.1)$$

is stable.

**Solution:** The General form of characteristic equation :

$$1 + G(s)H(s) = 0 \quad (2.4.1.2)$$

2.4.2. We draw nyquist plot for open loop transfer function, which is  $G(s)H(s)$ . When system is marginally stable nyquist plot ( $(G(s)H(s))$ ) passes through  $(-1,0)$ , then  $1+G(s)H(s)$  nyquist plot passes through  $(0,0)$ . We will make real and imaginary part of characteristic equation to 0. So, that we get  $k$  for system to be marginally stable. For the system to be stable, the range of  $k$  becomes any value greater than  $k$  minimum.

$$\text{Realpart} = \omega^4 - \omega^2(k+1) + k = 0 \quad (2.4.2.1)$$

$$\text{Imaginarypart} = -\omega^3 + \omega(\omega+1) = 0 \quad (2.4.2.2)$$

By equating real and imaginary to 0 .We get,

$$k = 0 \quad (2.4.2.3)$$

So, we got minimum value of  $k$  is 0 for system to be stable. Then the range of  $k$  is

$$0 < k < \infty \quad (2.4.2.4)$$

2.4.3. For a nyquist plot, no. of clock wise encirclement's around the point  $(-1,0)$  for a open loop transfer function gives the total no. right hand side zeros plus total no. of right hand side poles, which gives us a idea about stability of system.

2.4.4. Nyquist plot for different values of  $k$ .

In plot, we can see at  $k=0$ , the plot passes through  $(-1,0)$  and at  $k=1$  no. of encirclements about  $(-1,0)$  is 0 which implies system is stable as no. of right hand side zeros (positive values) are 0 and also verifies our above result of  $k$  range.

Code for Nyquist plot

```
codes/ee18btech11042_1.py
```

2.4.5. Verify using Routh hurwitz criterion

**Solution:** Routh -hurwitz criterion says system is marginally when no. of sign changes is 0 in matrix and any row of matrix is completely 0. From this, we get minimum value of  $k$  for system to be stable

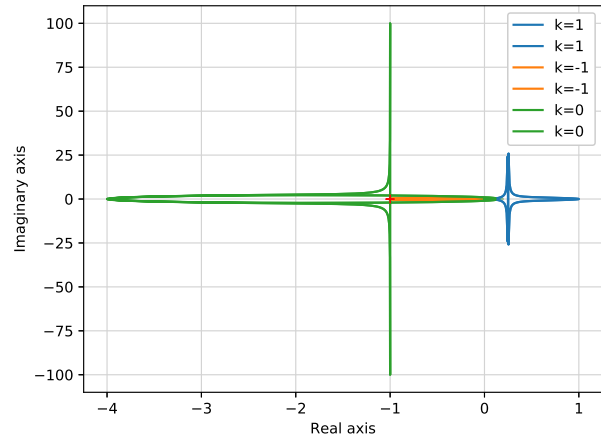


Fig. 2.4.1

$$s^4 + 2s^3 + s^2(k+1) + s(k+1) + k = 0 \quad (2.4.5.1)$$

$$\begin{vmatrix} s^4 & 1 & k+1 & k \\ s^3 & 2 & k+1 & 0 \\ s^2 & \frac{k+1}{2} & k & 0 \\ s^1 & \frac{(k-1)^2}{2} & 0 & 0 \\ s^0 & k & 0 & 0 \end{vmatrix}$$

2.4.6. For the system to be stable, all values of that matrix should be greater than or equal to 0. So, minimum value of  $k$  is,

$$k = 0 \quad (2.4.6.1)$$

The range of  $k$  system to be stable

$$0 < k < \infty \quad (2.4.6.2)$$

2.4.7. Verify it using following routh -hurwitz code.

```
codes/ee18btech11042_2.py
```

## 2.5 Nyquist and Routh-Hurwitz

2.5.1. In the block diagram Fig.2.5.1

$$G(s) = \frac{K}{(s+4)(s+5)} \quad (2.5.1.1)$$

2.5.2. Find the range of  $K$  for stability by Nyquist criterion

**Solution:**

The open loop transfer function from Fig.2.5.2

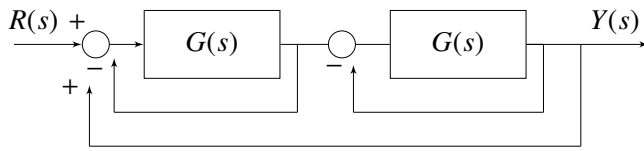


Fig. 2.5.1

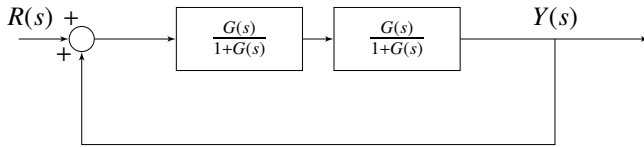


Fig. 2.5.2

$$T(s) = \left( \frac{\frac{K}{(s+4)(s+5)}}{1 + \frac{K}{(s+4)(s+5)}} \right)^2 \quad (2.5.2.1)$$

$$T(j\omega) = \left( \frac{\frac{K}{(j\omega+4)(j\omega+5)}}{1 + \frac{K}{(j\omega+4)(j\omega+5)}} \right)^2 \quad (2.5.2.2)$$

- Since it is connected in positive feedback the transfer function cuts at (1, j0)

$$\Rightarrow \operatorname{Re}\{T(j\omega)\} = 1 \quad (2.5.2.3)$$

$$\Rightarrow \operatorname{Im}\{T(j\omega)\} = 0 \quad (2.5.2.4)$$

$$\left( \frac{\frac{K}{(j\omega+4)(j\omega+5)}}{1 + \frac{K}{(j\omega+4)(j\omega+5)}} \right)^2 = 1 + j0 \quad (2.5.2.5)$$

$$(j\omega + 4)(j\omega + 5) + 2K = 0 \quad (2.5.2.6)$$

$$-\omega^2 + 9j\omega + 20 + 2K = 0 \quad (2.5.2.7)$$

From (2.5.2.4)

$$20 + 2K = 0 \quad (2.5.2.8)$$

$$\Rightarrow K = -10 \quad (2.5.2.9)$$

to be stable is

$$K_{min} > -10 \quad (2.5.2.10)$$

The range of K for which the system is stable is

$$-10 < K < \infty \quad (2.5.2.11)$$

2.5.3. From the table.2.5.1, Stability criterion for K is N+P=Z

K	P	N	Z	Description
-10	0	0	0	System is marginally stable
-9	0	0	0	System is stable
-11	0	1	1	System is unstable

TABLE 2.5.1

2.5.4. Verify the Nyquist plots by

codes/ee18btech11029\_1.py

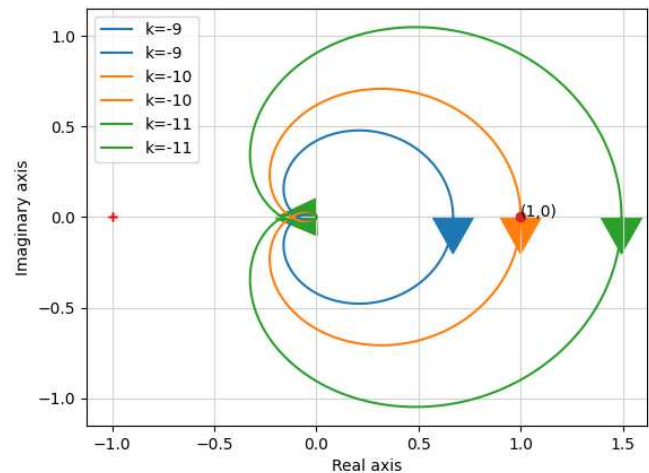


Fig. 2.5.3: Nyquist Plot

The minimum value of stability for the system 2.5.5. Verify the result using Routh-Hurwitz criterion

**Solution:** The characteristic equation is

$$1 - T(s) = 0 \quad (2.5.5.1)$$

$$1 - \left( \frac{\frac{K}{(s+4)(s+5)}}{1 + \frac{K}{(s+4)(s+5)}} \right)^2 = 0 \quad (2.5.5.2)$$

$$1 + 2 \left( \frac{K}{(s+4)(s+5)} \right) = 0 \quad (2.5.5.3)$$

$$s^2 + 9s + 20 + 2K = 0 \quad (2.5.5.4)$$

$$\begin{vmatrix} s^2 & 1 & 20 + 2K \\ s^1 & 9 & 0 \\ s^0 & 20 + 2K & 0 \end{vmatrix} \quad (2.5.5.5)$$

For a system to be stable it should not have any sign changes

$$20 + 2K > 0 \quad (2.5.5.6)$$

This is valid for all positive values of K but the minimum value of K is

$$K > -10 \quad (2.5.5.7)$$

So the range of K for stability is

$$-10 < K < \infty \quad (2.5.5.8)$$

2.5.6. Verify the result by

codes/ee18btech11029\_2.py

## 2.6 Nyquist

Consider the system shown in Fig. 2.6.1 below. Sketch the nyquist plot of the system when

- 1)  $G_c(s) = 1$
- 2)  $G_c(s) = 1 + \frac{1}{s}$

and determine the maximum value of K for stability. Take

$$G(s) = \frac{K}{s(1+s)(1+4s)} \quad (2.6.1)$$

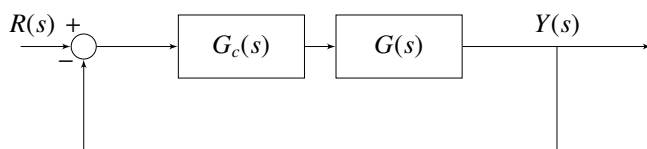


Fig. 2.6.1

**Solution:** For  $G_c(s) = 1$ ,

The open loop transfer function is

$$G_c(s)G(s) = \frac{K}{s(1+s)(1+4s)} \quad (2.6.2)$$

$$G_c(j\omega)G(j\omega) = \frac{K}{j\omega(1+j\omega)(1+4j\omega)} \quad (2.6.3)$$

$$= \frac{K}{j\omega(1-4\omega^2+5j\omega)} \quad (2.6.4)$$

$$= \frac{K(-5\omega - j(1-4\omega^2))}{\omega((1-4\omega^2)^2 + 25\omega^2)} \quad (2.6.5)$$

The maximum K for stability is where the nyquist plot of open loop transfer function cuts the coordinate  $(-1, j0)$

$$\Rightarrow \text{Re}\{G(j\omega)G_c(j\omega)\} = -1 \quad (2.6.6)$$

$$\Rightarrow \text{Im}\{G(j\omega)G_c(j\omega)\} = 0 \quad (2.6.7)$$

$$\Rightarrow \text{Re}\{G(j\omega)G_c(j\omega)\} = \frac{-5K\omega}{\omega((1-4\omega^2)^2 + 25\omega^2)} \quad (2.6.8)$$

$$\Rightarrow \text{Im}\{G(j\omega)G_c(j\omega)\} = \frac{-K(1-4\omega^2)}{\omega((1-4\omega^2)^2 + 25\omega^2)} \quad (2.6.9)$$

From (2.6.9) and (2.6.7)

$$1 - 4\omega^2 = 0 \Rightarrow \omega = \frac{1}{2} \quad (2.6.10)$$

From (2.6.8), (2.6.6) and substituting  $\omega = \frac{1}{2}$

$$\frac{-5K(\frac{1}{2})}{(\frac{1}{2})(\frac{25}{4})} = -1 \Rightarrow K = \frac{5}{4} = 1.25 \quad (2.6.11)$$

For  $K < 0$  the system with negative feedback is unstable the range of K is

$$0 < K < \frac{5}{4} \quad (2.6.12)$$

Sketching the Nyquist plot for  $G(s)G_c(s)$  in Fig. 2.6.2 The following code gives the nyquist plot

codes/ee18btech11034/ee18btech11034\_1.py

Stability Criterion for K

$$N + P = Z \quad (2.6.13)$$



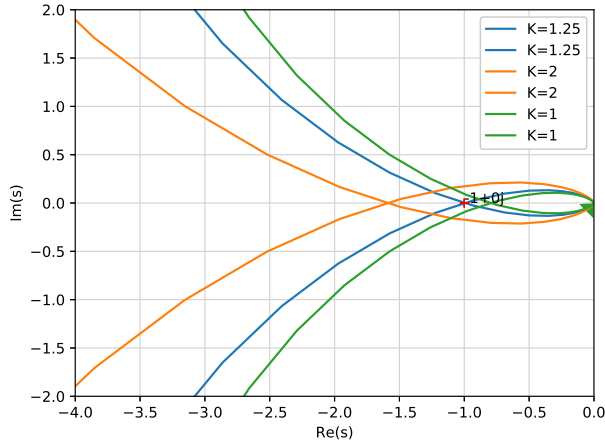


Fig. 2.6.2

K	P	N	Z	Description
1.25	0	0	0	System is marginally stable
2	0	1	1	System is unstable
1	0	0	0	System is stable

TABLE 2.6.1

From the Fig.2.6.2

$$K_{max} = \frac{5}{4} \quad (2.6.14)$$

**Solution:** For  $G_c(s) = \frac{1+s}{s}$ ,  
the open loop transfer function is

$$G_c(s)G(s) = \frac{K(s+1)}{s^2(1+s)(1+4s)} \quad (2.6.15)$$

$$G_c(s)G(s) = \frac{K}{s^2(1+4s)} \quad (2.6.16)$$

$$G_c(j\omega)G(j\omega) = \frac{K}{(j\omega)^2(1+4j\omega)} \quad (2.6.17)$$

$$= \frac{-K}{\omega^2(1-4j\omega)} = \frac{-K}{1+16\omega^2} \quad (2.6.18)$$

From (2.6.7)

$$\Rightarrow \text{Im}\{G(j\omega)G_c(j\omega)\} = \frac{4K}{\omega(1+16\omega^2)} = 0 \quad (2.6.19)$$

