

# Control Systems

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*Abstract*—This manual is an introduction to control systems based on GATE problems. Links to sample Python codes are available in the text.

Download python codes using

```
svn co https://github.com/gadepall/school/trunk/
control/codes
```

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## 1 SIGNAL FLOW GRAPH

### 1.1 Mason's Gain Formula

1.1.1. The Block diagram of a system is illustrated in the figure shown, where  $X(s)$  is the input and  $Y(s)$  is the output. Draw the equivalent signal flow graph.

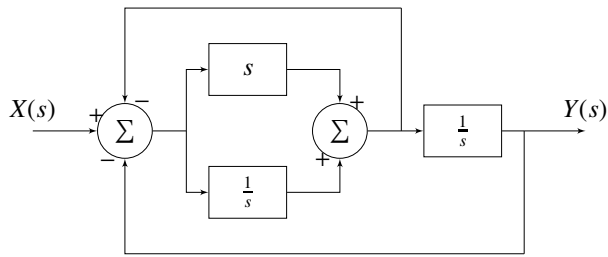


Fig. 1.1.1.1: Block Diagram

**Solution:** The signal flow graph of the block diagram in Fig. 1.1.1.1 is available in Fig. 1.1.1.2

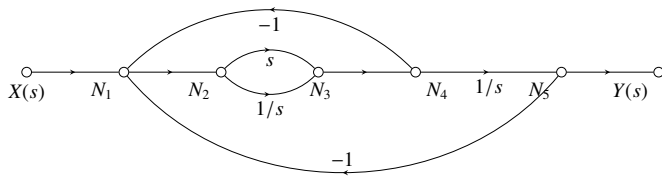


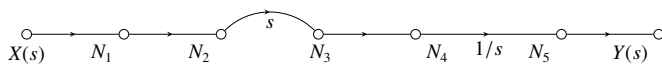
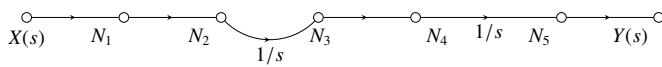
Fig. 1.1.1.2: Signal Flow Graph

1.1.2. Draw all the forward paths in Fig. 1.1.1.2 and compute the respective gains.

**Solution:** The forward paths are available in Figs. 1.1.2.3 and 1.1.2.4. The respective gains are

$$P_1 = s \left( \frac{1}{s} \right) = 1 \quad (1.1.2.1)$$

$$P_2 = (1/s)(1/s) = 1/s^2 \quad (1.1.2.2)$$

Fig. 1.1.2.3:  $P_1$ Fig. 1.1.2.4:  $P_2$ 

1.1.3. Draw all the loops in Fig. 1.1.1.2 and calculate the respective gains.

**Solution:** The loops are available in Figs.

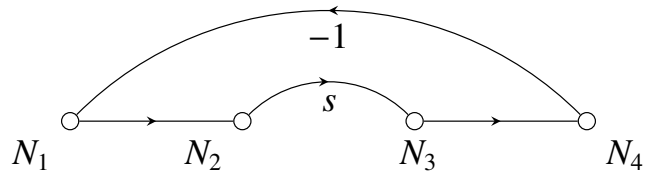
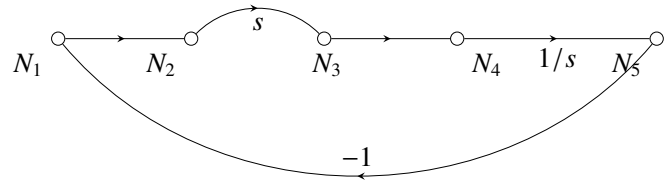
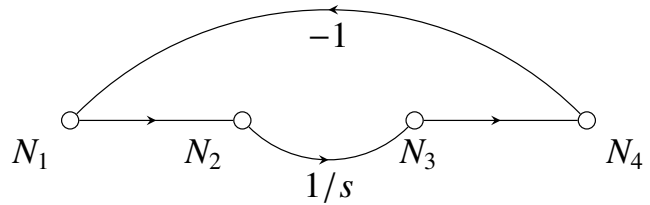
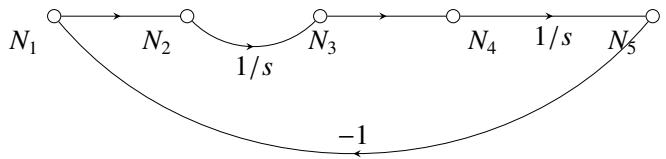
1.1.3.5-1.1.3.8 and the corresponding gains are

$$L_1 = (-1)(s) = -s \quad (1.1.3.1)$$

$$L_2 = s \left( \frac{1}{s} \right) (-1) = -1 \quad (1.1.3.2)$$

$$L_3 = \left( \frac{1}{s} \right) (-1) = -\frac{1}{s} \quad (1.1.3.3)$$

$$L_4 = \left( \frac{1}{s} \right) \left( \frac{1}{s} \right) (-1) = -\frac{1}{s^2} \quad (1.1.3.4)$$

Fig. 1.1.3.5:  $L_1$ Fig. 1.1.3.6:  $L_2$ Fig. 1.1.3.7:  $L_3$ Fig. 1.1.3.8:  $L_4$

1.1.4. State Mason's Gain formula and explain the parameters through a table.

**Solution:** According to Mason's Gain Formula,

$$T = \frac{Y(s)}{X(s)} \quad (1.1.4.1)$$

$$= \frac{\sum_{i=1}^N P_i \Delta_i}{\Delta} \quad (1.1.4.2)$$

where the parameters are described in Table 1.1.4

Variable	Description
$P_i$	$i$ th forward path
$L_j$	$j$ th loop
$\Delta$	$1 - \sum L_j + \sum_{L_i \cap L_j = \phi} L_i L_j - \sum_{L_i \cap L_j \cap L_k = \phi} L_i L_j L_k + \dots$
$\Delta_i$	$1 - \sum_{L_k \cap P_i = \phi} L_k + \sum_{L_k \cap L_j \cap P_i = \phi} L_k L_j - \dots$

TABLE 1.1.4

1.1.5. List the parameters in Table 1.1.4 for Fig. 1.1.1.2.

**Solution:** The parameters are available in Table 1.1.5

Path	Value	Parameter	Value	Remarks
$P_1$	1	$\Delta_1$	1	All loops intersect with $P_1$
$P_2$	$\frac{1}{s^2}$	$\Delta_2$	1	All loops intersect with $P_2$
$L_1$	$-s$	$\Delta$	$1 - \sum_i L_i$	All loops intersect
$L_2$	$-1$			
$L_3$	$-\frac{1}{s}$			
$L_4$	$-\frac{1}{s^2}$			

TABLE 1.1.5

1.1.6. Find the transfer function using Mason's Gain Formula.

**Solution:** From (1.1.4.2) and 1.1.5,

$$T(s) = \frac{P_1 \Delta_1 + P_2 \Delta_2}{\Delta} \quad (1.1.6.1)$$

$$= \frac{1 + \frac{1}{s^2}}{1 - (-s - 1 - \frac{1}{s} - \frac{1}{s^2})} \quad (1.1.6.2)$$

$$= \frac{s^2 + 1}{s^3 + 2s^2 + s + 1} \quad (1.1.6.3)$$

after simplification.

## 1.2 Matrix Formula

1.2.1. Write the transition equations in Fig. 1.1.1.2.

**Solution:** The equations are

$$N_1 = X(s) - N_4 - N_5 \quad (1.2.1.1)$$

$$N_2 = N_1 \quad (1.2.1.2)$$

$$N_3 = N_2(s + 1/s) \quad (1.2.1.3)$$

$$N_4 = N_3 \quad (1.2.1.4)$$

$$Y(s) = N_5 = N_4/s \quad (1.2.1.5)$$

1.2.2. Obtain the state transition matrix from (1.2.1.5)

**Solution:** The state transition matrix is

$$\mathbf{T} = \begin{pmatrix} 0 & 0 & 0 & -1 & -1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & s + 1/s & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1/s & 0 \end{pmatrix} \quad (1.2.2.1)$$

1.2.3. State the equivalent matrix form of Mason's gain formula

**Solution:** Let

$$\mathbf{U} = (\mathbf{I} - \mathbf{T})^{-1} \quad (1.2.3.1)$$

The gain from node m to node n of the graph is  $U_{nm}$

1.2.4. Find the transfer function for the system in Fig. 1.1.1.1

**Solution:** From (1.2.2.1) and (1.2.3.1),

$$\mathbf{I} - \mathbf{T} = \begin{pmatrix} 1 & 0 & 0 & 1 & 1 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & -s - 1/s & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1/s & 1 \end{pmatrix}$$

$$\Rightarrow U_{40} = \frac{\begin{vmatrix} -1 & 1 & 0 & 0 \\ 0 & -s - 1/s & 1 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1/s \end{vmatrix}}{\begin{vmatrix} 1 & 0 & 0 & 1 & 1 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & -s - 1/s & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1/s & 1 \end{vmatrix}}, \quad (1.2.4.1)$$

$$(1.2.4.2)$$

using the cofactor expansion and Problem

1.2.3. The gain is obtained as (1.1.6.3) after expanding the determinants and simplifying.

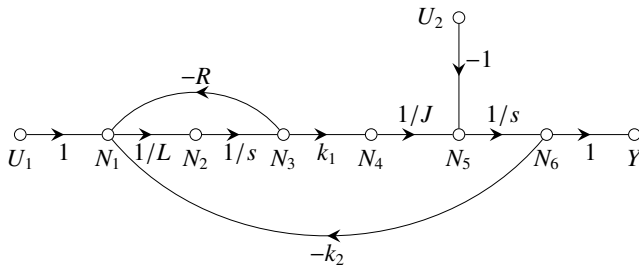
1.2.5. Write a program to compute the gain using the matrix method.

**Solution:** The following code computes the transfer function

codes/ee18btech11007/MasonsGain.py

### 1.3 Example

1.1. In a system whose signal flow graph is shown in the figure,  $U_1(s)$  and  $U_2(s)$  are inputs. Find the transfer function  $\frac{Y(s)}{U_1(s)}$ .



**Solution:** The desired transfer function is given by

$$\left. \frac{Y(s)}{U_1(s)} \right|_{U_2(s)=0} \quad (1.1.1)$$

The corresponding transition equations are

$$N_1 = U_1 - RN_3 - k_2N_6 \quad (1.1.2)$$

$$N_2 = \frac{N_1}{L} \quad (1.1.3)$$

$$N_3 = \frac{N_2}{s} \quad (1.1.4)$$

$$N_4 = k_1N_3 \quad (1.1.5)$$

$$N_5 = \frac{N_4}{J} \quad (1.1.6)$$

$$N_6 = \frac{N_5}{s} \quad (1.1.7)$$

and the state transition matrix is

$$\mathbf{T} = \begin{pmatrix} 0 & 0 & -R & 0 & 0 & -k_2 \\ \frac{1}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{s} & 0 & 0 & 0 & 0 \\ 0 & 0 & k_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{J} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{s} & 0 \end{pmatrix} \quad (1.1.8)$$

Defining

$$\mathbf{U} = (\mathbf{I} - \mathbf{T})^{-1} \quad (1.1.9)$$

$$= \begin{pmatrix} 1 & 0 & R & 0 & 0 & k_2 \\ \frac{-1}{L} & 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{-1}{s} & 1 & 0 & 0 & 0 \\ 0 & 0 & -k_1 & 1 & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{J} & 1 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{s} & 1 \end{pmatrix}^{-1} \quad (1.1.10)$$

the gain of the system is given by

$$U_{50} = \frac{Y(s)}{U_1(s)} = \frac{k_1}{s^2LJ + sRJ + k_1k_2} \quad (1.1.11)$$

computed by

codes/ee18btech11041.py

## 2 BODE PLOT

### 2.1 Introduction

2.1. For an LTI system, the Bode plot for its gain defined as

$$G(s) = 20 \log |H(s)| \quad (2.1.1)$$

is as illustrated in the Fig. 2.1. Express  $G(f)$  in terms of  $f$ .

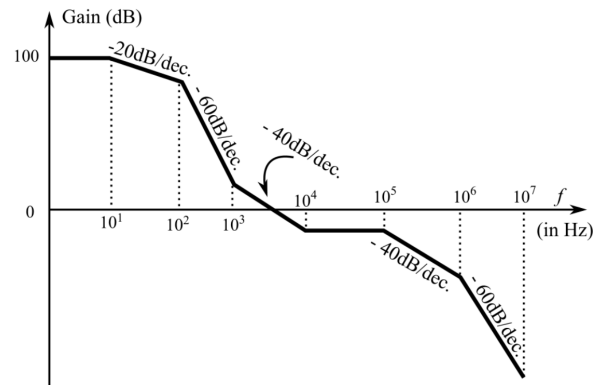


Fig. 2.1

**Solution:**

$$G(f) = \begin{cases} 100 & 0 < f < 10^1 \\ 120 - 20 \log(f) & 10 < f < 10^2 \\ 200 - 60 \log(f) & 10^2 < f < 10^3 \\ 140 - 40 \log(f) & 10^3 < f < 10^4 \\ -20 & 10^4 < f < 10^5 \\ 180 - 40 \log(f) & 10^5 < f < 10^6 \\ 300 - 60 \log(f) & 10^6 < f < 10^7 \end{cases} \quad (2.1.2)$$

2.2. Express the slope of  $G(f)$  in terms of  $f$ .

**Solution:** The desired slope is

$$\nabla G(f) = \frac{d(G(f))}{d(\log(f))} \quad (2.2.1)$$

$$\nabla G(f) = \begin{cases} 0 & 0 < f < 10^1 \\ -20 & 10 < f < 10^2 \\ -60 & 10^2 < f < 10^3 \\ -40 & 10^3 < f < 10^4 \\ 0 & 10^4 < f < 10^5 \\ -40 & 10^5 < f < 10^6 \\ -60 & 10^6 < f < 10^7 \end{cases} \quad (2.2.2)$$

2.3. Express the change of slope of  $G(f)$  in terms of  $f$ .

**Solution:**

$\Delta(\nabla G(f))$  = Change of slope  $G(f)$  at  $f$

$$\Delta(\nabla G(f)) = \begin{cases} -20 & f = 10^1 \\ -40 & f = 10^2 \\ +20 & f = 10^3 \\ +40 & f = 10^4 \\ -40 & f = 10^5 \\ -20 & f = 10^6 \end{cases} \quad (2.3.1)$$

2.4. Tabulate the poles and zeros of  $H(s)$  using (2.3.1).

**Solution:** Table 2.4 provides the details.

2.5. Obtain the transfer function of  $H(s)$ .

**Solution:** From Table 2.4,

$$H(s) = \frac{K(s + j2\pi 10^3)(s + j2\pi 10^4)^2}{(s + j2\pi 10^1)(s + j2\pi 10^2)^2(s + j2\pi 10^5)^2(s + j2\pi 10^6)} \quad (2.5.1)$$

2.6. Justify the above results.

**Solution:** Let us consider a generalized transfer

$f$ (Hz)	$\Delta(\nabla G(f))$	Pole	Zero
$10^1$	-20	1	0
$10^2$	-40	2	0
$10^3$	20	0	1
$10^4$	40	0	2
$10^5$	-40	2	0
$10^6$	-20	1	0
<b>Total</b>		<b>6</b>	<b>3</b>

TABLE 2.4

gain

$$H(s) = k \frac{(s - z_1)(s - z_2) \dots (s - z_{m-1})(s - z_m)}{(s - p_1)(s - p_2) \dots (s - p_{n-1})(s - p_n)} \quad (2.6.1)$$

The gain

$$\begin{aligned} G(f) &= 20 \log |H(s)| \\ &= 20 \log |k| + 20 \log |s - z_1| \\ &\quad + 20 \log |s - z_2| + \dots + 20 \log |s - z_m| \\ &\quad - 20 \log |s - p_1| - 20 \log |s - p_2| \\ &\quad - \dots - 20 \log |s - p_n| \end{aligned} \quad (2.6.2)$$

Substituting  $s = j\omega$ , for real  $z_1$

$$20 \log |s - z_1| = 20 \log \left| \sqrt{\omega^2 + z_1^2} \right| \quad (2.6.3)$$

$$= \begin{cases} 20 \log |z_1|, & \omega \ll z_1 \\ 20 \log |\omega|, & \omega \gg z_1 \end{cases} \quad (2.6.4)$$

Taking the derivative,

$$\frac{d(20 \log |s - z_1|)}{d(\log |\omega|)} = \begin{cases} 0, & \omega \ll z_1 \\ 20, & \omega \gg z_1 \end{cases} \quad (2.6.5)$$

Thus, when a zero is encountered, the gradient of  $H(j\omega)$  jumps by +20 in the log scale. When a pole is encountered, the gradient falls by -20. Note that this is a very loose justification, but works well in practice.

2.7. Obtain the Bode plot and the slope plot for  $H(s)$  and verify with Fig. 2.1

**Solution:** Bode Plot of obtained Transfer Function is Fig. ??, obtained from (2.5.1), is a close reconstruction of Fig. ??.

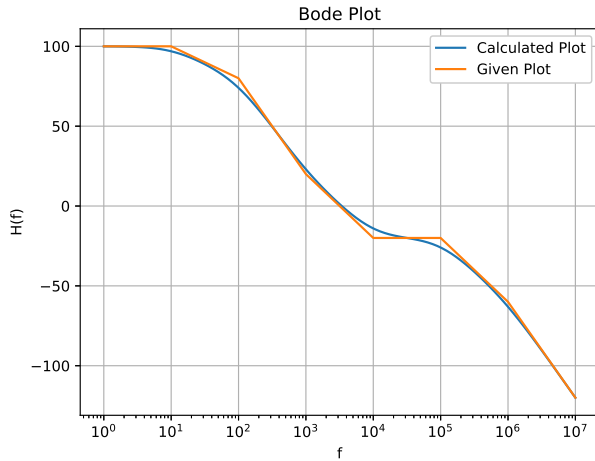


Fig. 2.7

## 2.2 Example

2.2.1. The asymptotic Bode magnitude plot of minimum phase transfer function  $G(s)$  is shown in Fig. 2.2.1. Express  $20 \log |G(j\omega)|$  as a function

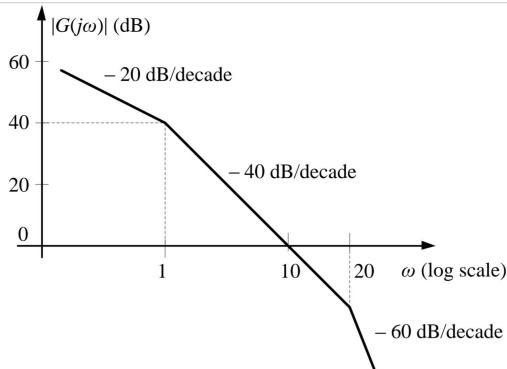


Fig. 2.2.1

of  $\omega$  using Fig. 2.2.1.

**Solution:** The desired expression (in dB) is

$$|G(j\omega)| = \begin{cases} 60 - 20(\log(\omega) - \log(0.1)) & 0.1 < \omega < 1 \\ 80 - 40(\log(\omega) - \log(0.1)) & 1 < \omega < 20 \\ 126.02 - 60(\log(\omega) - \log(0.1)) & 20 < \omega \end{cases} \quad (2.2.1.1)$$

2.2.2. Express the slope of  $20 \log |G(j\omega)|$  as a function of  $\omega$ .

**Solution:** The desired slope is

$$\nabla 20 \log |G(j\omega)| = \begin{cases} -20 & \omega < 1 \\ -40 & 1 < \omega < 20 \\ -60 & 20 < \omega \end{cases} \quad (2.2.2.1)$$

2.2.3. Express the change of slope of  $20 \log |G(j\omega)|$  as a function of  $\omega$ .

**Solution:**

$$\Delta(\nabla 20 \log |G(j\omega)|) = \begin{cases} -20 & \omega = 0 \\ -20 & \omega = 1 \\ -20 & \omega = 20 \end{cases} \quad (2.2.3.1)$$

2.2.4. Find the poles and zeros of  $G(s)$ .

**Solution:** From (2.2.3.1), the poles are located at 0, 1, 20. There are no zeros.

2.2.5. Find  $G(s)$

**Solution:**

$$G(s) = \frac{k}{s(1+s)(20+s)} \quad (2.2.5.1)$$

2.2.6. Obtain the Bode plot of  $G(s)$  through a python code and compare with the line plot of the expression that you obtained in Problem 2.2.1

**Solution:** Fig. 2.2.6 shows the Bode plot of the transfer function obtained. The **Line plot** is the approximation of the **calculated bode plot**.