This is possible when

$$K = 0 \quad (2.6.20)$$

The system is unstable for both

$$K < 0 \quad (2.6.21)$$

$$K > 0 \quad (2.6.22)$$

Sketching the Nyquist plot for  $G(s)G_c(s)$  in Fig. 2.6.3 The following code gives the nyquist plot

codes/ee18btech11034/ee18btech11034\_2.py

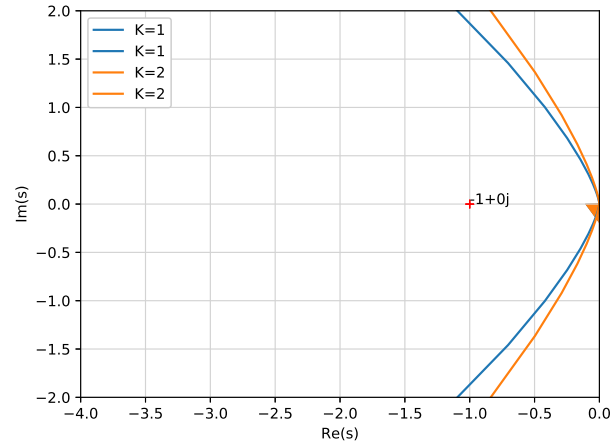


Fig. 2.6.3

From (2.6.13)

K	P	N	Z	Description
1	0	1	1	System is unstable
2	0	1	1	System is unstable

TABLE 2.6.2

From (2.6.20)  $K_{max}$  must be 0 which is not possible. Hence the system is unstable for all real K

## 2.7 Nyquist

Sketch the Nyquist plot for a closed loop system having open-loop transfer function

$$G(s)H(s) = \frac{2e^{-s\tau}}{s(1+s)(1+0.5s)} \quad (2.7.1)$$

Determine the maximum value of  $\tau$  for the system to be stable.

**Solution:** From (2.7.1),

$$\Rightarrow \operatorname{Re}\{G(j\omega)H(j\omega)\} = -4 \left[ \frac{3\omega^2 \cos(\omega\tau) - (\omega^3 - 2\omega) \sin(\omega\tau)}{(3\omega^2)^2 + (\omega^3 - 2\omega)^2} \right] \quad (2.7.2)$$

$$\Rightarrow \operatorname{Im}\{G(j\omega)H(j\omega)\} = 4 \left[ \frac{(\omega^3 - 2\omega) \cos(\omega\tau) + 3\omega^2 \sin(\omega\tau)}{(3\omega^2)^2 + (\omega^3 - 2\omega)^2} \right] \quad (2.7.3)$$

Determining the stability of closed loop transfer function using Nyquist stability Criterion.

$$Z = P + N \quad (2.7.4)$$

Poles of open loop transfer function are on left half of s-plane. Therefore,  $P = 0$

To ensure that the system is stable  $N$  should be 0  
For maximum value of  $\tau$  for stability, the nyquist plot cuts the real axis at  $-1+j0$ .

$$G(s)H(s) = -1 + j0 \quad (2.7.5)$$

$$\operatorname{Im}\{G(j\omega)H(j\omega)\} = 0 \quad (2.7.6)$$

$$\operatorname{Re}\{G(j\omega)H(j\omega)\} = -1 \quad (2.7.7)$$

From (2.7.3) and (2.7.6)

$$\Rightarrow \tan(\omega\tau) = \frac{-(\omega^3 - 2\omega)}{3\omega^2} \quad (2.7.8)$$

From (2.7.2) and (2.7.7) and substituting  $\tan(\omega\tau) = \frac{-(\omega^3 - 2\omega)}{3\omega^2}$

$$\Rightarrow \omega^6 + 5\omega^4 + 4\omega^2 - 16 = 0 \quad (2.7.9)$$

Solving (2.7.9) graphically.

Python code for the above plot is

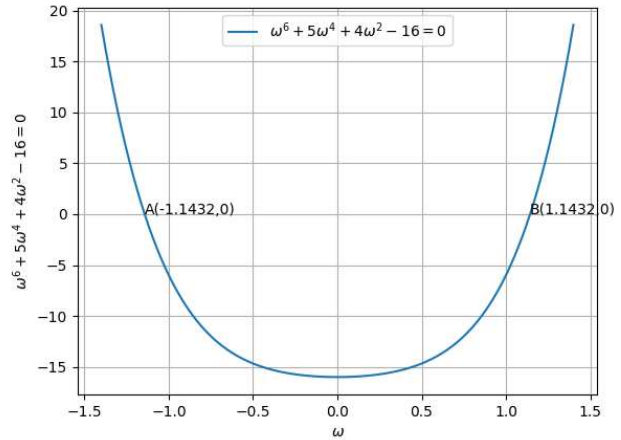


Fig. 2.7.1

codes/ee18btech11035\_1.py

$\omega = 1.1432, -1.1432$  (As,  $\omega$  is positive)  
Therefore,  $\omega = 1.1432$

Substituting  $\omega$  in (2.7.8)

$$\tan(1.1432\tau) = 0.2021 \quad (2.7.10)$$

$$\tau = 0.1744 \quad (2.7.11)$$

The following python code generates the Nyquist plot.

codes/ee18btech11035\_2.py

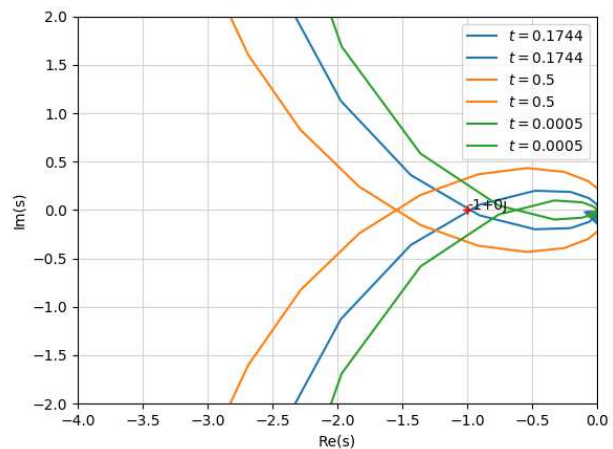


Fig. 2.7.2: Nyquist plot for variable  $\tau$

From the above figure (2.7.2)  $\tau \leq 0.1744$  for a stable system.

$\tau$	P	N	Z	Description
0.1744	0	1	1	System is Marginally stable
0.5	0	0	0	System is unstable
0.0005	0	0	0	System is stable

TABLE 2.7.1

Therefore,  $\tau_{max} = 0.1744$

### 3 DESIGN IN FREQUENCY DOMAIN

#### 3.1

#### 3.2 Lead Compensator

3.1. For a unity feedback system shown in 3.2.1,  $\frac{10}{s(s+1)}$ . Design a lead compensator such that the phase margin of the system is  $45^\circ$  and appropriate steady state error is less than or equal to  $\frac{1}{15}$  units of the final output value. Further the gain crossover frequency of the system must be less than 7.5rad/sec.

3.2. For the control system shown in 3.2.1 write the steady state output for step input.

**Solution:**

$$\lim_{t \rightarrow \infty} y(t) = \lim_{s \rightarrow 0} sY(s) \quad (3.2.1)$$

$$\lim_{s \rightarrow 0} sY(s) = \lim_{s \rightarrow 0} \frac{sR(s)G(s)}{1 + G(s)} \quad (3.2.2)$$

$$\lim_{s \rightarrow 0} sY(s) = \lim_{s \rightarrow 0} \frac{G(s)}{1 + G(s)} \quad (3.2.3)$$

3.3. What do you mean by steady state error and write the expression for steady state error for control system shown in 3.2.1 considering step input.

**Solution:** Steady-state error is the difference between the input and the output for a prescribed test input as time tends to infinity.

$$e_{ss} = \lim_{s \rightarrow 0} \frac{1}{1 + G(s)} \quad (3.3.1)$$

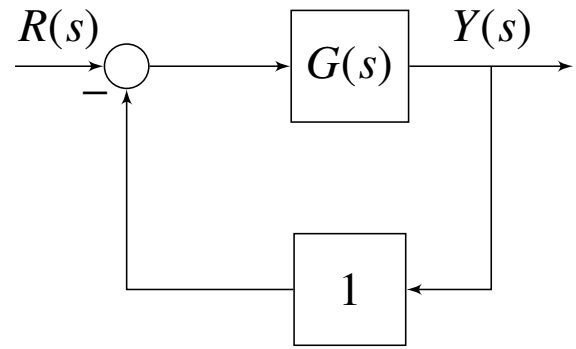


Fig. 3.2.1

3.4. Write the general expression for the transfer function of a phase lead compensator.

**Solution:**

$$G_c(s) = K_{comp} \frac{(1 + \alpha T s)}{(1 + T s)} \quad (3.4.1)$$

3.2.2 shows the compensated control system.

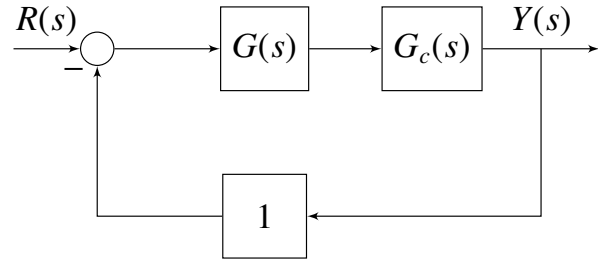


Fig. 3.2.2

3.5. Calculate the steady state output value and steady state error for the control system shown in 3.2.1, where  $G(s) = \frac{10}{s(s+1)}$ . Consider the input to be unit step.

**Solution:**

**Steady state value:**

$$\lim_{t \rightarrow \infty} y(t) = \lim_{s \rightarrow 0} \frac{10}{10 + s(s+1)} \quad (3.5.1)$$

$$\lim_{t \rightarrow \infty} y(t) = 1 \quad (3.5.2)$$

**Steady state error:**

$$e_{ss} = \lim_{s \rightarrow 0} \frac{s(s+1)}{10 + s(s+1)} \quad (3.5.3)$$

$$e_{ss} = 0 \quad (3.5.4)$$

3.6. Choose a value of  $K_{comp}$  which satisfies the steady state error condition.

**Solution:** As the steady state error for unit step response is always zero, any value of

$K_{comp}$  satisfies the steady state error condition in compensated system. For simplicity let us choose  $K_{comp} = 1$ .

- 3.7. Calculate phase margin and gain cross over frequency of open-loop transfer function  $G(S)$ .

**Solution:**

**Gain cross over frequency:**

$$G(j\omega) = \frac{10}{j\omega(j\omega + 1)} \quad (3.7.1)$$

$$|G(j\omega)| = \frac{10}{\sqrt{\omega^4 + \omega^2}} \quad (3.7.2)$$

$$\frac{10}{\sqrt{\omega^4 + \omega^2}} = 1 \quad (3.7.3)$$

$$\omega_{gc} = 3.084 \quad (3.7.4)$$

**Phase Margin:**

$$\phi = -90^\circ - \tan^{-1}(\omega) \quad (3.7.5)$$

$$pm = 180^\circ - 90^\circ - \tan^{-1}(\omega_{gc}) \quad (3.7.6)$$

$$pm = 17.966^\circ \quad (3.7.7)$$

$$(3.7.8)$$

- 3.8. Write the expression for maximum phase of a lead compensator and the frequency where it occurs

**Solution:**

$$\phi_{max} = \sin^{-1}\left(\frac{\alpha - 1}{\alpha + 1}\right) \quad (3.8.1)$$

$$\omega_m = \frac{1}{T\alpha} \quad (3.8.2)$$

- 3.9. Calculate the value of  $\phi_{max}$  required to meet desired phase margin.

**Solution:**

$$\phi_{max} = 45^\circ - pm + 15^\circ \quad (3.9.1)$$

$$\phi_{max} = 45^\circ - 17.966^\circ + 15^\circ \quad (3.9.2)$$

$$\phi_{max} = 42.034^\circ \quad (3.9.3)$$

Here the extra  $15^\circ$  has been added to compensate for the shift in  $\omega_{gc}$ .

- 3.10. Using (3.8.1) calculate the value of  $\alpha$

**Solution:**

$$\sin(42.034^\circ) = \frac{\alpha - 1}{\alpha + 1} \quad (3.10.1)$$

$$0.669 = \frac{\alpha - 1}{\alpha + 1} \quad (3.10.2)$$

$$0.331\alpha = 1.669 \quad (3.10.3)$$

$$\alpha = 5.04 \quad (3.10.4)$$

- 3.11. Choose appropriate value for  $\omega_m$ .

**Solution:**

- For maximum increase in phase margin we have to ensure that  $\phi_{max}$  occurs at frequency close to  $\omega_{gc}$  of  $G(s)$ .

$$\omega_m = 3.084 \text{ rad/sec} \quad (3.11.1)$$

- We know that  $\omega_{gc}$  gets shifted slightly when we cascade a compensator to original transfer function, to compensate for the shift we have already added an extra  $15^\circ$  to  $\phi_{max}$ .

- 3.12. Using (3.8.2) calculate the value of  $T$ .

**Solution:**

$$T = \frac{1}{\omega_m \alpha} \quad (3.12.1)$$

$$T = \frac{1}{15.54} \quad (3.12.2)$$

$$T = 0.064 \quad (3.12.3)$$

- 3.13. Write the final expression of the Lead compensator designed.