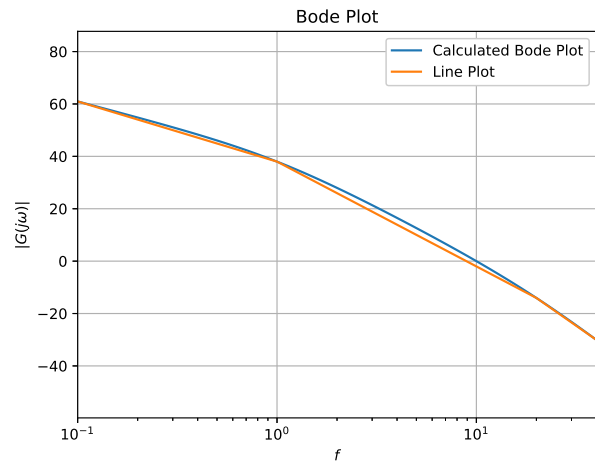


Fig. 2.2.6

2.2.7. Verify if at very high frequency ( $\omega \rightarrow \infty$ ), the phase angle  $\angle G(j\omega) = -3\pi/2$ .

**Solution:** Phase  $\phi$  is the sum of all the phases

corresponding to each pole and zero.

$$\Rightarrow G(j\omega) = \frac{k}{j\omega(1+j\omega)(20+j\omega)} \quad (2.2.7.1)$$

$$\Rightarrow \phi = -\tan^{-1}\left(\frac{\omega}{0}\right) - \tan^{-1}(\omega) - \tan^{-1}\left(\frac{\omega}{20}\right) \quad (2.2.7.2)$$

$$= -90^\circ - \tan^{-1}(\omega) - \tan^{-1}\left(\frac{\omega}{20}\right) \quad (2.2.7.3)$$

$$\Rightarrow \lim_{\omega \rightarrow \infty} \phi = -3\pi/2 \quad (2.2.7.4)$$

## 2.3 Phase

2.3.1. The asymptotic Bode phase plot of

$$G(s) = \frac{k}{(s+0.1)(s+10)(s+p_1)} \quad (2.3.1.1)$$

with  $k$  and  $p_1$  both positive, is shown in Fig. 2.3.1. Express it as a piecewise linear function of  $\log(\omega)$ .

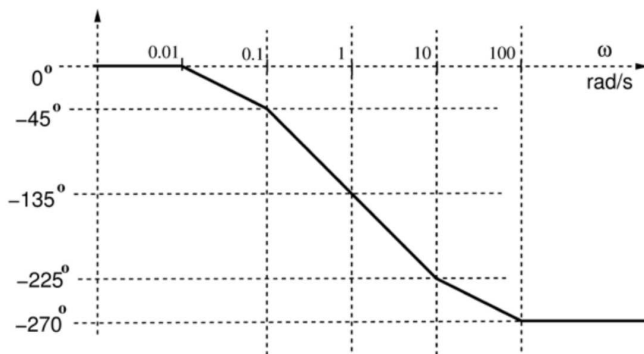


Fig. 2.3.1

**Solution:** The desired expression is

$$\phi(\omega) = \begin{cases} 0 & 0 < \omega < 0.01 \\ -90 - 45 \log(\omega) & 0.01 < \omega < 0.1 \\ -135 - 90 \log(\omega) & 0.1 < \omega < 10 \\ -180 - 45 \log(\omega) & 10 < \omega < 100 \\ -90 & 100 < \omega \end{cases} \quad (2.3.1.2)$$

2.3.2. Find  $p_1$ .

**Solution:** Let

$$G_1(s) = \frac{1}{(s+p_1)} \quad (2.3.2.1)$$

The equivalent Bode phase is

$$\phi_1(\omega) = \angle G_1(j\omega) = \begin{cases} 0 & 0 < \omega < \frac{p_1}{10} \\ -45 \times \left(\log\left(\frac{10\omega}{p_1}\right)\right) & \frac{p_1}{10} < \omega < 10p_1 \\ -90 & 10p_1 < \omega \end{cases} \quad (2.3.2.2)$$

Similarly, let

$$G_2(s) = \frac{k}{(s+0.1)(s+10)}. \quad (2.3.2.3)$$

The equivalent Bode phase is

$$\phi_2(\omega) = \angle G_2(j\omega) = \begin{cases} 0 & 0 < \omega < 0.01 \\ -90 - 45 \log(\omega) & 0.01 < \omega < 100 \\ -180 & 100 < \omega \end{cases} \quad (2.3.2.4)$$

Hence, from (2.3.2.2) and (2.3.2.4),

$$\phi(\omega) = \phi_1(\omega) + \phi_2(\omega) \quad (2.3.2.5)$$

From (2.3.1.2) and (2.3.2.4)

$$\phi(\omega) = \phi_2(\omega) \quad 0 < \omega < 0.1 \quad (2.3.2.6)$$

$$\Rightarrow \phi_1(\omega) = 0 \quad 0 < \omega < 0.1 \quad (2.3.2.7)$$

This is obvious from Figs. 2.3.2 and Fig. 2.3.1. Thus,

$$\frac{p_1}{10} = 0.1 \Rightarrow p_1 = 1 \quad (2.3.2.8)$$

The following code generates Fig. 2.3.2

codes/ee18btech11037.py

2.3.3. Find the value of  $p_1$  using phase of the transfer function.

**Solution:**

$$\phi(\omega) = -\tan^{-1}\left(\frac{\omega}{0.1}\right) - \tan^{-1}\left(\frac{\omega}{10}\right) - \tan^{-1}\left(\frac{\omega}{p_1}\right) \quad (2.3.3.1)$$

From the plot,

$$-45^\circ = -\tan^{-1}\left(\frac{0.1}{0.1}\right) - \tan^{-1}\left(\frac{0.1}{10}\right) - \tan^{-1}\left(\frac{0.1}{p_1}\right) \quad (2.3.3.2)$$

$p_1$  is approximately 1, i.e., for  $p_1$  in 0.95 to 1.05 the  $\phi$  is approximately equals to  $-45^\circ$ .

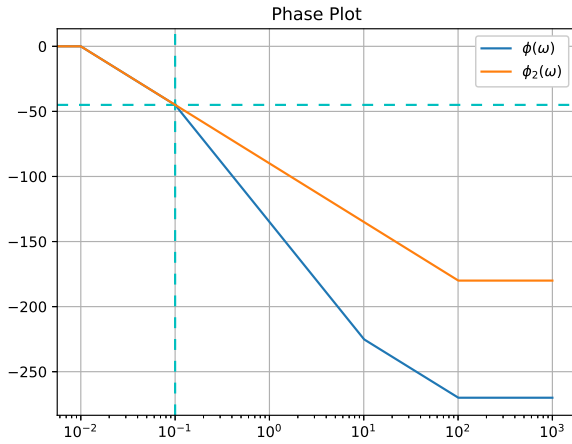


Fig. 2.3.2

#### 2.4 Example

2.1. For an LTI system, the Bode plot for its gain defined as

$$G(s) = 20 \log |H(s)| \quad (2.1.1)$$

is as illustrated in the Fig. 2.1. Find the corner frequencies  $\omega_{01}$  and  $\omega_{02}$  from the plot.

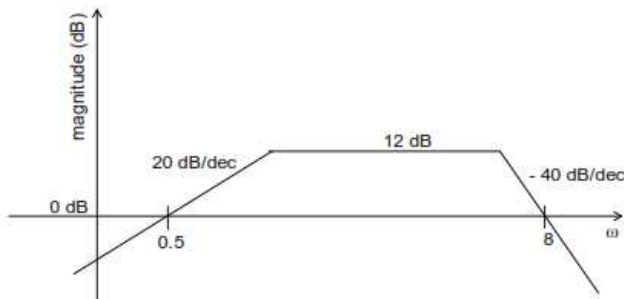


Fig. 2.1

**Solution:** The corner frequencies can be calculated using

$$\text{slope} = \frac{M_2 - M_1}{\log \omega_2 - \log \omega_1} \quad (2.1.2)$$

$$\Rightarrow -40 = \frac{0 - 12}{\log 8 - \log \omega_{02}} \quad \text{and} \quad (2.1.3)$$

$$20 = \frac{0 - 12}{\log 0.5 - \log \omega_{01}} \quad (2.1.4)$$

$$\Rightarrow \omega_{02} = 4, \omega_{01} = 2 \quad (2.1.5)$$

2.2. Express the given bode plot as a piece-wise linear function.

**Solution:**

$$|G(j\omega)| = \begin{cases} 20 \log 2\omega & 0 < \omega \leq 2 \\ 12 & 2 \leq \omega \leq 4 \\ -40 \log \frac{\omega}{8} & \omega \geq 4 \end{cases} \quad (2.2.1)$$

2.3. Find the transfer function from the calculated frequencies.

**Solution:** From Fig. 2.1 we observe the following

- Since the initial slope is +20, there must be a zero at the origin.
- At  $\omega_{01}$ , the change in slope is -20dB, so there exists one pole at this frequency.
- At  $\omega_{02}$ , the change in slope is -40dB, so there exist two poles at this frequency.

Therefore, the transfer function is,

$$G(s) = \frac{Ks}{\left(1 + \frac{s}{2}\right)\left(1 + \frac{s}{4}\right)^2} \quad (2.3.1)$$

2.4. Verify (2.3.1) by plotting the bode plot and comparing with Fig. 2.1.

**Solution:** Se Fig. 2.4 generated by

codes/ep18btech11016.py

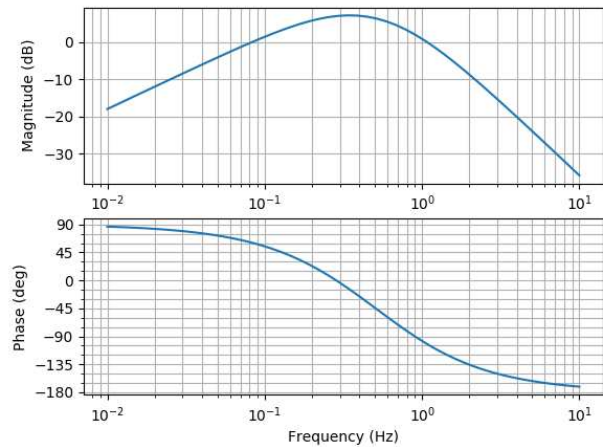


Fig. 2.4: Plot of G(s)



### 3 SECOND ORDER SYSTEM

#### 3.1 Damping

3.1.1. List the different kinds of damping for a second order system defined by

$$H(s) = \frac{\omega^2}{s^2 + 2\zeta\omega + \omega^2} \quad (3.1.1.1)$$

where  $\omega$  is the natural frequency and  $\zeta$  is the damping factor.