**Solution:**

$$G_c(s) = \frac{(1 + 0.322s)}{(1 + 0.064s)} \quad (3.13.1)$$

- Zero at  $s = -3.084$
- Pole at  $s = -15.54$

- 3.14. Verify using a python plot.

**Solution:**

codes/ee18btech11044\_2.py

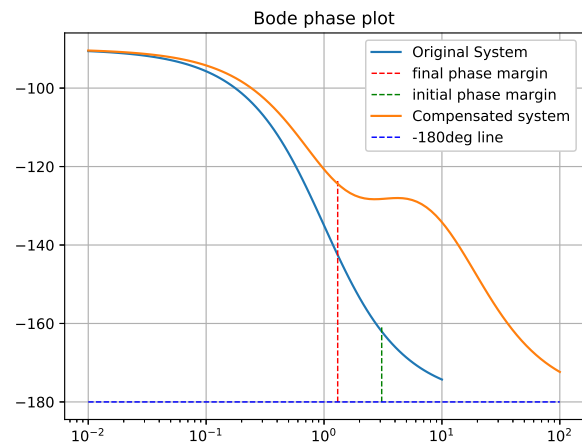


Fig. 3.2.3

### 3.3 Lag Compensator

3.3.1. Given the unity feedback system, with

$$G(s) = \frac{K(s+10)(s+11)}{s(s+3)(s+6)(s+9)} \quad (3.3.1.1)$$

Use frequency response method to design a lag compensator to yield  $K_v = 1000$  and peak overshoot of 15%. Use second order approximation.

**Solution:** Fig. 3.3.1 models the equivalent of compensated closed loop system.

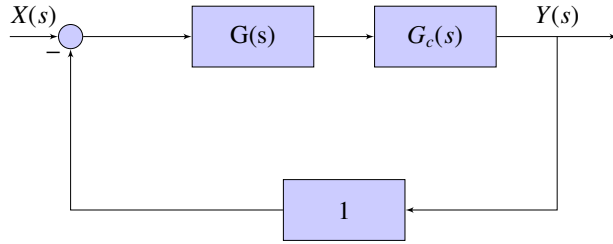


Fig. 3.3.1

Velocity constant

$$K_v = \lim_{t \rightarrow 0} sG(s) \quad (3.3.1.2)$$

$$\lim_{t \rightarrow 0} s \frac{K(s+10)(s+11)}{s(s+3)(s+6)(s+9)} = 1000 \quad (3.3.1.3)$$

$$\Rightarrow K = 1473 \quad (3.3.1.4)$$

Bode plot of  $G(s)$  for the value of  $k$

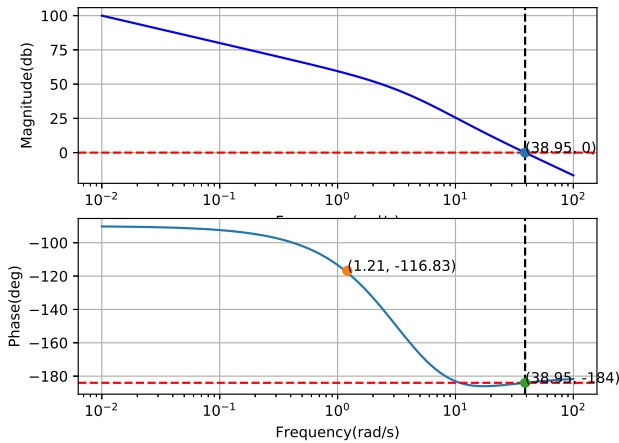


Fig. 3.3.2

The following code verifies the result.

```
codes/ee18btech11030/ee18btech11030.py
```

Relation between %OS and Damping ratio

$$\zeta = \frac{-\ln(\%OS/100)}{\sqrt{(\pi)^2 + (\ln(\%OS/100))^2}} \quad (3.3.1.5)$$

$$\Rightarrow \zeta = 0.517 \quad (3.3.1.6)$$

Phase Margin for a Damping ratio is given by Eq (3.3.1.7)

$$\phi_m = 90^\circ - \arctan\left(\frac{\sqrt{-2\zeta^2 + \sqrt{1 + 4\zeta^4}}}{2\zeta}\right) \quad (3.3.1.7)$$

$$\Rightarrow \phi_m = 53.17^\circ \quad (3.3.1.8)$$

From Fig : 3.3.2 of uncompensated system with  $K = 1473$

$$\phi_m = -4^\circ, \omega_{PM} = 38.95 \text{ rad/sec} \quad (3.3.1.9)$$

$$\phi_{ml} \text{ lies in } (5, 12) \quad (3.3.1.10)$$

$$\phi_{total} = 53.17^\circ - (-4^\circ) + \phi_{ml} \quad (3.3.1.11)$$

$$\phi_{total} = 63.17^\circ \quad (3.3.1.12)$$

**Note :** Adding 6 degrees phase angle to compensate the phase angle contribution of the lag compensator.

From Figure 3.3.2

$$\phi_{total} = 63.17^\circ \text{ at } \omega_{PM} = 1.21 \text{ rad/sec} \quad (3.3.1.13)$$

At this Phase Margin frequency, the magnitude plot must go through 0 dB. But The magnitude of uncompensated system at 1.21 rad/sec is 57.55 dB = 754.2

3.3.2. Designing Lag Compensator  $G_c(s)$

**Solution:** General lag compensator

$$G_c(s) = \left( \frac{s + \frac{1}{T}}{s + \frac{1}{T\alpha}} \right) \alpha > 1 \quad (3.3.2.1)$$

- First draw the high-frequency asymptote at -57.55 dB. So that magnitude at 1.21 rad/sec becomes 0 dB.
- Arbitrarily select the higher break frequency to be about one decade below the phase-margin frequency, or 0.121 rad/sec.
- Starting at the intersection of this frequency

with the lag compensator's high-frequency asymptote, draw a -20 dB/decade line until 0 dB is reached. That intersection gives the lower break frequency.

- The lower break frequency is found to be 0.0001604 rad/sec.
- The compensator must have a dc gain of unity to retain the value of  $K_v$  that we have already designed by setting  $K = 1473$ .
- Gain in the lag compensator = 0.001326

$$\text{Gain} = \frac{0.0001604}{0.121} = 0.001326 \quad (3.3.2.2)$$

Hence the lag compensator transfer function is

$$G_c(s) = \frac{0.001326(s + 0.121)}{s + 0.0001604} \quad (3.3.2.3)$$

### 3.3.3. Verifying Lag Compensator using Plots

**Solution:** Magnitude and Phase plot

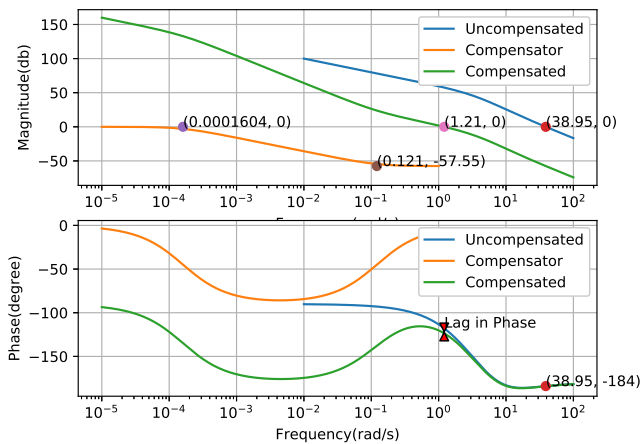


Fig. 3.3.3

The following code

```
codes/ee18btech11030/ee18btech11030_1.py
```

Specification	Proposed	Actual
OS%	15%	15.16%
$K_v$	1000	1000.47

TABLE 3.3.1: Comparing the Proposed and Actual results

### 3.3.4. Verifying in time domain

**Solution:** Time response for a unit step function

The following code

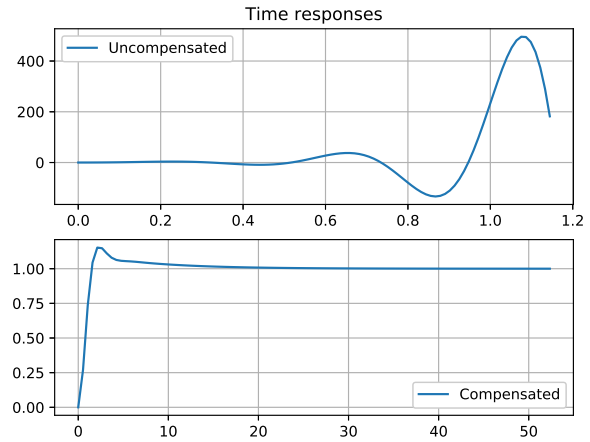


Fig. 3.3.4

```
codes/ee18btech11030/ee18btech11030_2.py
```

## 3.4 Lead Compensator

3.4.1. For a unity feedback system shown in Fig. 1

$$G(s) = \frac{K}{s(s+2)(s+4)(s+6)} \quad (3.4.1.1)$$

Design a lead compensator to yield a  $K_v = 2$  and a phase margin of  $30^\circ$ .

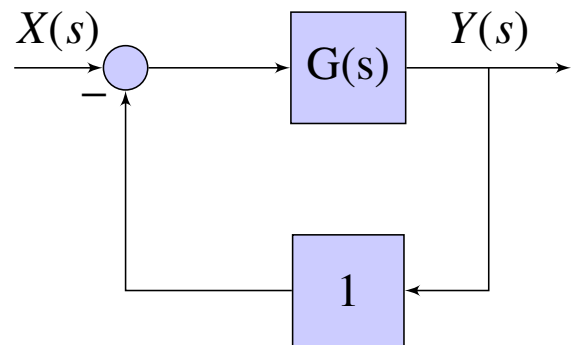


Fig. 3.4.1

**Solution:** For unity feedback we have Velocity error constant ( $K_v$ )

$$K_v = \lim_{s \rightarrow 0} sG(s) \quad (3.4.1.2)$$

$$\lim_{s \rightarrow 0} \left( \frac{K}{(2+s)(4+s)(6+s)} \right) = 2 \quad (3.4.1.3)$$

$$\Rightarrow K = 96 \quad (3.4.1.4)$$

Check the phase margin and gain crossover frequency by running the following code

```
codes/ee18btech11036_1.py
```

- The Phase margin:  $19.76^\circ$
- Gain Crossover Frequency:  $1.469 \text{ rad/sec}$

The Bode plot of system is as shown,

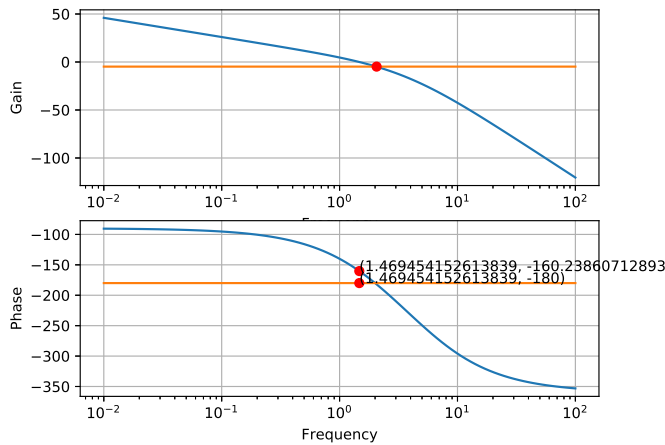


Fig. 3.4.2

Therefor amount of phase to be added:  $30 - 19.76 = 10.24$

The circuit of lead compensator is given by

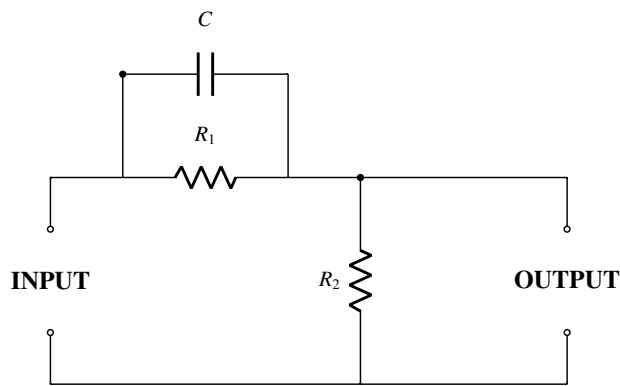


Fig. 3.4.3

Transfer function:

$$C(s) = \beta \left( \frac{1 + j\tau\omega}{1 + j\beta\tau\omega} \right) \quad (3.4.1.5)$$

$$\beta = \left( \frac{R_2}{R_1 + R_2} \right) \quad (3.4.1.6)$$

$$\tau = R_1 C \quad (3.4.1.7)$$

Find the values of  $\beta$  and  $\tau$

**Solution:** The maximum phase lead compensated by a lead compensator is given by

$$\phi = \sin^{-1} \frac{1 - \beta}{1 + \beta} \quad (3.4.1.8)$$

at

$$\omega = \frac{1}{\sqrt{\beta}\tau} \quad (3.4.1.9)$$

Now we know that from Gain crossover frequency

$$\omega = 1.469 \text{ rad/sec} \quad (3.4.1.10)$$

and the phase margin to be added:

$$\phi = 10.24^\circ \quad (3.4.1.11)$$

But to compensate for the added magnitude of lead compensator, a correction factor of  $10^\circ - 20^\circ$  is added. Hence

$$\phi = 30.24^\circ \Rightarrow \beta = 0.33 \quad (3.4.1.12)$$

From the bode plot  $\omega$  is chosen at which gain of original system is

$$-20 \log(1/\sqrt{\beta}) = -4.81 \quad (3.4.1.13)$$

Find the plot using the following code

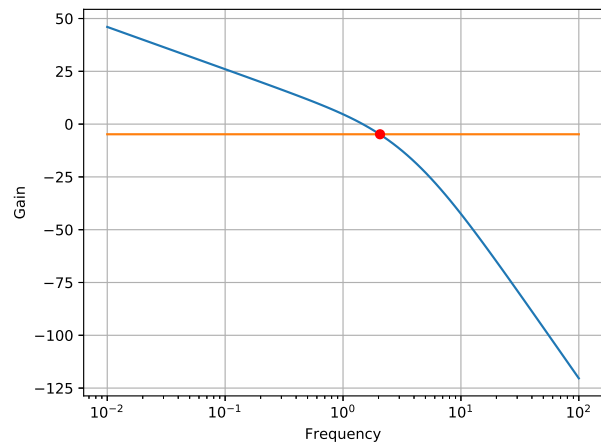


Fig. 3.4.4

```
codes/ee18btech11036_4.py
```

From plot  $\omega=2.009$  rad/sec  
Solving equations 3.4.1.8 and 3.4.1.9:

$$\tau = 0.828 \quad (3.4.1.14)$$

$$\beta = 0.33 \quad (3.4.1.15)$$

$$(3.4.1.16)$$

New Transfer Function:

$$G(s) = \frac{96(1 + 0.828s)}{(s)(2 + s)(4 + s)(6 + s)(1 + 0.273s)} \quad (3.4.1.17)$$

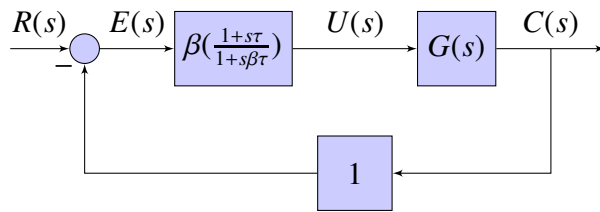


Fig. 3.4.5

Verify your results from the following code:

```
codes/ee18btech11036_2.py
```

- The Phase margin: 29.269°
- The Gain Crossover Frequency: 2.02 rad/sec

The Bode plot is as shown,

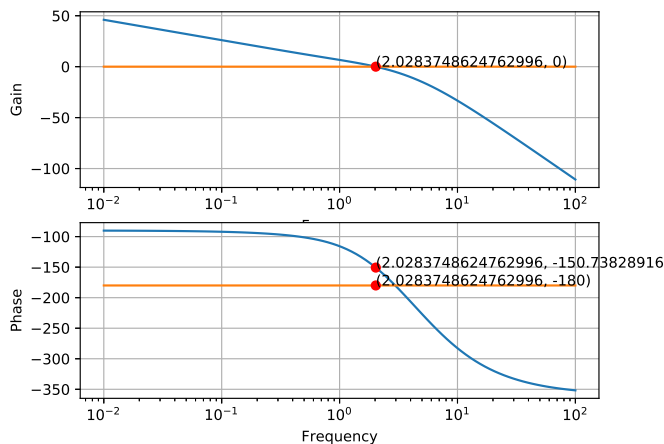


Fig. 3.4.6

### 3.4.2. For a unity feedback system

$$G(s) = \frac{K}{(s)(s + 2)(s + 4)(s + 6)} \quad (3.4.2.1)$$

Design a lag compensator to yield a  $K_v = 2$  and Phase Margin of 30° **Solution:** Fig.3.4.7

models the equivalent of compensated closed loop system.

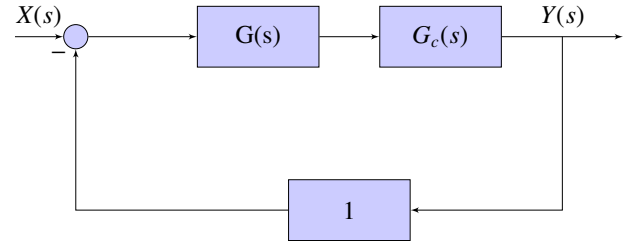


Fig. 3.4.7

Static Velocity Error Constant  $K_v$  is the steady-state error of a system for a unit-ramp input i.e.,

$$K_v = \lim_{s \rightarrow 0} sG(s)G_c(s) \quad (3.4.2.2)$$

Therefore,

$$\begin{aligned} K_v &= \lim_{s \rightarrow 0} s \frac{K}{s(s+2)(s+4)(s+6)} \frac{Ts+1}{\beta Ts+1} \\ \Rightarrow 2 &= \frac{K}{(0+2)(0+4)(0+6)} \frac{T(0)+1}{\beta T(0)+1} \\ \therefore K &= 96 \quad (3.4.2.3) \end{aligned}$$

$$G(s) = \frac{96}{s(s+2)(s+4)(s+6)} \quad (3.4.2.4)$$

Substituting  $s = j\omega$  in (3.4.2.4),

$$G(j\omega) = \frac{96}{(j\omega)(j\omega+2)(j\omega+4)(j\omega+6)} \quad (3.4.2.5)$$

$$|G(j\omega)| = \frac{|96|}{\omega \sqrt{4 + \omega^2} \sqrt{16 + \omega^2} \sqrt{36 + \omega^2}} \quad (3.4.2.6)$$

$$\begin{aligned} \angle G(j\omega) &= -90^\circ - \tan^{-1}\left(\frac{\omega}{2}\right) - \tan^{-1}\left(\frac{\omega}{4}\right) \\ &\quad - \tan^{-1}\left(\frac{\omega}{6}\right) \quad (3.4.2.7) \end{aligned}$$

The standard Transfer equation of Lag Com-



compensator and its Phase and Gain

$$G_c(s) = \frac{Ts + 1}{\beta Ts + 1} \quad (3.4.2.8)$$

$$|G_c(s)| = \frac{1}{\beta} \frac{1 + \left(\frac{\omega}{T}\right)^2}{1 + \left(\frac{\omega}{\beta T}\right)^2} \quad (3.4.2.9)$$

$$\angle G_c(s) = \tan^{-1}(\omega T) - \tan^{-1}(\omega \beta T) \quad (3.4.2.10)$$

Where  $\beta > 1$ .

It can be approximated that for  $\omega > \frac{1}{T}$

$$|G_c(s)| = \frac{1}{\beta} \quad (3.4.2.11)$$

and Phase to be very small ( $< 12^\circ$ ).

The Phase Margin(PM) of the Transfer function G(s)

From (3.4.2.6) and (3.4.2.6)

At Gain Crossover,

$$|G(s)| = 1 \quad (3.4.2.12)$$

$$\Rightarrow \omega_{gc} = 1.47 \text{ rad/sec} \quad (3.4.2.13)$$

$$\Rightarrow \angle G(j\omega_{gc}) = -160.26^\circ \quad (3.4.2.14)$$

$$PM = 180^\circ + \angle G(j\omega_{gc}) \quad (3.4.2.15)$$

$$\Rightarrow PM = 19.74^\circ \quad (3.4.2.16)$$

The following are the Bode plots of uncompensated system

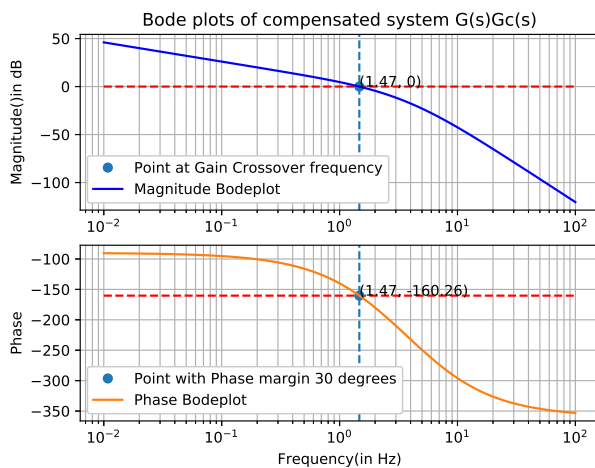


Fig. 3.4.8

The code for Bode plots of uncompensated system

```
codes/ee18btech11046_1.py
```

The lag compensator form is given in (3.4.2.8),  
Let

$$G'(s) = G(s)G_c(s) \quad (3.4.2.17)$$

The  $PM = 30^\circ$  when  $\angle G'(j\omega) = -150^\circ$

Since the addition of compensator reduces Gain of system, thereby reducing Gain Crossover frequency which increases Phase Margin(PM) of system.

Since, Compensator also has small negative phase(say  $\epsilon$ ), let  $\epsilon = 5^\circ$  i.e.,  $\angle G_c(s) = 5^\circ$

$$\angle G'(s) = \angle G(s) + \angle G_c(s) \quad (3.4.2.18)$$

$$\Rightarrow -150^\circ = \angle G(s) - 5^\circ \quad (3.4.2.19)$$

$$\Rightarrow \angle G(s) = -145^\circ \quad (3.4.2.20)$$

The value of  $\omega$  where  $\angle G(s) = -145^\circ$  is

$$\angle G(s) = -145^\circ \quad (3.4.2.21)$$

$$\Rightarrow \omega_{req} = 1.10953 \text{ rad/sec} \quad (3.4.2.22)$$

The value  $\frac{1}{T}$  is exactly 2 octaves below  $\omega_{req}$  obtained in (3.4.2.22)

$$\frac{1}{T} = \frac{\omega_{req}}{4} \quad (3.4.2.23)$$

$$\Rightarrow T = 3.605 \quad (3.4.2.24)$$

Now we should take  $\beta$  such that Gain Crossover frequency occurs at  $\omega_{req}$  i.e., to make

$$|G'(j\omega)| = 1$$

From (3.4.2.11),

$$|G'(j\omega_{gc})| = |G(j\omega_{gc})| |G_c(j\omega_{gc})| = 1 \quad (3.4.2.25)$$

$$\Rightarrow 1.4936 \times \frac{1}{\beta} = 1 \quad (3.4.2.26)$$

$$\Rightarrow \beta = 1.4936 \quad (3.4.2.27)$$

Substituting values of T and  $\beta$  obtained from (3.4.2.24) and (3.4.2.27) in (3.4.2.8) The required Compensator Transfer is

$$G_c(s) = \frac{3.605s + 1}{5.384s + 1} \quad (3.4.2.28)$$

The following are the Bode plots of compensated system

The code for Bode plots of compensated system

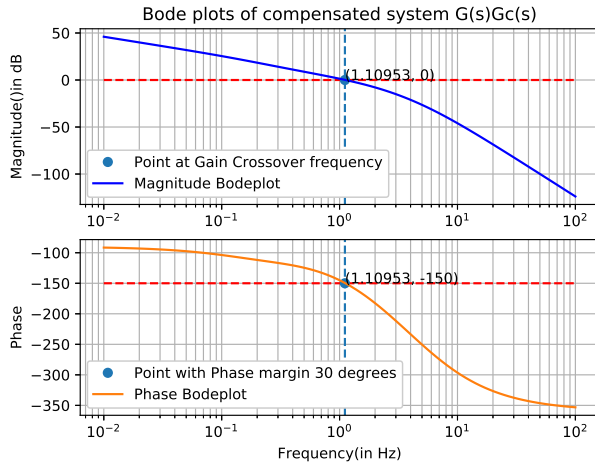


Fig. 3.4.9

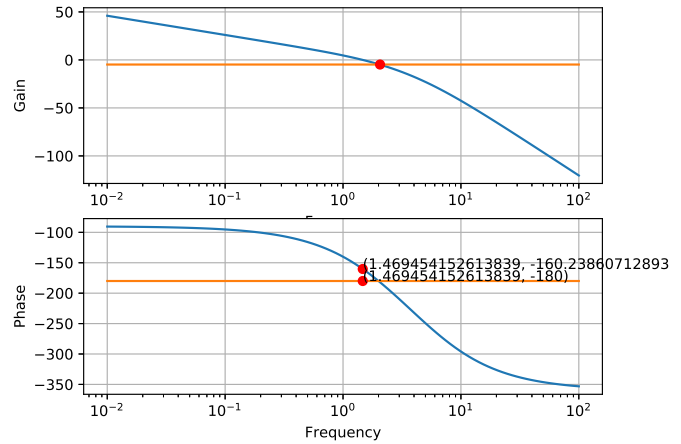


Fig. 3.4.10

```
codes/ee18btech11046_2.py
```

3.4.3. For a unity feedback system

$$G(s) = \frac{K}{s(s+2)(s+4)(s+6)} \quad (3.4.3.1)$$

Design a lag lead compensator to yield a  $K_v = 2$  and a phase margin of  $30^\circ$ . First we will design a lead compensator and for that whole system we will design a lag compensator which will finally be the lag lead compensator of the original transfer function.