**Solution:** The details are available in Table 3.1.1

Damping Ratio	Damping Type
$\zeta > 1$	Overdamped
$\zeta = 1$	Critically Damped
$0 < \zeta < 1$	Underdamped
$\zeta = 0$	Undamped

TABLE 3.1.1

3.1.2. Classify the following second-order systems according to damping.

a)  $H(s) = \frac{15}{s^2 + 5s + 15}$

b)  $H(s) = \frac{25}{s^2 + 10s + 25}$

c)  $H(s) = \frac{35}{s^2 + 18s + 35}$

**Solution:** For

$$H(s) = \frac{25}{s^2 + 10s + 25}, \quad (3.1.2.1)$$

$$\omega^2 = 25, 2\zeta\omega = 10 \quad (3.1.2.2)$$

$$\Rightarrow \omega = 5, \zeta = 1 \quad (3.1.2.3)$$

and the system is critically damped. Similarly, the damping factors for other systems in Problem 3.1.2 are calculated and listed in Table 3.1.2

H(s)	$\omega$	$\zeta$	Damping Type
$\frac{35}{s^2 + 18s + 35}$	$\sqrt{35}$	$\sqrt{\frac{81}{35}} > 1$	Overdamped
$\frac{25}{s^2 + 10s + 25}$	5	1	Critically Damped
$\frac{15}{s^2 + 5s + 15}$	$\sqrt{15}$	$\sqrt{\frac{5}{12}} < 1$	Underdamped

TABLE 3.1.2

3.1.3. Find the step response of each  $H(s)$  in Table 3.1.2.

**Solution:**

a) For

$$H(s) = \frac{15}{s^2 + 5s + 15}, \quad (3.1.3.1)$$

the step response is

$$y(t) = 25te^{-5t}u(t) \quad (3.1.3.2)$$

b) For

$$H(s) = \frac{25}{s^2 + 10s + 25}, \quad (3.1.3.3)$$

the step response is

$$y(t) = \frac{30}{\sqrt{35}}e^{-\frac{5}{2}t} \sin\left(\frac{\sqrt{35}}{2}t\right)u(t) \quad (3.1.3.4)$$

c) For

$$H(s) = \frac{35}{s^2 + 18s + 35}, \quad (3.1.3.5)$$

the step response is

$$y(t) = \frac{35}{2\sqrt{46}} \left[ e^{(-9+\sqrt{46})t} - e^{(-9-\sqrt{46})t} \right] u(t) \quad (3.1.3.6)$$

3.1.4. Illustrate the effect of damping by plotting the step responses in (3.1.3.2)-(3.1.3.6)

**Solution:** The following code

```
codes/ee18btech11012.py
```

plots the desired graphs in Fig. 3.1.4.

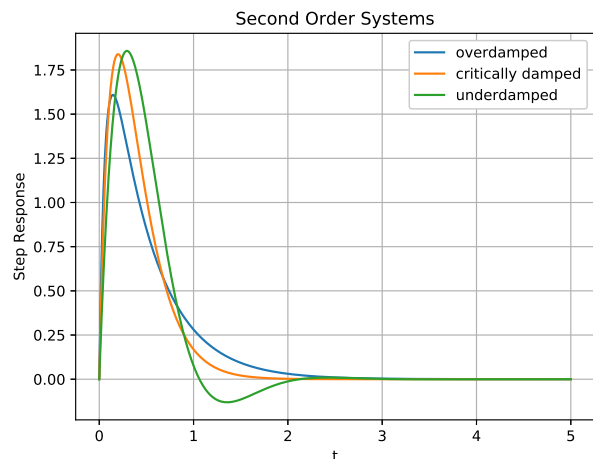


Fig. 3.1.4

### 3.2 Peak Overshoot

3.2.1. Find the peak overshoot for the second order control system given by:

$$G(s) = \frac{100}{s^2 + 10s + 100} \quad (3.2.1.1)$$

**Solution:** The step response is

$$\Rightarrow C(s) = \frac{100}{s(s^2 + 10s + 100)} \quad (3.2.1.2)$$

From the Final Value theorem

$$\lim_{s \rightarrow 0} sC(s) = \lim_{t \rightarrow \infty} c(t) = 1 \quad (3.2.1.3)$$

and by taking the inverse laplace transform

$$c(t) = 1 - \frac{2e^{-5t}}{\sqrt{3}} \cdot \sin\left(5\sqrt{3}t + \frac{\pi}{3}\right) \quad (3.2.1.4)$$

At  $t_p$ ,  $c(t)$  is maximum if

$$c'(t)|_{t=t_p} = 0 \quad (3.2.1.5)$$

$$\Rightarrow t_p = \frac{n\pi}{5\sqrt{3}}, \quad n = 1 \quad (3.2.1.6)$$

$$= \frac{\pi}{5\sqrt{3}} \quad (3.2.1.7)$$

after some algebra. From (3.2.1.4)

$$c(t_p) = 1 + e^{\frac{-\pi}{\sqrt{3}}} \quad (3.2.1.8)$$

$$\Rightarrow c(t_p) - c(\infty) = e^{\frac{-\pi}{\sqrt{3}}} \quad (3.2.1.9)$$

$$= 0.163 \quad (3.2.1.10)$$

which is the peak overshoot. The following code illustrates this in Fig. 3.2.1

codes/ee18btech11045.py

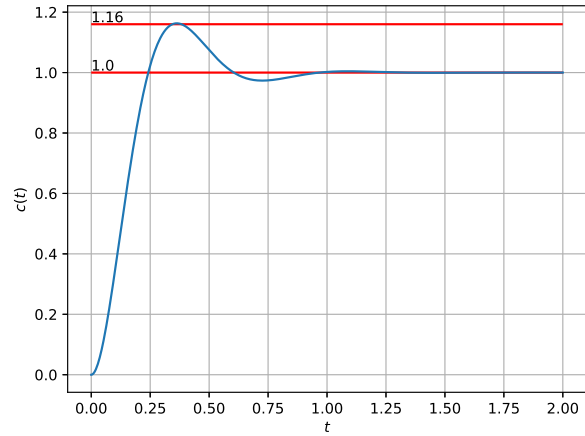


Fig. 3.2.1

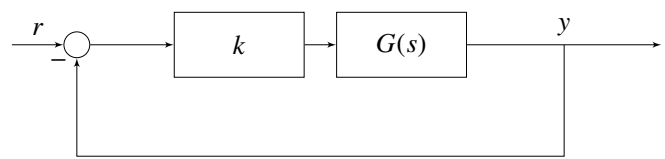


Fig. 3.3.1

after substituting from (3.3.1.1).

3.3.2. Find the step response of the system.

**Solution:** From (3.3.1.3), the step response is

$$Y(s) = \frac{k}{s^2 + 2s + k} \frac{1}{s} \quad (3.3.2.1)$$

$$\begin{aligned} \Rightarrow y(t) = & \left[ 1 + \frac{k}{(2\sqrt{1-k})(-1 + \sqrt{1-k})} e^{(-1 + \sqrt{1-k})t} \right. \\ & \left. + \frac{k}{(2\sqrt{1-k})(1 + \sqrt{1-k})} e^{(-1 - \sqrt{1-k})t} \right] u(t) \end{aligned} \quad (3.3.2.2)$$

$k \neq 1$

and

$$y(t) = (1 - e^{-t} - te^{-t}) u(t) \quad k = 1 \quad (3.3.2.3)$$

3.3.3. Find the steady state step response of the system using the final value theorem.

**Solution:** From (3.3.2.1),

$$\lim_{t \rightarrow \infty} y(t) = \lim_{s \rightarrow 0} sY(s) \quad (3.3.3.1)$$

$$= 1 \quad (3.3.3.2)$$

3.3.4. Find the step response for an overdamped

### 3.3 Settling Time

3.3.1. Find the closed loop transfer function for the system in Fig. given that

$$G(s) = \frac{1}{s^2 + 2s} \quad (3.3.1.1)$$

**Solution:** The closed loop transfer function is

$$H(s) = \frac{kG(s)}{1 + kG(s)} \quad (3.3.1.2)$$

$$= \frac{k}{s^2 + 2s + k} \quad (3.3.1.3)$$

system.

**Solution:** For an overdamped system,  $k < 1$ ,

$$\Rightarrow y(t) = \left[ 1 - e^{-t} \left\{ \frac{\sinh(\sqrt{1-k})t}{\sqrt{1-k}} + \cosh(\sqrt{1-k})t \right\} \right] u(t) \quad (3.3.4.1)$$

3.3.5. Find the step response for an underdamped system.

**Solution:** In this case,  $k > 1$ .

$$\Rightarrow y(t) = \left[ 1 - e^{-t} \left\{ \frac{\sin(\sqrt{k-1})t}{\sqrt{k-1}} + \cos(\sqrt{k-1})t \right\} \right] u(t) \quad (3.3.5.1)$$

3.3.6. Find the step response for a critically damped system.

**Solution:** For  $k = 1$ ,

$$y(t) = (1 - e^{-t} - te^{-t}) u(t) \quad (3.3.6.1)$$

3.3.7. The settling time  $t_s$  is defined as the first instant where

$$|y(t_s) - y_{ss}| \leq 0.02 \quad (3.3.7.1)$$

where  $y_{ss}$  is the steady state value of  $y(t)$ . Find  $k$  for which the settling time is minimum.

### 3.4 Example

3.1. Consider the following second order system with the transfer function

$$G(s) = \frac{1}{1 + 2s + s^2} \quad (3.1.1)$$

Is the system stable?

**Solution:** The poles of

$$G(s) = \frac{1}{1 + 2s + s^2} \quad (3.1.2)$$

are at

$$s = -1 \quad (3.1.3)$$

i.e., the left half of s-plane. Hence the system is stable.