**Solution:** For unity feedback we have Velocity error constant ( $K_v$ )

$$K_v = \lim_{s \rightarrow 0} sG(s) \quad (3.4.3.2)$$

$$\lim_{s \rightarrow 0} \left( \frac{K}{(2+s)(4+s)(6+s)} \right) = 2 \quad (3.4.3.3)$$

$$\Rightarrow K = 96 \quad (3.4.3.4)$$

Check the phase margin and gain crossover frequency by running the following code

```
codes/es17btech11019_1.py
```

- The Phase margin:  $19.76^\circ$
- Gain Crossover Frequency:  $1.469 \text{ rad/sec}$

The plot of system is as shown,  
Therefor amount of phase to be added:  $30 - 19.76 = 10.24$

Transfer function:

$$C(s) = \beta \left( \frac{1 + j\tau\omega}{1 + j\beta\tau\omega} \right) \quad (3.4.3.5)$$

Find the values of  $\beta$  and  $\tau$

**Solution:** The maximum phase lead compensated by a lead compensator is given by

$$\phi = \sin^{-1} \frac{1 - \beta}{1 + \beta} \quad (3.4.3.6)$$

at

$$\omega = \frac{1}{\sqrt{\beta}\tau} \quad (3.4.3.7)$$

Now we know that from Gain crossover frequency

$$\omega = 1.469 \text{ rad/sec} \quad (3.4.3.8)$$

and the phase margin to be added:

$$\phi = 10.24^\circ \quad (3.4.3.9)$$

But to compensate for the added magnitude of lead compensator, a correction factor of  $10^\circ - 20^\circ$  is added. Hence

$$\phi = 30.24^\circ \Rightarrow \beta = 0.33 \quad (3.4.3.10)$$

From the bode plot  $\omega$  is chosen at which gain of original system is

$$-20 \log(1/\sqrt{\beta}) = -4.81 \quad (3.4.3.11)$$

Find the plot using the following code

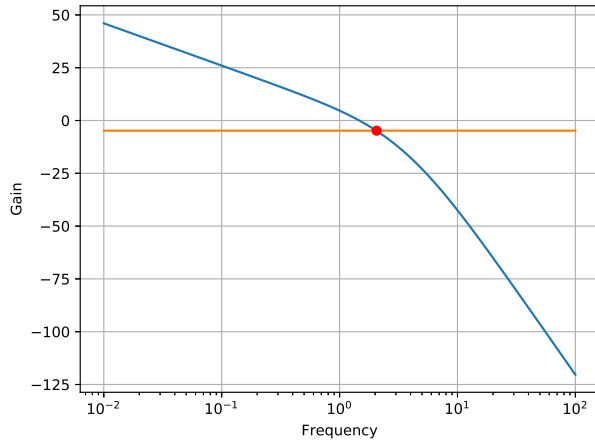


Fig. 3.4.11

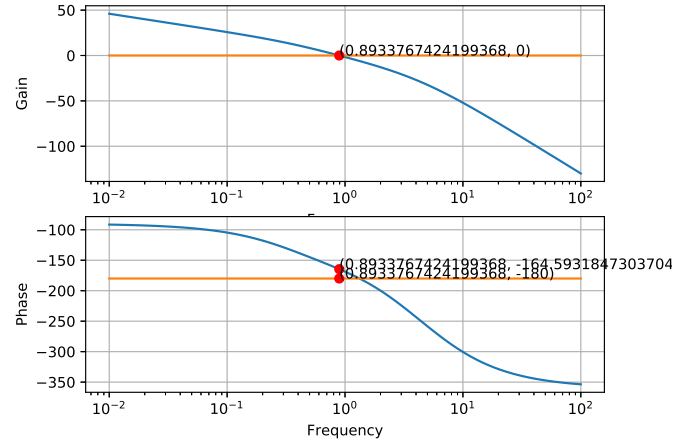


Fig. 3.4.12

```
codes/es17btech11019_2.py
```

From plot  $\omega=2.009$  rad/sec

Solving equations 3.4.3.6 and 3.4.3.7

$$\tau = 0.828 \quad (3.4.3.12)$$

$$\beta = 0.33 \quad (3.4.3.13)$$

$$(3.4.3.14)$$

New Transfer Function:

$$G(s) = \frac{96(1 + 0.828s)}{(s)(2 + s)(4 + s)(6 + s)(1 + 0.273s)} \quad (3.4.3.15)$$

Verify your results from the following code:

```
codes/es17btech11019_3.py
```

- The Phase margin:  $29.269^\circ$
- The Gain Crossover Frequency: 2.02 rad/sec

The plot is as shown,

Now for lag compensator of this whole lead compensated part Transfer function:

$$C'(s) = \left( \frac{1 + j\tau\omega}{1 + j\alpha\tau\omega} \right) \quad (3.4.3.16)$$

Find the values of  $\alpha$

**Solution:**

$$\alpha = \frac{1}{\beta} \quad (3.4.3.17)$$

Solving equations 3.4.3.17

$$\alpha = 3.03 \quad (3.4.3.18)$$

New Transfer Function:

$$G(s) = \frac{96(1 + 0.828s)(1 + 0.828s)}{(s)(2 + s)(4 + s)(6 + s)(1 + 0.273s)(1 + 2.50884s)} \quad (3.4.3.19)$$

Final plot is,

Find the plot using the following code

```
codes/es17btech11019_4.py
```

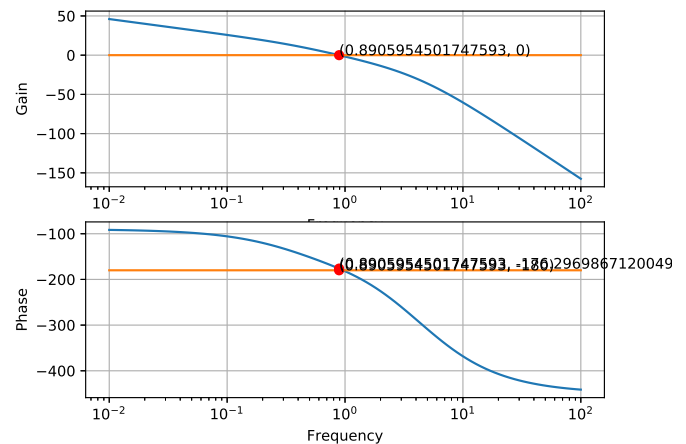


Fig. 3.4.13

### 3.5 Compensator for Overshoot

3.5.1. Given the unity feedback system of Fig. 3.5.1, with

$$G(s) = \frac{K}{s(s+5)(s+20)} \quad (3.5.1.1)$$

The uncompensated system has about 55% peak overshoot and a peak time of 0.5 seconds when  $K_v = 10$ . Use frequency response technique to design a lead compensator to reduce the percent overshoot to 10%, while keeping the peak time and steady state error about the same or less. Consider second order approximations.

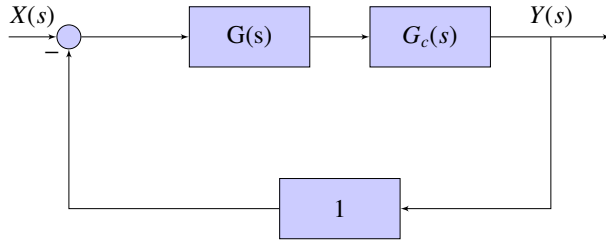


Fig. 3.5.1

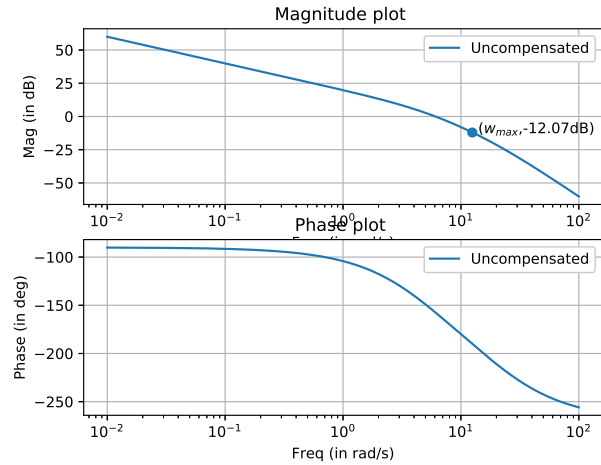


Fig. 3.5.2: G(s) Bode Plot

Specifications	Actual	Expected
OS%	55%	10%
$\zeta$	0.186	0.591
$\phi_m$	21.16°	58.59°
$T_p$	0.5	$\leq 0.5$
$K_v$	10	$\leq 10$

TABLE 3.5.1: Table of Specifications

3.5.2. **Solution:**

$$K_v = \lim_{s \rightarrow 0} sG(s) = 10 \quad (3.5.2.1)$$

$$\Rightarrow K = 1000 \quad (3.5.2.2)$$

The bode plot for G(s) is as follows :

$$G(s) = \frac{1000}{s(s+5)(s+20)} \quad (3.5.2.3)$$

$$\zeta = \frac{-\ln\left(\frac{OS\%}{100}\right)}{\sqrt{\pi^2 + \left(\ln\left(\frac{OS\%}{100}\right)\right)^2}} \quad (3.5.2.4)$$

$$PhaseMargin = \phi_M = \tan^{-1} \left( \frac{2\zeta}{\sqrt{-2\zeta^2 + \sqrt{4\zeta^4 + 1}}} \right) \quad (3.5.2.5)$$

The following code computes the above quantities.

codes/ee18btech11026/ee18btech11026\_1.py

The required additional phase contribution by the compensator will be:

$$\phi_{max} = 58.9 - 21.16 + \text{correction factor} \quad (3.5.2.6)$$

$$\text{Correction Factor} = 25^\circ \quad (3.5.2.7)$$

$$\phi_{max} = 62^\circ \quad (3.5.2.8)$$

**Note :** Since we know that the lead network will also increase the phase-margin frequency, we add a correction factor to compensate for the lower uncompensated system's phase angle. Choosing the correction factor is a trial and error procedure so as to reach our expected specifications.

The gain compensator's T.F will be of the form:

$$G_c(s) = \frac{1}{\beta} \left( \frac{s + \frac{1}{T}}{s + \frac{1}{T\beta}} \right) \quad (3.5.2.9)$$

This form of T.F does not influence the steady

state error.

**Important Relations to find T and  $\beta$ :**

$$\phi_{max} = \tan^{-1} \frac{1 - \beta}{2\sqrt{\beta}} \quad (3.5.2.10)$$

The Compensator's magnitude at the phase margin frequency  $\omega_{max}$

$$|G_c(j\omega_{max})| = \frac{1}{\sqrt{\beta}} \quad (3.5.2.11)$$

$$T = \frac{1}{\omega_{max} \sqrt{\beta}} \quad (3.5.2.12)$$

Using the above formulae :

$$\beta = 0.062 \quad (3.5.2.13)$$

$$|G_c(j\omega_{max})| = 12.07dB \quad (3.5.2.14)$$

If we select  $\omega_{max}$  to be the new phase-margin frequency, the uncompensated system's magnitude at this frequency must be -12.07 dB to yield a 0 dB crossover at  $\omega_{max}$  for the compensated system.

From the bode plot of the un-compensated system, find  $\omega_{max}$  where the magnitude is -12.07 dB. This becomes our new phase-margin frequency.

$$\omega_{max} = 12.5 rad/sec \quad (3.5.2.15)$$

$$T = 0.321 \quad (3.5.2.16)$$

The Compensator's T.F is as follows :

$$G_c(s) = 16.13 \left( \frac{s + 3.115}{s + 50.25} \right) \quad (3.5.2.17)$$

The open loop T.F for the compensated system is :

$$G(s).G_c(s) = 16130 \left( \frac{(s + 3.115)}{s(s + 50.25)(s + 5)(s + 20)} \right) \quad (3.5.2.18)$$

**3.5.3. Verification :** We could observe the affect of the lead-phase compensator from the phase plots.

The time responses for a unit step input in a unity feedback system with and without a compensator are as follows :

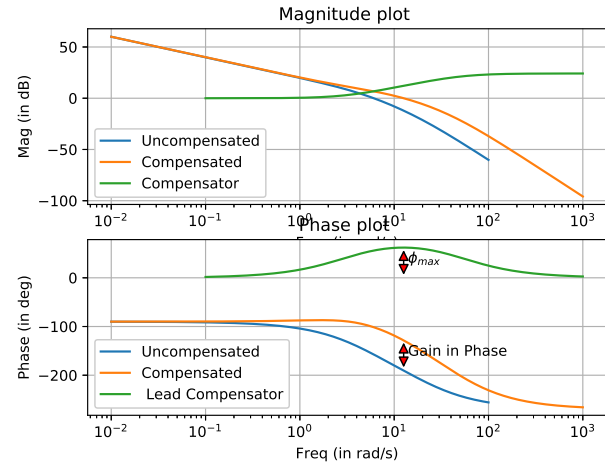


Fig. 3.5.3: Combined Bode Plots

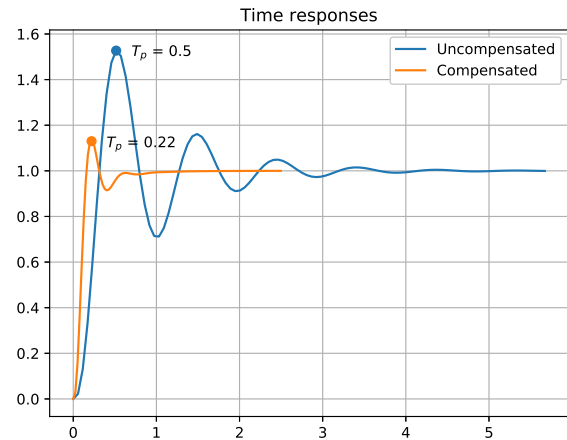


Fig. 3.5.4: Time response for a unit step input

These plots are generated using the below code:

```
codes/ee18btech11026/ee18btech11026_2.py
```

**3.5.4. Result :** The below is the summary for the designed lead-compensator

Specifications	Expected	Proposed
OS%	10%	11%
$T_p$	$\leq 0.5$	0.22
$K_v$	$\leq 10$	10