3.2. Find and sketch the step response  $c(t)$  of the system.

**Solution:** For step-response, we take input as

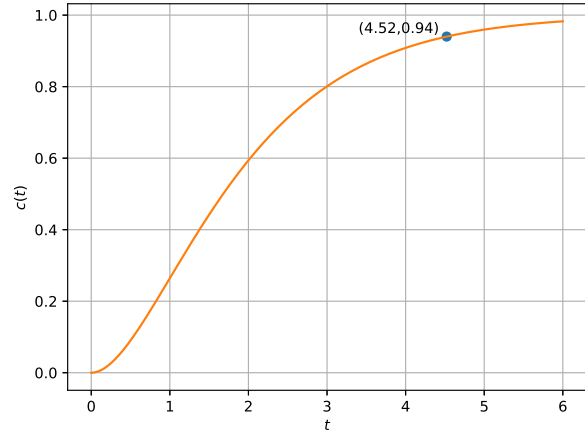


Fig. 3.2

unit-step function  $u(t)$

$$C(s) = U(s).G(s) = \left[ \frac{1}{s} \right] \left[ \frac{1}{1 + 2s + s^2} \right] \quad (3.2.1)$$

$$= \frac{1}{s(1 + s)^2} \quad (3.2.2)$$

$$= \frac{1}{s} - \frac{1}{(1 + s)} - \frac{1}{(1 + s)^2} \quad (3.2.3)$$

Taking the inverse Laplace transform,

$$c(t) = L^{-1} \left[ \frac{1}{s} \right] - L^{-1} \left[ \frac{1}{1 + s} \right] - L^{-1} \left[ \frac{1}{(1 + s)^2} \right] \quad (3.2.4)$$

$$= (1 - e^{-t} - te^{-t}) u(t) \quad (3.2.5)$$

The following code plots  $c(t)$  in Fig. 3.2

codes/ee18btech11002/plot.py

3.3. Find the steady state response of the system using the final value theorem. Verify using 3.2.5

**Solution:** To know the steady response value of  $c(t)$ , using final value theorem,

$$\lim_{t \rightarrow \infty} c(t) = \lim_{s \rightarrow 0} sC(s) \quad (3.3.1)$$

We get

$$\lim_{s \rightarrow 0} s \left( \frac{1}{s} \right) \left( \frac{1}{1 + s + s^2} \right) = \frac{1}{1 + 0 + 0} = 1 \quad (3.3.2)$$

Using 3.2.5,

$$\lim_{t \rightarrow \infty} c(t) = \lim_{t \rightarrow \infty} (1 - e^{-t} - te^{-t}) u(t) \quad (3.3.3)$$

$$= (1 - 0 - 0) = 1 \quad (3.3.4)$$

3.4. Find the time taken for the system output  $c(t)$  to reach 94% of its steady state value.

**Solution:** Now, 94% of 1 is 0.94, so we should now solve for a positive  $t$  such that

$$1 - e^{-t} - te^{-t} = 0.94 \quad (3.4.1)$$

The following code

```
codes/ee18btech11002/solution.py
```

provides the necessary solution as

$$t = 4.5228 \quad (3.4.2)$$

### 3.5 Example

3.1. A second-order real system has the following properties

- the damping ratio  $\zeta = 0.5$  and undamped natural frequency  $\omega_n = 10\text{rad/s}$
- the steady state value of the output, to a unit step input, is 1.02.

Find the transfer function of the system.

**Solution:** The general transfer function of a second order system is given by (3.1.1.1)

$$H(s) = \frac{k\omega^2}{s^2 + 2\zeta\omega s + \omega^2} \quad (3.1.1)$$

From the given information,

$$\zeta = 0.5 \quad (3.1.2)$$

$$\omega = 10 \quad (3.1.3)$$

$$c(\infty) = \lim_{s \rightarrow 0} s \frac{kH(s)}{s} = 1.02 \quad (3.1.4)$$

$$\Rightarrow c(\infty) = k = 1.02 \quad (3.1.5)$$

using the final value theorem, where  $c(t)$  is the step response.  $\therefore$ , transfer function of the system is

$$H(s) = \frac{102}{s^2 + 10s + 100} \quad (3.1.6)$$

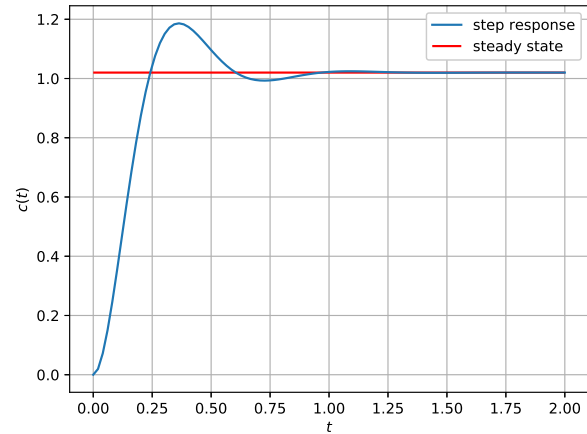


Fig. 3.1

The step response of the transfer function is

$$c(t) = e^{-5t} \left\{ \left( \frac{-51}{50} \right) \cos(5\sqrt{3}t) - \left( \frac{17\sqrt{3}}{50} \right) \sin(5\sqrt{3}t) \right\} + \frac{51}{50} u(t) \quad (3.1.7)$$

The following code plots the step response in Fig. 3.1.

```
codes/es17btech11015.py
```

## 4 ROUTH HURWITZ CRITERION

### 4.1 Routh Array

4.1.1. Generate the Routh array for the polynomial,

$$f(s) = s^7 + s^6 + 7s^5 + 14s^4 + 31s^3 + 73s^2 + 25s + 200 \quad (4.1.1.1)$$

**Solution:**

$$\begin{vmatrix} s^7 \\ s^6 \\ s^5 \end{vmatrix} \begin{vmatrix} 1 & 7 & 31 & 25 \\ 1 & 14 & 73 & 200 \\ -7 & -42 & -175 & 0 \end{vmatrix} \quad (4.1.1.2)$$

$$\begin{vmatrix} s^7 \\ s^6 \\ s^5 \\ s^4 \end{vmatrix} \begin{vmatrix} 1 & 7 & 31 & 25 \\ 1 & 14 & 73 & 200 \\ -7 & -42 & -175 & 0 \\ 8 & 48 & 200 & 0 \end{vmatrix} \quad (4.1.1.3)$$

$$\begin{array}{c|cccc} s^7 & 1 & 7 & 31 & 25 \\ s^6 & 1 & 14 & 73 & 200 \\ s^5 & -7 & -42 & -175 & 0 \\ s^4 & 8 & 48 & 200 & 0 \\ s^3 & 0 & 0 & 0 & \end{array} \quad (4.1.1.4)$$

When such a case is encountered, we take the derivative of the expression formed the the coefficients above it i.e derivative of  $8s^4+48s^2+200$ .

$$\frac{d}{dx}(8s^4 + 48s^2 + 200) = 32s^3 + 96s \quad 4.1.3.$$

The coefficients of obtained expression are placed in the table.

$$\begin{array}{c|cccc} s^7 & 1 & 7 & 31 & 25 \\ s^6 & 1 & 14 & 73 & 200 \\ s^5 & -7 & -42 & -175 & 0 \\ s^4 & 8 & 48 & 200 & 0 \\ s^3 & 32 & 96 & 0 & \end{array} \quad (4.1.1.5)$$

$$\begin{array}{c|cccc} s^7 & 1 & 7 & 31 & 25 \\ s^6 & 1 & 14 & 73 & 200 \\ s^5 & -7 & -42 & -175 & 0 \\ s^4 & 8 & 48 & 200 & 0 \\ s^3 & 32 & 96 & 0 & \\ s^2 & 24 & 200 & 0 & \end{array} \quad (4.1.1.6)$$

$$\begin{array}{c|cccc} s^7 & 1 & 7 & 31 & 25 \\ s^6 & 1 & 14 & 73 & 200 \\ s^5 & -7 & -42 & -175 & 0 \\ s^4 & 8 & 48 & 200 & 0 \\ s^3 & 32 & 96 & 0 & \\ s^2 & 24 & 200 & 0 & \\ s^1 & -170.67 & 0 & & \end{array} \quad (4.1.1.7)$$

$$\begin{array}{c|cccc} s^7 & 1 & 7 & 31 & 25 \\ s^6 & 1 & 14 & 73 & 200 \\ s^5 & -7 & -42 & -175 & 0 \\ s^4 & 8 & 48 & 200 & 0 \\ s^3 & 32 & 96 & 0 & \\ s^2 & 24 & 200 & 0 & \\ s^1 & -170.67 & 0 & & \\ s^0 & 200 & & & \end{array} \quad (4.1.1.8)$$

So, the above one is the Routh-Hurwitz Table. Find the number of roots of the polynomial in the right half of the  $s$ -plane.

**Solution:** The number of roots of the polynomial that are in the right half-plane is equal to the number of sign changes in the first column. From 4.1.1.8, the polynomial in (4.1.1.1) has 4 roots lie on right-side of Imaginary Axis.

4.1.3. Write a Python code for generating each stage of the Routh Table.

**Solution:** The following code

```
codes/ee18btech11014/ee18btech11014.py
```

generates the various stages.

4.1.4. Find the roots of the polynomial in in (4.1.1.1) and verify that 4 roots are in the right half  $s$ -plane.

**Solution:** The following code generates the necessary roots.

```
codes/ee18btech11014/Roots.py
```

## 4.2 Marginal Stability

4.2.1. Consider a unity feedback system as shown in Fig. 4.2.1, with an integral compensator  $\frac{k}{s}$  and open-loop transfer function

$$G(s) = \frac{1}{s^2 + 3s + 2} \quad (4.2.1.1)$$

where  $k$  greater than 0. Find its closed loop transfer function.

**Solution:**  $\because H(s) = 1$  in Fig. 4.2.1, due to unity feedback, the transfer function is given by

$$\frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)H(s)} \quad (4.2.1.2)$$

$$\Rightarrow T(s) = \frac{k}{s^3 + 3s^2 + 2s} \quad (4.2.1.3)$$

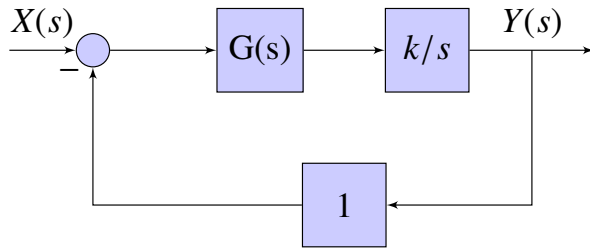


Fig. 4.2.1

4.2.2. Find the *characteristic* equation for  $G(s)$ .

**Solution:** The characteristic equation is

$$1 + G(s)H(s) = 0 \quad (4.2.2.1)$$

$$\Rightarrow 1 + \left[ \frac{k}{s^3 + 3s^2 + 2s} \right] = 0 \quad (4.2.2.2)$$

$$\text{or, } s^3 + 3s^2 + 2s + k = 0 \quad (4.2.2.3)$$

4.2.3. Using the tabular method for the Routh hurwitz criterion, find  $k > 0$  for which there are two poles of unity feedback system on  $j\omega$  axis.