TABLE 3.5.2: Comparing the desired and obtained results

### 3.6 Lead Compensator

3.6.1. An aircraft roll control system can be represented by a block diagram shown in Fig. 3.6.1 with  $G(s)$  in feedback system, whose error  $K_v = 5$ . Determine  $K$

$$G(s) = \frac{10K}{s(s+1)(s+5)} \quad (3.6.1.1)$$

The block diagram is given by Fig.3.6.1

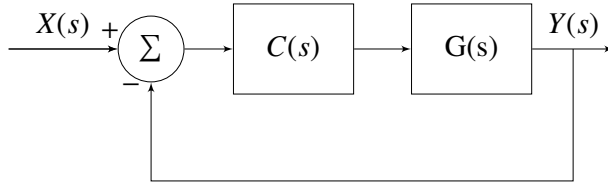


Fig. 3.6.1

For unity feedback we have Velocity error constant ( $K_v$ )

$$K_v = \lim_{s \rightarrow 0} sG(s) \quad (3.6.1.2)$$

$$\lim_{s \rightarrow 0} \left( \frac{10K}{(s+1)(s+5)} \right) = 5 \quad (3.6.1.3)$$

$$\Rightarrow K = 2.5 \quad (3.6.1.4)$$

It's Phase Margin =  $3.94^\circ$   
and Gain Crossover Frequency =  $2.03 \text{ rad/s}$   
Refer Fig. 3.6.2 for plot  $G(s)$ .

codes/es17btech11002\_1\_new.py

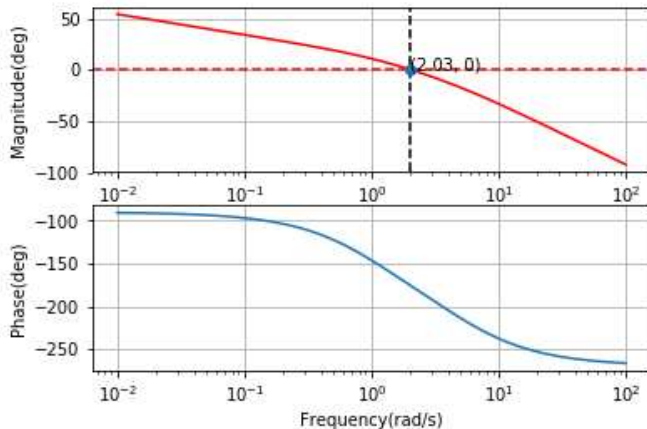


Fig. 3.6.2

Compensator required phase angle ( $\phi_m$ ) and

Phase Margin Frequency ( $\omega_{pm}$ ),

$$\phi_m = -(180^\circ + \theta) + PM + 5 = 65^\circ \quad (3.6.1.5)$$

$$\omega_{pm} = 1.25 \text{ rad/s}. \quad (3.6.1.6)$$

Attenuation factor ( $\alpha\beta$ ) is given by

$$\alpha = 0.5 \quad (3.6.1.7)$$

$$\beta = 20 \quad (3.6.1.8)$$

Lead and Lag Compensator Design Parameter is given in TABLE 3.6.1 And Compensator

Zeros/Poles	Parameter	Value
$z_{lead}$	$\omega_{pm} \sqrt{\alpha}$	0.279
$p_{lead}$	$\frac{z_{lead}}{\alpha}$	5.590
$z_{lag}$	$0.1\omega_{pm}$	0.125
$p_{lag}$	$\frac{z_{lag}}{\beta}$	0.00625

TABLE 3.6.1: Zeroes and Poles

obtained has transfer function

$$G_c(s) = \frac{(s + 0.279)(s + 0.125)}{(s + 5.590)(s + 0.00625)} \quad (3.6.1.9)$$

Refer Fig.3.6.3 for plot  $G(s)G_c(s)$ .

codes/es17btech11002\_2\_new.py

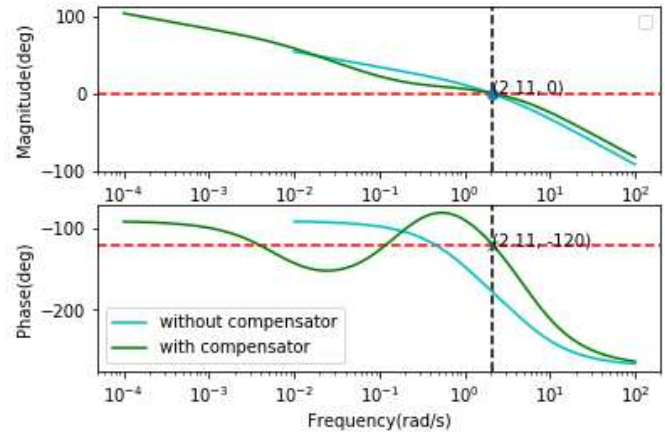


Fig. 3.6.3

**NOTE :** The idea of using a lead-lag network is to provide the attenuation of a phase-lag network and the lead-phase angle of a phase-lead network. This points should be noted while designing a controller, and parameters to be changed accordingly to get exact results.

3.6.2. For a unity feedback system given below refer, 3.6.4, with

$$G(s) = \frac{K}{s(s+5)(s+11)} \quad (3.6.2.1)$$

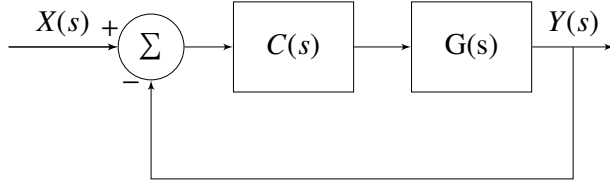


Fig. 3.6.4

Find the value of the gain,  $K$ , of the uncompensated system operating at 30% overshoot.

**Solution:**

The damping ratio  $\zeta$  is given by:

$$\zeta = -\frac{\ln \frac{\%OS}{100}}{\sqrt{\pi^2 + \ln^2 \frac{\%OS}{100}}} \quad (3.6.2.2)$$

Therefore, solving the above equation with  $\%OS = 30$ , we get,

$$\zeta = 0.358 \quad (3.6.2.3)$$

Further, we need to find the point on the root locus which crosses the 0.358 damping ratio line.

Let this point be  $-\sigma_d + j\omega_d$ , where  $\sigma_d$  is the exponential damping frequency and  $\omega_d$  is the damped frequency of oscillation.

And the relation between  $\sigma_d$  and  $\omega_d$  is given by,

$$\omega_d = \sigma \tan(\arccos \zeta) \quad (3.6.2.4)$$

where,

$$\sigma_d = \zeta \omega_n \quad (3.6.2.5)$$

$$\omega_d = \omega_n \sqrt{1 - \zeta^2} \quad (3.6.2.6)$$

$\omega_n$  is the natural frequency.

Now, by solving the below equation and equating the real and imaginary parts to zero,

$$1 + G(-\sigma_d + j\omega_d) = 0 \quad (3.6.2.7)$$

We get,

$$\sigma_d = 1.464 \quad (3.6.2.8)$$

$$\omega_d = 3.818 \quad (3.6.2.9)$$

$$\text{Gain, } K = 218.6 \quad (3.6.2.10)$$

The peak time,  $T_p$  is given by,

$$T_p = \frac{\pi}{\omega_d} \quad (3.6.2.11)$$

And, settling time is given by,

$$T_s = \frac{4}{\sigma_d} \quad (3.6.2.12)$$

So, we get,

$$T_p = 0.823 \quad (3.6.2.13)$$

$$T_s = 2.732 \quad (3.6.2.14)$$

$$K_v = \lim_{s \rightarrow 0} sG(s) \quad (3.6.2.15)$$

$$\lim_{s \rightarrow 0} \left( \frac{K}{(s+5)(s+11)} \right) = \frac{218.6}{(5)(11)} \quad (3.6.2.16)$$

$$\Rightarrow K_v = 3.975 \quad (3.6.2.17)$$

Design a lag-lead compensator to:

- Decrease the peak time by a factor of 2
- Decrease the percent overshoot by a factor of 2
- Improve the steady state error by a factor of 30

**Solution:**

**Lead Design:** Using the required specifications, we can calculate the damping ratio and the natural frequency, Using eq. 3.6.2.2, we get,

$$\zeta = 0.517 \quad (3.6.2.18)$$

And,

$$\omega_d = \frac{\pi}{T_p} = \omega_n \sqrt{1 - \zeta^2} = 7.634. \quad (3.6.2.19)$$

Hence,  $\omega_n = 8.919$ .

Thus, the desired pole is located at,

$$-\zeta \omega_n + j\omega_n \sqrt{1 - \zeta^2} = -4.61 + j7.634 \quad (3.6.2.20)$$

Let us now assume a lead compensator zero at -5. The summation of the system's original poles and lead compensator zero to the design point is  $-171.2^\circ$ . Thus, the compensator pole must contribute  $171.2^\circ - 180^\circ = -8.8^\circ$ .

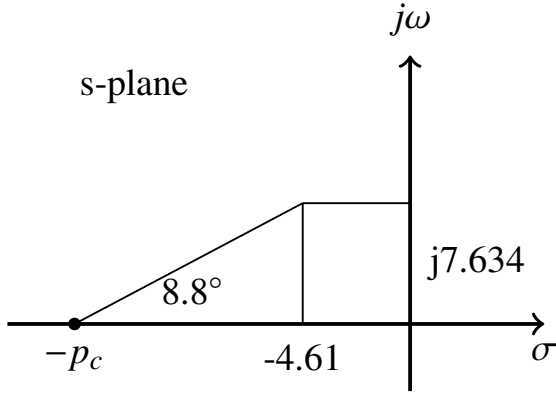


Fig. 3.6.5

Refer figure 3.6.5 for clarification.

$$\tan(8.8^\circ) = \frac{7.634}{p_c - 4.61} \quad (3.6.2.21)$$

Hence,  $p_c = 53.92$ .

Therefore, the compensated open-loop transfer function is,

$$\frac{K}{s(s+11)(s+53.92)} \quad (3.6.2.22)$$

Evaluating the gain for this function at the desired pole, we get  $K = 4430$ .

### Lag Design:

The lead compensated  $K_v = 7.469$ .

We need an improvement over the lead compensated system of,

$$\frac{(30)(3.975)}{7.469} = \frac{119.25}{7.469} \quad (3.6.2.23)$$

$$\Rightarrow = 15.97 \quad (3.6.2.24)$$

$$K_v = \lim_{s \rightarrow 0} sG(s) \quad (3.6.2.25)$$

Choose  $p_c$  (compensator pole) = 0.001, we get  $z_c$  (compensator zero) = 0.001597. Thus, the compensator is given by,

$$G_{lag}(s) = \frac{s + 0.001597}{s + 0.001} \quad (3.6.2.26)$$

So, the final compensated open loop transfer function is,

$$C(s)G(s) = \frac{4430(s + 0.001597)}{s(s + 11)(s + 53.92)(s + 0.001)} \quad (3.6.2.27)$$

Plot the graph after adding a lag-lead compensator.

### Solution:

See Fig. 3.6.6 generated by

codes/ep18btech11016/ep18btech11016.py

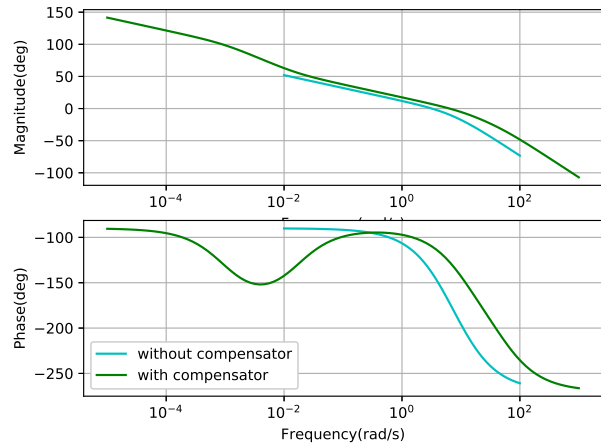


Fig. 3.6.6

## 3.7 Lag Lead Compensator

3.1. For the unity feedback system shown in Fig. 3.7.1, with

$$G(s) = \frac{K}{s(s+1)(s+4)} \quad (3.1.1)$$

Design a lag-lead compensator to yield a  $K_v = 12$  as well as peak overshoot of 12% and peak time of less than or equal to 2 seconds.

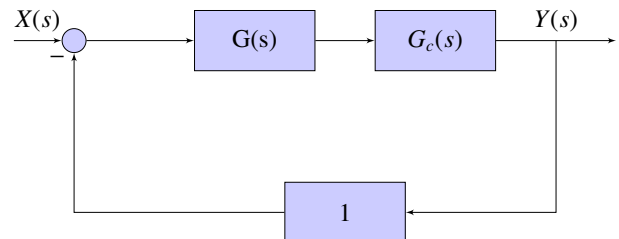


Fig. 3.7.1



### 3.2. Solution:

$$K_v = \lim_{s \rightarrow 0} sG(s) = 12 \quad (3.2.1)$$

$$\Rightarrow K = 48 \quad (3.2.2)$$

The bode plot for  $G(s)$  is as follows :

$$G(s) = \frac{48}{s(s+1)(s+4)} \quad (3.2.3)$$

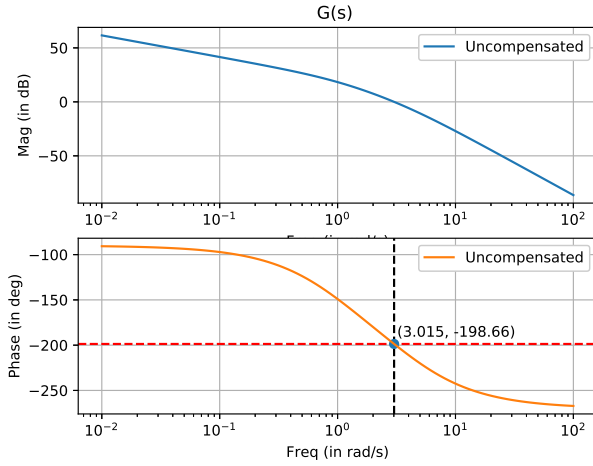


Fig. 3.7.2:  $G(s)$  Bode Plot

Damping Ratio  $\zeta$

$$\zeta = \frac{-\ln\left(\frac{OS\%}{100}\right)}{\sqrt{\pi^2 + \left(\ln\left(\frac{OS\%}{100}\right)\right)^2}} \quad (3.2.4)$$

Phase Margin  $\phi_M$

$$\phi_M = \tan^{-1} \left( \frac{2\zeta}{\sqrt{-2\zeta^2 + \sqrt{4\zeta^4 + 1}}} \right) \quad (3.2.5)$$

closed-loop Bandwidth  $\omega_{bw}$

$$\omega_{bw} = \frac{\pi}{T_p \sqrt{1 - \zeta^2}} \sqrt{1 - 2\zeta^2 + \sqrt{4\zeta^4 - 4\zeta^2 + 2}} \quad (3.2.6)$$

The following code computes the above quantities.

codes/ee18btech11049/ee18btech11049\_1.py

$$\zeta = 0.557 \quad (3.2.7)$$

$$\phi_M = 56.13^\circ \quad (3.2.8)$$

$$\omega_{bw} = 2.27 \text{ rad/sec} \quad (3.2.9)$$

The required phase margin to yield a 12% OS is  $56.13^\circ$

Let us select  $\omega = 1.83$  rad/s as the new phase-margin frequency.

At this frequency, the uncompensated phase is  $-176$  and would require, if we add a  $-6$  contribution from the lag compensator, a  $+56$  contribution from the lead compensator.

$$G_{Lead}(s) G_{Lag}(s) = \left( \frac{s + \frac{1}{T_1}}{s + \frac{\gamma}{T_1}} \right) \left( \frac{s + \frac{1}{T_2}}{s + \frac{1}{\gamma T_2}} \right) \quad (3.2.10)$$

Choose the lag compensator 1-decade below, so that its will have minimal effect at the new phase-margin frequency.

$$\phi_{max,lead} = 56 = \sin^{-1} \frac{1 - \beta}{1 + \beta} \quad (3.2.11)$$

$$\beta = 0.092 \quad (3.2.12)$$

$$\gamma = 10.86 \text{ since } \gamma = \frac{1}{\beta} \quad (3.2.13)$$

Thus with  $\gamma = 10.86$

$$G_{Lag}(s) = \left( \frac{s + \frac{1}{T_2}}{s + \frac{1}{\gamma T_2}} \right) = \frac{s + 0.183}{s + 0.0168} \quad (3.2.14)$$

$$\omega_{max} = \frac{1}{T_1 \sqrt{\beta}} \quad (3.2.15)$$

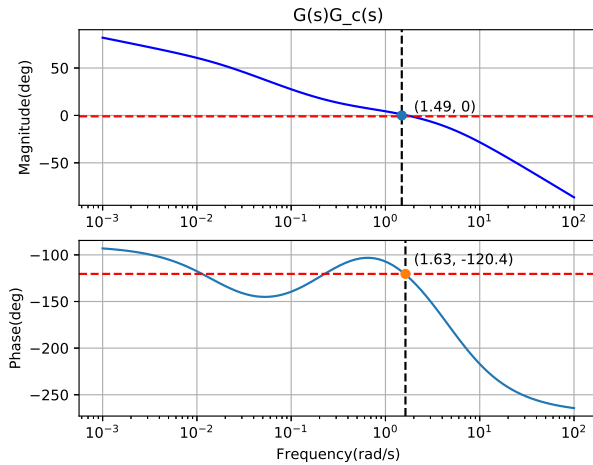
Using Values of  $\omega_{max} = 1.83$  and  $\beta = 0.094$

$$G_{Lag}(s) = \left( \frac{s + \frac{1}{T_1}}{s + \frac{\gamma}{T_1}} \right) = \frac{s + 0.55}{s + 5.69} \quad (3.2.16)$$

The lag-lead Compensated System's open loop transfer function is

$$G_{total}(s) = \frac{48(s + 0.183)(s + 0.55)}{s(s + 1)(s + 4)(s + 0.0168)(s + 5.69)} \quad (3.2.17)$$

3.3. **Verification :** We could observe the affect of the lag-lead compensator from these phase

Fig. 3.7.3:  $G(s)$  Compensated Bode Plot

plots.

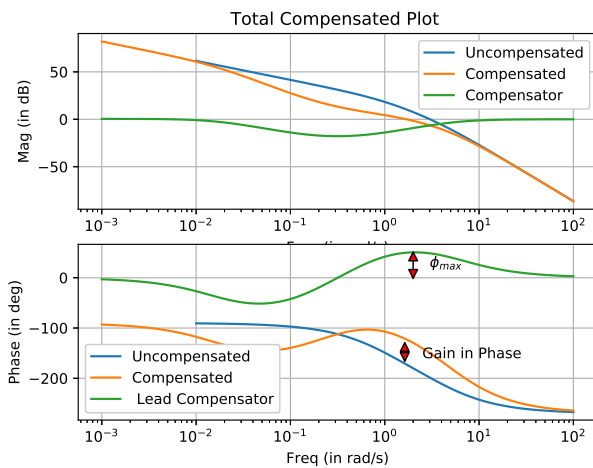


Fig. 3.7.4: Combined Bode Plots

These plots are generated using the below code:

```
codes/ee18btech11049/ee18btech11049_2.py
```

3.4. **Result :** The below is the summary for the designed lead-lead compensator.

### 3.8 Lag Lead Compensator

3.8.1. Using the frequency response method, design a lag-lead compensator for the unity feedback

Specifications	Expected	Proposed
OS%	12%	10.2%
$T_p$	$\leq 2$	1.61
$\phi_M$	56	59.6
$\omega_{bw}$	$\geq 2.27$	3
$\omega_{gc}$	-	1.63
$K_v$	12	12

TABLE 3.7.1: Comparing the desired and obtained results

system given

$$G(S) = \frac{K(s+7)}{s(s+5)(s+15)} \quad (3.8.1.1)$$

The following specifications must be met: Peak overshoot = 15%, settling time = 0.1 second and velocity error constant = 1000 Use second order approximation.

**Solution:** Figure: ?? models the equivalent of compensated closed loop system. Velocity

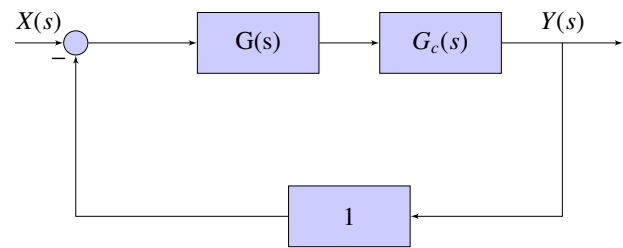


Fig. 3.8.1

error constant

$$K_v = \lim_{s \rightarrow 0} sG(s) \quad (3.8.1.2)$$

$$\lim_{s \rightarrow 0} s \frac{K(s+7)}{s(s+5)(s+15)} = 1000 \quad (3.8.1.3)$$

$$\Rightarrow K = 10714 \quad (3.8.1.4)$$

Bode plot of  $G(s)$  for the value of  $K$  The following code verifies the result.

```
codes/ee18btech11012/ee18btech11012_1.py
```

Relation between %OS and Damping ratio

$$\zeta = \frac{-\ln(\%OS/100)}{\sqrt{(\pi)^2 + (\ln(\%OS/100))^2}} \quad (3.8.1.5)$$

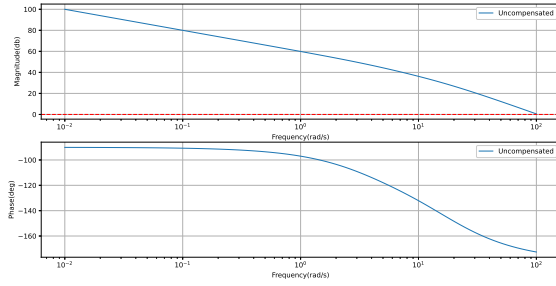


Fig. 3.8.2

$$\Rightarrow \zeta = 0.517 \quad (3.8.1.6)$$

Phase Margin for a Damping ratio is given by

$$\phi_m = 90^\circ - \arctan\left(\frac{\sqrt{-2\zeta^2 + \sqrt{1 + 4\zeta^4}}}{2\zeta}\right) \quad (3.8.1.7)$$

$$\Rightarrow \phi_m = 53.17^\circ \quad (3.8.1.8)$$

For an additional  $5^\circ$  for lag compensation, Phase margin is

$$\phi_m = 53.17^\circ + 5^\circ = 58.17^\circ \quad (3.8.1.9)$$

**Note :** Adding  $5^\circ$  phase angle to compensate the phase angle contribution of the lag compensator. Bandwidth frequency is given by

$$\omega_{BW} = \omega_n \left( \sqrt{(1 - 2\zeta^2) + \sqrt{4\zeta^4 - 4\zeta^2 + 2}} \right) \quad (3.8.1.10)$$

where

$$\omega_n = \frac{4}{T_s \zeta} \quad (3.8.1.11)$$

Given settling time = 0.1 sec then

$$\omega_n = 77.37 \text{ rad/sec} \quad (3.8.1.12)$$

then

$$\omega_{BW} = 96.91 \text{ rad/sec} \quad (3.8.1.13)$$

### 3.8.2. Designing Lag-Lead Compensator $G_c(s)$

**Solution:** General lag-lead compensator

$$G_c(s) = \left( \frac{s + \frac{1}{T_1}}{s + \frac{\gamma}{T_1}} \right) \left( \frac{s + \frac{1}{T_2}}{s + \frac{1}{\gamma T_2}} \right) \quad (3.8.2.1)$$

- Choose the new phase-margin frequency

$$\omega_{Pm} = 0.8\omega_{BW} = 77.53 \text{ rad/sec} \quad (3.8.2.2)$$

- At this phase-margin frequency, Phase angle is  $-170.52^\circ$ .
- Then the contribution required from the lead is

$$\phi_{max} = 58.17 - (180 - 170.52) = 48.69^\circ \quad (3.8.2.3)$$

- Now Using the relation

$$\phi_{max} = \sin^{-1}\left(\frac{1 - \beta}{1 + \beta}\right) \quad (3.8.2.4)$$

then we get

$$\beta = 0.142 \quad (3.8.2.5)$$

- **Lag Compensator Design:** The Compensator must have a dc gain of unity to retain the value of  $K_v$  that we have already designed by setting  $K = 10714$ .

$$z_{clag} = \frac{\omega_{Pm}}{10} = \frac{77.53}{10} = 7.753 \quad (3.8.2.6)$$

$$p_{clag} = z_{clag} * \beta = 1.102 \quad (3.8.2.7)$$

Gain in the lag compensator is

$$K_{clag} = \frac{p_{clag}}{z_{clag}} = 0.1421 \quad (3.8.2.8)$$

- Hence the lag compensator transfer function is

$$G_{clag}(s) = \frac{0.1421(s + 7.753)}{s + 1.102} \quad (3.8.2.9)$$

- **Lead Compensator Design:** DC gain for this must be unity.

**Relations to find  $T$  and  $\beta$ :** The Compensator's magnitude at the phase margin frequency  $\omega_{max}$

$$|G_c(j\omega_{max})| = \frac{1}{\sqrt{\beta}} \quad (3.8.2.10)$$

$$T = \frac{1}{\omega_{max} \sqrt{\beta}} \quad (3.8.2.11)$$

So, To find transfer function

$$z_{lead} = \frac{1}{T_2} = \omega_{Pm} * \sqrt{\beta} = 29.92 \quad (3.8.2.12)$$

$$p_{lead} = \frac{z_{lead}}{\beta} = 205.74, K_{lead} = \frac{p_{lead}}{z_{lead}} = 7.04 \quad (3.8.2.13)$$

- Thus lead compensator transfer function is

$$G_{lead} = \frac{7.04(s + 29.22)}{s + 205.74} \quad (3.8.2.14)$$

- So the overall compensator transfer function is

$$G_c(s) = G_{clag}(s)G_{lead}(s) \quad (3.8.2.15)$$

$$G_c(s) = \frac{1.000384(s + 7.753)(s + 29.23)}{(s + 1.102)(s + 205.7)} \quad (3.8.2.16)$$

### 3.8.3. Verifying Lag-lead Compensator using Plots

**Solution:** Magnitude and Phase plot The fol-

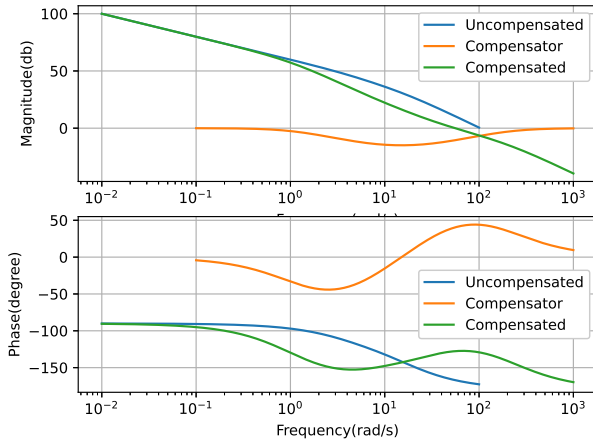


Fig. 3.8.3

lowing code

```
codes/ee18btech11012/ee18btech11012_2.py
```

### 3.8.4. Verifying in time domain

**Solution:** Time response for a unit step function The following code can be verified

```
codes/ee18btech11012/ee18btech11012_3.py
```