**Solution:** This criterion is based on arranging the coefficients of characteristic equation into an array called Routh array. For any characteristic equation

$$q(s) = a_0 s^n + a_1 s^{n-1} + \dots + a_{n-1} s + a_n = 0 \quad (4.2.3.1)$$

the Routh array can be constructed as

$$\begin{array}{c|cccc} s^n & a_0 & a_2 & a_4 & \dots \\ s^{n-1} & a_1 & a_3 & a_5 & \dots \\ s^{n-2} & b_1 & b_2 & b_3 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{array} \quad (4.2.3.2)$$

where

$$b_1 = \frac{a_1 a_2 - a_0 a_3}{a_1} \quad (4.2.3.3)$$

$$b_2 = \frac{a_1 a_4 - a_0 a_5}{a_1} \quad (4.2.3.4)$$

$$c_1 = \frac{b_1 a_3 - a_1 b_2}{b_1} \quad (4.2.3.5)$$

$$c_2 = \frac{b_1 a_5 - a_1 b_3}{b_1} \quad (4.2.3.6)$$

For poles to lie on imaginary axis any one entire row of hurwitz matrix should be zero. Constructing the routh array for the character-

istic equation obtained in 4.2.2.1,

$$s^3 + 3s^2 + 2s + k = 0 \quad (4.2.3.7)$$

$$\begin{array}{c|cc} s^3 & 1 & 2 \\ s^2 & 3 & k \\ s^1 & \frac{6-k}{3} & 0 \\ s^0 & k & 0 \end{array} \quad (4.2.3.8)$$

For poles on  $j\omega$  axis any one of the row should be zero.

$$\therefore \frac{6-k}{3} = 0 \text{ or } k = 0 \quad (4.2.3.9)$$

$$\Rightarrow k = 6 \quad \because k > 0 \quad (4.2.3.10)$$

4.2.4. Repeat the above using the determinant method.

**Solution:** The *Routh matrix* can be expressed as

$$\mathbf{R} = \begin{pmatrix} a_0 & a_2 & a_4 & \dots \\ a_1 & a_3 & a_5 & \dots \\ 0 & a_0 & a_2 & \dots \\ 0 & a_1 & a_3 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \quad (4.2.4.1)$$

and the corresponding Routh determinants are

$$D_1 = |a_0| \quad (4.2.4.2)$$

$$D_2 = \begin{vmatrix} a_0 & a_2 \\ a_1 & a_3 \end{vmatrix} \quad (4.2.4.3)$$

$$D_3 = \begin{vmatrix} a_0 & a_2 & a_4 \\ a_1 & a_3 & a_5 \\ 0 & a_0 & a_2 \end{vmatrix} \quad (4.2.4.4)$$

$$\dots \quad (4.2.4.5)$$

If at least any one of the Determinants are zero then the poles lie on imaginary axes. From (4.2.2.1),

$$D_1 = 1 \neq 0 \quad (4.2.4.6)$$

$$D_2 = \begin{vmatrix} 1 & 2 \\ 3 & k \end{vmatrix} = k - 6 = 0 \Rightarrow k = 6 \quad (4.2.4.7)$$

4.2.5. Verify your answer using a python code for both the determinant method as well as the tabular method.

**Solution:** The following code verifies the stability using the tabular method

```
codes/ee18btech11005_2.py
```

and the following one verifies using the determinant method.

codes/ee18btech11005.py

provides the necessary solution.

- For the system to be stable all coefficients should lie on left half of s-plane. Because if any pole is in right half of s-plane then there will be a component in output that increases without bound, causing system to be unstable. All the coefficients in the characteristic equation should be positive. This is necessary condition but not sufficient. Because it may have poles on right half of s plane. Poles are the roots of the characteristic equation.
- A system is stable if all of its characteristic modes go to finite value as  $t$  goes to infinity. It is possible only if all the poles are on the left half of s plane. The characteristic equation should have negative roots only. So the first column should always be greater than zero. That means no sign changes.
- A system is unstable if its characteristic modes are not bounded. Then the characteristic equation will also have roots in the right side of s-plane. That means it has sign changes.

### 4.3 Stability

4.3.1. The characteristic equation of linear time invariant system is given by

$$\nabla(s) = s^4 + 3s^3 + 3s^2 + s + k = 0 \quad (4.3.1.1)$$

Find the condition for the system to be BIBO stable using the Routh Array.

**solution**

$$\nabla(s) = s^4 + 3s^3 + 3s^2 + s + k = 0 \quad (4.3.1.2)$$

The Routh Hurwitz criterion:-

$$\begin{array}{c|ccc} s^4 & 1 & 3 & k \\ s^3 & 3 & 1 & 0 \\ s^2 & \frac{8}{3} & k & 0 \\ s^1 & \frac{8}{3} - 3k & 0 & 0 \\ s^0 & k & 0 & 0 \end{array} \quad (4.3.1.3)$$

From the above array, the given system is stable if

$$k > 0 \quad (4.3.1.4)$$

$$\frac{\frac{8}{3} - 3k}{\frac{8}{3}} > 0$$

$$\Rightarrow 0 < k < \frac{8}{9} \quad (4.3.1.5)$$

4.3.2. Modify the Python code in Problem 4.2.5 to verify your solution by choosing two different values of  $k$ .

**Solution:** The following code

codes/ee18btech11008.py

provides the necessary solution for  $k = 0.5, 3$ .

- $k = 0.5 < \frac{8}{9}$  has no sign changes in first column of its Routh array. So the system is stable.
- $k = 3 > \frac{8}{9}$  has 2 sign changes in first column of its Routh array. So the system is unstable.

### 4.4 Example

4.4.1. Consider a standard control system with negative feedback and the transfer functions

$$G(s) = \frac{1}{(s+1)(s+2)} \quad (4.4.1.1)$$

and

$$H(s) = \frac{s+\alpha}{s} \quad (4.4.1.2)$$

Find  $\alpha$  so that the closed loop system has poles on the imaginary axis. **Solution:** The Characteristic equation is

$$1 + G(s)H(s) = 0 \quad (4.4.1.3)$$

$$\Rightarrow 1 + \left[ \frac{1}{(s+1)(s+2)} \right] \left[ \frac{s+\alpha}{s} \right] = 0 \quad (4.4.1.4)$$

$$\Rightarrow s^3 + 3s^2 + 3s + \alpha = 0 \quad (4.4.1.5)$$

Constructing the routh array for (4.4.1.5),

$$\begin{array}{c|cc} s^3 & 1 & 3 \\ s^2 & 3 & \alpha \end{array} \quad (4.4.1.6)$$

$$\Rightarrow \begin{array}{c|cc} s^3 & 1 & 3 \\ s^2 & 3 & \alpha \\ s^1 & \frac{9-\alpha}{3} & 0 \end{array} \quad (4.4.1.7)$$

$$\Rightarrow \begin{array}{c|cc} s^3 & 1 & 3 \\ s^2 & 3 & \alpha \\ s^1 & \frac{9-\alpha}{3} & 0 \\ s^0 & \alpha & 0 \end{array} \quad (4.4.1.8)$$

For poles on the imaginary axis any one of the rows should be zero. Thus,

$$\frac{9-\alpha}{3} = 0 \Rightarrow \alpha = 9 \quad (4.4.1.9)$$

Substituting  $\alpha = 9$  in (4.4.1.5),

$$s^3 + 3s^2 + 3s + 9 = 0 \quad (4.4.1.10)$$

$$\Rightarrow s = -3, \pm j\sqrt{3} \quad (4.4.1.11)$$

verifying that poles lie on the imaginary axis.

#### 4.5 Example

4.5.1. A closed loop system has the characteristic equation given by

$$s^3 + Ks^2 + (K+2)s + 3 = 0 \quad (4.5.1.1)$$

Determine the condition for K for which the system is stable.

**Solution:** The Routh array for (4.5.1.1) is

$$\begin{array}{c|ccc} s^3 & 1 & K+2 & 0 \\ s^2 & K & 3 & 0 \\ s^1 & \frac{K^2+2K-3}{K} & 0 & 0 \\ s^0 & 3 & 0 & 0 \end{array} \quad (4.5.1.2)$$

For the system to be stable, there should be no sign changes in the first column of the Routh array. Thus,

$$\{K > 0\} \cap \left\{ \frac{K^2 + 2K - 3}{K} > 0 \right\} \quad (4.5.1.3)$$

$$\Rightarrow K > 1 \quad (4.5.1.4)$$

The following program computes the routh array and stability for different values of K.

```
codes/ee18btech11039.py
```

## 5 STATE-SPACE MODEL

### 5.1 Controllability and Observability

5.1. State the general model of a state space system specifying the dimensions of the matrices and vectors.

**Solution:** The model is given by

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \\ \mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) \end{aligned} \quad (5.1.1)$$

with parameters listed in Table 5.1.

Variable	Size	Description
<b>u</b>	$p \times 1$	input(control) vector
<b>y</b>	$q \times 1$	output vector
<b>x</b>	$n \times 1$	state vector
<b>A</b>	$n \times n$	state or system matrix
<b>B</b>	$n \times p$	input matrix
<b>C</b>	$q \times n$	output matrix
<b>D</b>	$q \times p$	feedthrough matrix

TABLE 5.1

5.2. Find the transfer function  $\mathbf{H}(s)$  for the general system.

**Solution:** Taking Laplace transform on both sides we have the following equations

$$s\mathbf{IX}(s) - \mathbf{x}(0) = \mathbf{AX}(s) + \mathbf{BU}(s) \quad (5.2.1)$$

$$(s\mathbf{I} - \mathbf{A})\mathbf{X}(s) = \mathbf{BU}(s) + \mathbf{x}(0) \quad (5.2.2)$$

$$\mathbf{X}(s) = (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{BU}(s) \quad (5.2.3)$$

$$+ (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{x}(0) \quad (5.2.4)$$

and

$$\mathbf{Y}(s) = \mathbf{CX}(s) + \mathbf{DU}(s) \quad (5.2.5)$$

Substituting from (5.2.3) in the above,

$$\begin{aligned} \mathbf{Y}(s) &= (\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D})\mathbf{U}(s) \\ &+ \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{x}(0) \end{aligned} \quad (5.2.6)$$

5.3. Find  $H(s)$  for a SISO (single input single output) system.

**Solution:**

$$H(s) = \frac{Y(s)}{U(s)} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \quad (5.3.1)$$



5.4. Given

$$H(s) = \frac{1}{s^3 + 3s^2 + 2s + 1} \quad (5.4.1)$$

$$D = 0 \quad (5.4.2)$$

$$\mathbf{B} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (5.4.3)$$

find  $\mathbf{A}$  and  $\mathbf{C}$  such that the state-space realization is in *controllable canonical form*.

**Solution:**

$$\therefore \frac{Y(s)}{U(s)} = \frac{Y(s)}{V(s)} \times \frac{V(s)}{U(s)}, \quad (5.4.4)$$

letting

$$\frac{Y(s)}{V(s)} = 1, \quad (5.4.5)$$

results in

$$\frac{U(s)}{V(s)} = s^3 + 3s^2 + 2s + 1 \quad (5.4.6)$$

giving

$$U(s) = s^3 V(s) + 3s^2 V(s) + 2s V(s) + V(s) \quad (5.4.7)$$

so the above equation can be written as

$$\begin{pmatrix} sV(s) \\ s^2 V(s) \\ s^3 V(s) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -3 \end{pmatrix} \begin{pmatrix} V(s) \\ sV(s) \\ s^2 V(s) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} U \quad (5.4.8)$$

Letting

$$\mathbf{A} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -3 \end{pmatrix} \quad (5.4.9)$$

$$\mathbf{X}_1 = \begin{pmatrix} sV(s) \\ s^2 V(s) \\ s^3 V(s) \end{pmatrix} \quad (5.4.10)$$

$$\mathbf{X} = \begin{pmatrix} V(s) \\ sV(s) \\ s^2 V(s) \end{pmatrix}, \quad (5.4.11)$$

$$\mathbf{X}_1(s) = \mathbf{A}\mathbf{X}(s) + \mathbf{B}U(s) \quad (5.4.12)$$

$$Y = \mathbf{C}\mathbf{X}_1(s) \quad (5.4.13)$$

where

$$\mathbf{C} = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \quad (5.4.14)$$

5.5. Obtain  $\mathbf{A}$  and  $\mathbf{C}$  so that the state-space realization is in *observable canonical form*.

**Solution:** Given that

$$H(s) = \frac{1}{s^3 + 3s^2 + 2s + 1}, \quad (5.5.1)$$

$$\frac{Y(s)}{U(s)} = \frac{1}{s^3 + 3s^2 + 2s + 1} \quad (5.5.2)$$

$$\Rightarrow U(s) = Y(s)(s^3 + 3s^2 + 2s + 1) \quad (5.5.3)$$

$$\text{or, } Y(s) = -3s^{-1}Y(s) - 2s^{-2}Y(s) + s^{-3}(U(s) - Y(s)) \quad (5.5.4)$$

Let

$$X_1(s) = Y(s) = -3s^{-1}Y(s) - 2s^{-2}Y(s) + s^{-3}(U(s) - Y(s)) \quad (5.5.5)$$

$$X_2(s) = -2s^{-1}Y(s) + s^{-2}(U(s) - Y(s)) \quad (5.5.6)$$

$$X_3(s) = s^{-1}(U(s) - Y(s)) \quad (5.5.7)$$

$$sX_1(s) = -3Y(s) + X_2(s)$$

$$\Rightarrow sX_2(s) = -2Y(s) + X_3(s) \quad (5.5.8)$$

$$sX_3(s) = U(s) - Y(s)$$

Substituting  $Y = X_1(s)$  the above,

$$sX_1(s) = -3X_1(s) + X_2(s) \quad (5.5.9)$$

$$sX_2(s) = -2X_1(s) + X_3(s) \quad (5.5.10)$$

$$sX_3(s) = U(s) - X_1(s) \quad (5.5.11)$$

which can be expressed as

$$\begin{pmatrix} sX_1(s) \\ sX_2(s) \\ sX_3(s) \end{pmatrix} = \begin{pmatrix} -3 & 1 & 0 \\ -2 & 0 & 1 \\ -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} X_1(s) \\ X_2(s) \\ X_3(s) \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} U \quad (5.5.12)$$

$$\text{or, } s\mathbf{X}(s) = \mathbf{A}\mathbf{X}(s) + \mathbf{B}U(s) \quad (5.5.13)$$

where

$$\mathbf{A} = \begin{pmatrix} -3 & 1 & 0 \\ -2 & 0 & 1 \\ -1 & 0 & 0 \end{pmatrix} \quad (5.5.14)$$

$$\mathbf{B} = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \quad (5.5.15)$$

5.6. Find the eigenvalues of  $\mathbf{A}$  and the poles of  $H(s)$  using a python code.

**Solution:** The following code

codes/ee18btech11004.py

gives the necessary values. The roots are the same as the eigenvalues.

5.7. Theoretically, show that eigenvalues of  $\mathbf{A}$  are the poles of  $H(s)$ .

**Solution:** As we know that the characteristic equation is  $\det(s\mathbf{I}-\mathbf{A})$

$$s\mathbf{I} - \mathbf{A} = \begin{pmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{pmatrix} - \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -3 \end{pmatrix} \quad (5.7.1)$$

$$= \begin{pmatrix} s & -1 & 0 \\ 0 & s & -1 \\ 1 & 2 & s+3 \end{pmatrix} \quad (5.7.2)$$

$$\Rightarrow |s\mathbf{I} - \mathbf{A}| = s(s^2 + 3s + 2) + 1(1) \quad (5.7.3)$$

$$= s^3 + 3s^2 + 2s + 1 \quad (5.7.4)$$

which is the denominator of  $H(s)$  in (5.4.1)

## 5.2 Second Order System

5.2.1. Consider a state-variable model of a system

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\alpha & -2\beta \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} r \quad (5.2.1.1)$$

$$y = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (5.2.1.2)$$

where  $y$  is the output, and  $r$  is the input.

5.2.2. List the various state matrices in (5.2.1.1)

5.2.3. Find the the system transfer function  $H(s)$ .

**Solution:** From (5.1.1) and , (5.3.1), the transfer function for the state space model is

$$H(s) = C(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + D \quad (5.2.3.1)$$

$$= \frac{\begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} s+2\beta & 1 \\ -\alpha & s \end{pmatrix} \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}}{s(s+2\beta) + \alpha} \quad (5.2.3.2)$$

$$= \frac{b_1(s+2\beta) + b_2}{s^2 + 2s\beta + \alpha} \quad (5.2.3.3)$$

$$\Rightarrow H(s) = \frac{b_1 s}{s^2 + 2s\beta + \alpha} + \frac{2b_1\beta + b_2}{s^2 + 2s\beta + \alpha} \quad (5.2.3.4)$$

5.2.4. Find the Damping ratio  $\zeta$  and the Undamped natural frequency  $\omega_n$  of the system.

**Solution:** Generally for a second order system the transfer function is given by 3.1.1.1

$$H(s) = \frac{\omega_n^2}{s^2 + 2s\zeta\omega_n + \omega_n^2} \quad (5.2.4.1)$$

Comparing the denominator of the above with (5.2.3.4),

$$2\zeta\omega_n = 2\beta, \quad (5.2.4.2)$$

$$\omega_n^2 = \alpha \quad (5.2.4.3)$$

$$\Rightarrow \zeta = \frac{\beta}{\sqrt{\alpha}}, \omega_n = \sqrt{\alpha} \quad (5.2.4.4)$$

5.2.5. Using Table 3.1.1, explain how the damping conditions depend upon  $\alpha$  and  $\beta$ .

## 5.3 Example

5.3.1. The state equation and the output equation of a control system are

$$\dot{\mathbf{x}} = \begin{pmatrix} -4 & -1.5 \\ 4 & 0 \end{pmatrix} \mathbf{x} + \begin{pmatrix} 4 \\ 0 \end{pmatrix} \mathbf{u} \quad (5.3.1.1)$$

$$\mathbf{y} = \begin{pmatrix} 1.5 & 0.625 \end{pmatrix} \mathbf{x} \quad (5.3.1.2)$$

Find the transfer function of the system

**Solution:** The system matrices are

$$\mathbf{A} = \begin{pmatrix} -4 & -1.5 \\ 4 & 0 \end{pmatrix} \quad (5.3.1.3)$$

$$\mathbf{B} = \begin{pmatrix} 4 \\ 0 \end{pmatrix} \quad (5.3.1.4)$$

$$\mathbf{C} = \begin{pmatrix} 1.5 & 0.625 \end{pmatrix} \quad (5.3.1.5)$$

and the transfer function is

$$T(s) = \mathbf{C} [s\mathbf{I} - \mathbf{A}]^{-1} \mathbf{B} + \mathbf{D} \quad (5.3.1.6)$$

$$= \left( \frac{6s+10}{(s^2+4s+6)} \right) \quad (5.3.1.7)$$

5.3.2. Verify your answer using a python code

**Solution:** The following python code gives the desired answer

codes/ee18btech11023.py

## 5.4 Example

5.4.1. Consider the state space realization :

$$\dot{\mathbf{x}}(t) = \begin{pmatrix} 0 & 0 \\ 0 & -9 \end{pmatrix} \mathbf{x}(t) + \begin{pmatrix} 0 \\ 45 \end{pmatrix} u(t) \quad (5.4.1.1)$$

with initial conditions

$$\mathbf{x}(0) = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad (5.4.1.2)$$

where  $u(t)$  is the step function. Find

$$\lim_{t \rightarrow \infty} \|\mathbf{x}(t)\| \quad (5.4.1.3)$$

**Solution:** From (5.2.4),

$$X(s) = (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}U(s) + (s\mathbf{I} - \mathbf{A})^{-1}\mathbf{x}(0) \quad (5.4.1.4)$$

where

$$\mathbf{A} = \begin{pmatrix} 0 & 0 \\ 0 & -9 \end{pmatrix} \quad (5.4.1.5)$$

$$\mathbf{B} = \begin{pmatrix} 0 \\ 45 \end{pmatrix} \quad (5.4.1.6)$$

$$U(s) = \frac{1}{s} \quad (5.4.1.7)$$

The following code

```
codes/ee18btech11026.py
```

yields

$$\mathbf{X}(s) = \begin{pmatrix} 0 \\ \frac{45}{s(s+9)} \end{pmatrix} \quad (5.4.1.8)$$

Using the final value theorem,

$$\lim_{t \rightarrow \infty} \mathbf{x}(t) = \lim_{s \rightarrow 0} s\mathbf{X}(s) \quad (5.4.1.9)$$

$$= \begin{pmatrix} 0 \\ 5 \end{pmatrix} \quad (5.4.1.10)$$

$$\Rightarrow \lim_{t \rightarrow \infty} \|\mathbf{x}(t)\| = 5 \quad (5.4.1.11)$$

## 5.5 Example

5.5.1. A second-order LTI system is described by the following state equations

$$\frac{\partial x_1(t)}{\partial t} - x_2(t) = 0 \quad (5.5.1.1)$$

$$\frac{\partial x_2(t)}{\partial t} + 2x_1(t) + 3x_2(t) = r(t) \quad (5.5.1.2)$$

$$c(t) = x_1(t). \quad (5.5.1.3)$$

where  $x_1(t)$  and  $x_2(t)$  are the two state variables and  $r(t)$  denotes the input. The output is  $c(t)$ . Express this in terms of the state space model.