### 3.8.5. Verifying the designed lag-lead compensator

**Solution:**

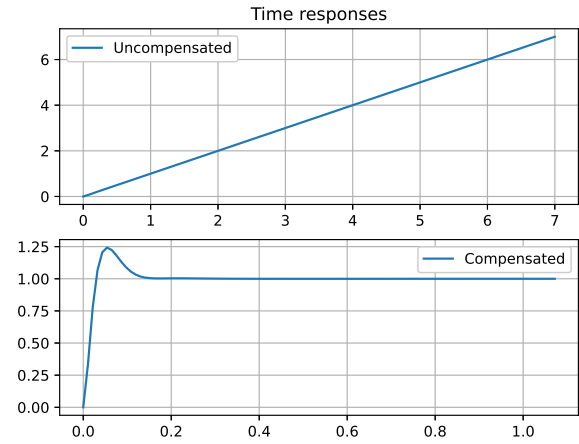


Fig. 3.8.4

Parameter Specification	Proposed	Actual
Phase Margin	53.17°	53.3994°
$K_v$	1000	1023.67
Phase Margin frequency	77.53	55.5874

TABLE 3.8.1: Comparing the desired and obtained results

3.9

3.10

3.11

## 4 PID CONTROLLER DESIGN

### 4.1 PD

4.1. For a unity feedback system shown in Fig. 4.1.1

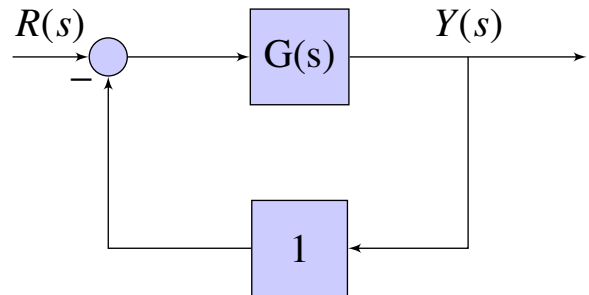


Fig. 4.1.1

$$G(s) = \frac{K}{s(s+1)} \quad (4.1.1)$$

Design a PD controller such that the phase margin is  $45^\circ$  and appropriate steady state error is less than or equal to  $\frac{1}{15}$  units of the final output value. Further the gain crossover frequency of the system must be less than 7.5 rad/s.

**Solution:** Using TABLE 4.2.1 The gain after cascading the PD controller with  $G(s)$  is

$$G_c(s) = \frac{K_P(1 + T_d s)K}{s(s+1)} \quad (4.1.2)$$

Type	Poles	Input	Steady State Error
Type 0	0	Step	$e_{ss} = \frac{1}{1 + \lim_{s \rightarrow 0} G(s)}$
Type 1	1	Ramp	$e_{ss} = \frac{1}{\lim_{s \rightarrow 0} sG(s)}$
Type 2	2	Parabolic	$e_{ss} = \frac{1}{\lim_{s \rightarrow 0} s^2 G(s)}$

TABLE 4.1.1: System Types and Poles at Origin

Using TABLE 4.1.1, (4.1.2) is Type 1 system.

$$e_{ss} = \frac{1}{\lim_{s \rightarrow 0} sG_c(s)} \quad (4.1.3) \quad 4.2 \text{ PID}$$

$$e_{ss} \leq \frac{1}{15} \lim_{s \rightarrow 0} sG_c(s) \quad (4.1.4)$$

$$\Rightarrow K_P K \geq \sqrt{15} \quad (4.1.5)$$

For Phase Margin  $45^\circ$ , at gain crossover frequency  $\omega$ ,

$$\tan^{-1}(T_d \omega) - \tan^{-1}(\omega) = -45^\circ \quad (4.1.6)$$

$$|G_c(j\omega)| = \frac{\sqrt{15} \sqrt{T_d^2 \omega^2 + 1}}{\omega \sqrt{\omega^2 + 1}} = 1 \quad (4.1.7)$$

By Hit and Trial, one of the best combinations is

$$\omega = 2.893 \quad (4.1.8)$$

$$T_d = -0.71 \quad (4.1.9)$$

Parameters	Required	Obtained
$\omega$	$\leq 7.5$	2.893
Phase Margin	$45^\circ$	$45^\circ$
$T_d$	Not Given	-0.71

TABLE 4.1.2

4.2. Verify using a Python Plot

**Solution:** The following code plots Fig. 4.1.2

```
codes/ee17btech11031_pd_ke.py
```

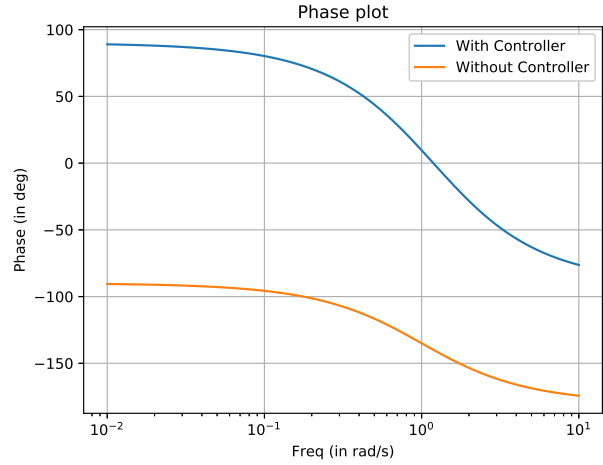


Fig. 4.1.2

Controller	Gain
PID	$K_p \left(1 + T_d s + \frac{1}{T_i s}\right)$
PD	$K_p(1 + T_d s)$
PI	$K_p \left(1 + \frac{1}{T_i s}\right)$

TABLE 4.2.1

4.2.2. For a unity Feedback system

$$G(s) = \frac{K}{s(s+2)(s+4)(s+6)} \quad (4.2.2.1)$$

Design a PD Controller with  $K_v = 2$  and Phase Margin  $30^\circ$

**Solution:** The gain after cascading the PD Controller with  $G(s)$  is

$$G_c(s) = \frac{K_p(1 + T_d s)K}{s(s+2)(s+4)(s+6)} \quad (4.2.2.2)$$

Choosing  $K_p = 1$  in ,

$$K_v = \lim_{s \rightarrow 0} sG_c(s) = 2 \quad (4.2.2.3)$$

$$\Rightarrow K = 96 \quad (4.2.2.4)$$

For Phase Margin  $30^\circ$ , at Gain Crossover Fre-

quency  $\omega$ ,

$$\tan^{-1}(T_d\omega) - \tan^{-1}\left(\frac{\omega}{2}\right) - \tan^{-1}\left(\frac{\omega}{4}\right) - \tan^{-1}\left(\frac{\omega}{6}\right) = -60^\circ \quad (4.2.2.5)$$

$$|G_1(j\omega)| = \frac{96\sqrt{T_d^2\omega^2 + 1}}{\omega\sqrt{(\omega^2 + 4)(\omega^2 + 16)(\omega^2 + 36)}} = 1 \quad (4.2.2.6)$$

By Hit and Trial, one of the best combinations is

$$\omega = 4 \quad (4.2.2.7)$$

$$T_d = 1.884 \quad (4.2.2.8)$$

We get a Phase Margin of  $30.31^\circ$

#### 4.2.3. Verify using a Python Plot

**Solution:** The following code plots Fig. 4.2.1

```
codes/ee18btech11021/EE18BTECH11021_3.py
```

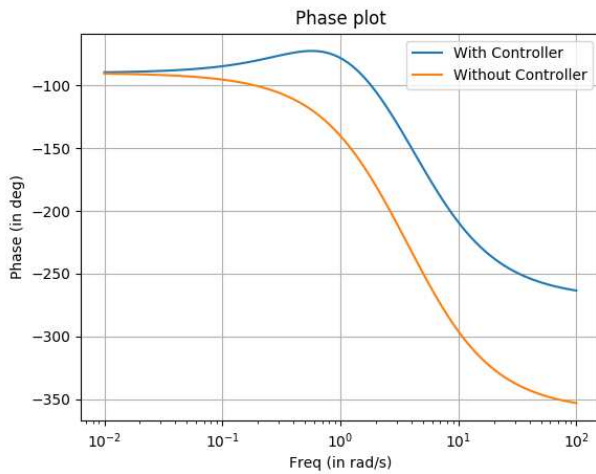


Fig. 4.2.1

#### 4.2.4. Design a PI Controller with $K_v = \infty$ and Phase Margin $30^\circ$

**Solution:** From Table 4.2.1, the open loop gain in this case is

$$G_1(s) = \frac{K_p \left(1 + \frac{1}{T_i s}\right) K}{s(s+2)(s+4)(s+6)} \quad (4.2.4.1)$$

Choose  $K_p K = 96$ . Then

$$G_1(s) = \frac{96(T_i s + 1)}{T_i s^2(s+2)(s+4)(s+6)} \quad (4.2.4.2)$$

For Phase Margin  $30^\circ$ , at Gain Crossover Frequency  $\omega$

$$\tan^{-1}(T_i\omega) - \tan^{-1}\left(\frac{\omega}{2}\right) - \tan^{-1}\left(\frac{\omega}{4}\right) - \tan^{-1}\left(\frac{\omega}{6}\right) = 30 \quad (4.2.4.3)$$

and

$$|G_1(j\omega)| = \frac{96\sqrt{T_i^2\omega^2 + 1}}{T_i^2\omega^2\sqrt{(\omega^2 + 4)(\omega^2 + 16)(\omega^2 + 36)}} = 1 \quad (4.2.4.4)$$

By Hit and Trial, one of the best combinations is

$$\omega = 0.75 \quad (4.2.4.5)$$

$$T_i = 2.713 \quad (4.2.4.6)$$

We get a Phase Margin of  $25.53^\circ$

#### 4.2.5. Verify using a Python Plot

**Solution:** The following code plots Fig. 4.2.2.

```
codes/ee18btech11021/EE18BTECH11021_4.py
```

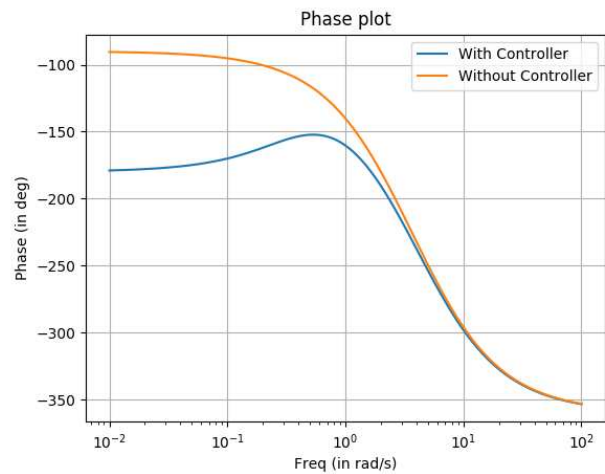


Fig. 4.2.2

#### 4.2.6. Design a PID Controller with $K_v = \infty$ and Phase Margin $30^\circ$

**Solution:**

$$G_1(s) = \frac{K_p \left(1 + T_d s + \frac{1}{T_i s}\right) K}{s(s+2)(s+4)(s+6)} \quad (4.2.6.1)$$

Choose  $K_p K = 96$ . The open loop gain is

$$G_1(s) = \frac{96(T_i T_d s^2 + T_i s + 1)}{T_i s^2(s+2)(s+4)(s+6)} \quad (4.2.6.2)$$

For Phase Margin  $30^\circ$ , at Gain Crossover Frequency  $\omega$ ,

$$\begin{aligned} \tan^{-1} \left( \frac{T_i \omega}{1 - T_i T_d \omega^2} \right) - \tan^{-1} \left( \frac{\omega}{2} \right) - \tan^{-1} \left( \frac{\omega}{4} \right) \\ - \tan^{-1} \left( \frac{\omega}{6} \right) = 30 \end{aligned} \quad (4.2.6.3)$$

$$\begin{aligned} |G_1(j\omega)| \\ = \frac{96 \sqrt{(1 - T_i T_d \omega^2)^2 + T_i^2}}{T_i^2 \omega^2 \sqrt{(\omega^2 + 4)(\omega^2 + 16)(\omega^2 + 36)}} = 1 \end{aligned} \quad (4.2.6.4)$$

By Hit and Trial, one of the best combinations is

$$\omega = 1 \quad (4.2.6.5)$$

$$T_i = 1.738 \quad (4.2.6.6)$$

$$T_d = 0.4 \quad (4.2.6.7)$$

We get a Phase Margin of  $30^\circ$

4.2.7. Verify using a Python Plot

**Solution:** The following code plots Fig. 4.2.3

```
codes/ee18btech11021/EE18BTECH11021_5.
py
```

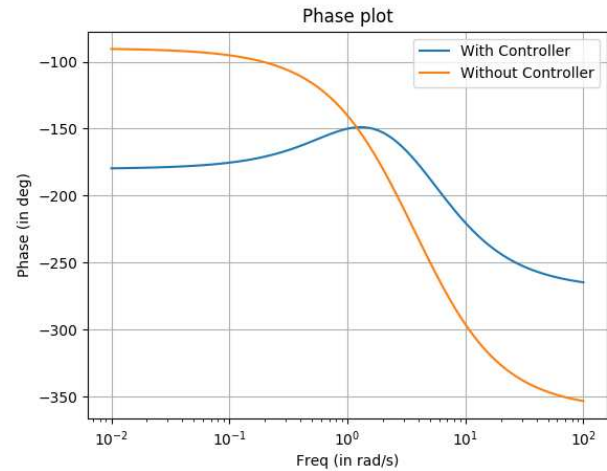


Fig. 4.2.3