**Solution:** From (5.1.1), (5.5.1.1)-(5.5.1.3) can be expressed as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}u(t) \quad (5.5.1.4)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}u(t) \quad (5.5.1.5)$$

where

$$\mathbf{A} = \begin{pmatrix} 0 & 1 \\ -2 & -3 \end{pmatrix} \quad (5.5.1.6)$$

$$\mathbf{B} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (5.5.1.7)$$

$$\mathbf{C} = \begin{pmatrix} 1 & 0 \end{pmatrix} \quad (5.5.1.8)$$

$$\mathbf{D} = 0 \quad (5.5.1.9)$$

5.5.2. Find the system transfer function  $H(s)$ .

**Solution:** From (5.3.1),

$$H(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D}\mathbf{I} \quad (5.5.2.1)$$

$$= \frac{1}{s^2 + 3s + 2} \quad (5.5.2.2)$$

using the code in

```
codes/ee18btech11031/ee18btech11031.py
```

5.5.3. Identify the damping type.

**Solution:** From (3.1.1.1) and

$$\omega = \sqrt{2}, \zeta = \frac{3}{2\sqrt{2}} > 1 \quad (5.5.3.1)$$

From Table 3.1.1, the system is overdamped.

5.5.4. Find and plot the unit step response for the system.

**Solution:**

$$Y(s) = U(s)H(s) \quad (5.5.4.1)$$

$$= \frac{1}{s(s+1)(s+2)} \quad (5.5.4.2)$$

$$\Rightarrow y(t) = \left( \frac{1}{2} - e^{-t} + \frac{e^{-2t}}{2} \right) u(t) \quad (5.5.4.3)$$

The following code plots the step response in Fig. 5.5.4 using the code in

```
codes/ee18btech11031/ee18btech11031_2.py
```

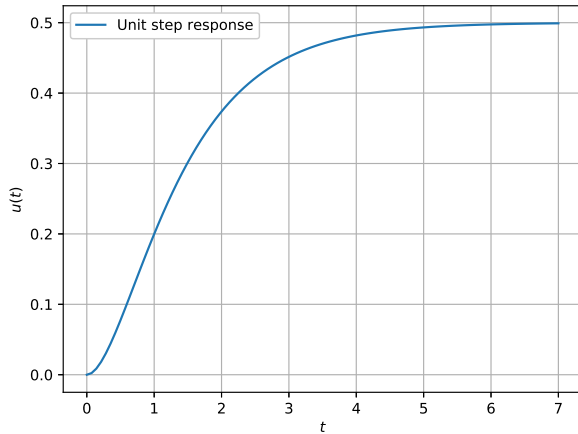


Fig. 5.5.4

### 5.6 Example

5.6.1. Consider the system described by the following state space representation

$$\dot{\mathbf{x}} = \begin{pmatrix} 0 & 1 \\ 0 & -2 \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} \mathbf{u} \quad (5.6.1.1)$$

$$\mathbf{y} = \begin{pmatrix} 1 & 0 \end{pmatrix} \mathbf{x} \quad (5.6.1.2)$$

If  $u(t)$  is a unit step input and

$$\mathbf{x}(0) = \begin{pmatrix} x_1(0) \\ x_2(0) \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (5.6.1.3)$$

Find the output  $y(1)$ .

**Solution:** From 5.6.1.4

$$\mathbf{Y}(s) = (\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D})\mathbf{U}(s) + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{x}(0) \quad (5.6.1.4)$$

where

$$\mathbf{A} = \begin{pmatrix} 0 & 1 \\ 0 & -2 \end{pmatrix} \quad (5.6.1.5)$$

$$\mathbf{B} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (5.6.1.6)$$

$$\mathbf{C} = \begin{pmatrix} 1 & 0 \end{pmatrix} \quad (5.6.1.7)$$

$$\mathbf{D} = \begin{pmatrix} 0 & 0 \end{pmatrix} \quad (5.6.1.8)$$

$$\mathbf{x}(0) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (5.6.1.9)$$

The following code computes

```
codes/ee18btech11047.py
```

$$Y(s) = \frac{s^2 + 2s + 1}{s^3 + 2s^2} \quad (5.6.1.10)$$

$$\Rightarrow y(t) = \left( \frac{1}{4}e^{-2t} + \frac{3}{4} + \frac{1}{2}t \right) u(t) \quad (5.6.1.11)$$

$$\text{or, } y(1) = \frac{1}{4} (5 + e^{-2}) \quad (5.6.1.12)$$

### 5.7 Example

5.7.1. Find the transfer function of the following system

$$\dot{\mathbf{x}} = \begin{pmatrix} 1 & 2 \\ 2 & 0 \end{pmatrix} \mathbf{x} + \begin{pmatrix} 1 \\ 2 \end{pmatrix} u(t) \quad (5.7.1.1)$$

$$\mathbf{y} = \begin{pmatrix} 1 & 0 \end{pmatrix} \mathbf{x} \quad (5.7.1.2)$$

**Solution:** By comparing the above equations to (5.1.1),

$$\mathbf{D} = 0 \quad (5.7.1.3)$$

$$\mathbf{C} = \begin{pmatrix} 1 & 0 \end{pmatrix} \quad (5.7.1.4)$$

$$\mathbf{B} = \begin{pmatrix} 1 \\ 2 \end{pmatrix} \quad (5.7.1.5)$$

$$\mathbf{A} = \begin{pmatrix} 1 & 2 \\ 2 & 0 \end{pmatrix} \quad (5.7.1.6)$$

From (5.3.1)

$$H(s) = \frac{Y(s)}{U(s)} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \quad (5.7.1.7)$$

$$= \frac{s + 4}{s^2 - s - 4} \quad (5.7.1.8)$$

where the following code computes the transfer function.

```
codes/ee18btech11040.py
```

## 6 NYQUIST PLOT

### 6.1 Introduction

6.1.1. The open loop transfer function of a unity feedback system is given by

$$G(s) = \frac{\pi e^{-0.25s}}{s} \quad (6.1.1.1)$$

6.1.2. Find  $\text{Re}\{G(j\omega)\}$  and  $\text{Im}\{G(j\omega)\}$ .

**Solution:** From (6.1.1.1),

$$G(j\omega) = \frac{\pi}{\omega}(-\sin 0.25\omega - j\cos 0.25\omega) \quad (6.1.2.1)$$

$$\Rightarrow \text{Re}\{G(j\omega)\} = \frac{\pi}{\omega}(-\sin 0.25\omega) \quad (6.1.2.2)$$

$$\text{Im}\{G(j\omega)\} = \frac{\pi}{\omega}(-j\cos 0.25\omega) \quad (6.1.2.3)$$

6.1.3. Sketch the Nyquist plot.

**Solution:** The Nyquist plot is a graph of  $\text{Re}\{G(j\omega)\}$  vs  $\text{Im}\{G(j\omega)\}$ . The following python code generates the Nyquist plot in Fig. 6.1.3

```
codes/ee18btech11007/ee18btech11007.py
```

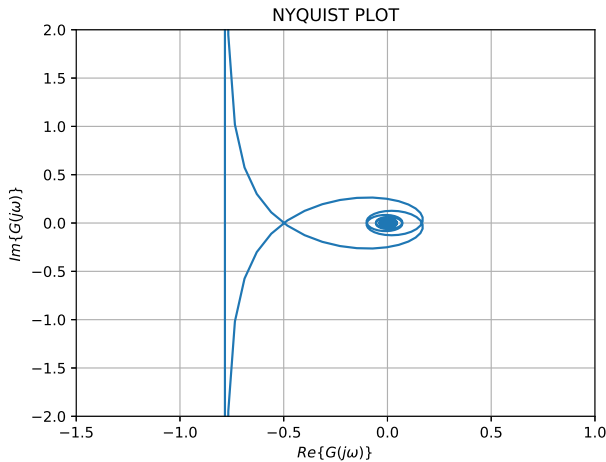


Fig. 6.1.3

6.1.4. Find the point at which the Nyquist plot of  $G(s)$  passes through the negative real axis

**Solution:** Nyquist plot cuts the negative real axis at  $\omega$  for which

$$\angle G(j\omega) = -\pi \quad (6.1.4.1)$$

From (6.1.1.1),

$$G(j\omega) = \frac{\pi e^{-j\frac{\omega}{4}}}{j\omega} = \frac{\pi e^{-j(\frac{\omega}{4} + \frac{\pi}{2})}}{\omega} \quad (6.1.4.2)$$

$$\Rightarrow \angle G(j\omega) = -\left(\frac{\omega}{4} + \frac{\pi}{2}\right) \quad (6.1.4.3)$$

From (6.1.4.3) and (6.1.4.1),

$$\frac{\omega}{4} + \frac{\pi}{2} = \pi \quad (6.1.4.4)$$

$$\Rightarrow \omega = 2\pi \quad (6.1.4.5)$$

Also, from (6.1.1.1),

$$|G(j\omega)| = \frac{\pi}{|\omega|} \quad (6.1.4.6)$$

$$\Rightarrow |G(j2\pi)| = \frac{1}{2} \quad (6.1.4.7)$$

6.1.5. Use the Nyquist Stability criterion to determine if the system in (6.1.4.3) is stable.

Variable	Value	Description
Z	0	Poles of $\frac{G(s)}{1+G(s)H(s)}$ in right half of s plane
P	0	Poles of $G(s)H(s)$ in right half of s plane
N	0	No of clockwise encirclements of $G(s)H(s)$ about $-1+j0$ in the Nyquist plot

TABLE 6.1.5

**Solution:** Consider Table 6.1.5. According to the Nyquist stability criterion,

- If the open-loop transfer function  $G(s)$  has a zero pole of multiplicity  $l$ , then the Nyquist plot has a discontinuity at  $\omega = 0$ . During further analysis it should be assumed that the phasor travels  $l$  times clock-wise along a semicircle of infinite radius. After applying this rule, the zero poles should be neglected, i.e. if there are no other unstable poles, then the open-loop transfer function  $G(s)$  should be considered stable.
- If the open-loop transfer function  $G(s)$  is stable, then the closed-loop system is unstable for any encirclement of the point  $-1$ . If the open-loop transfer function  $G(s)$  is unstable, then there must be one counter clock-wise encirclement of  $-1$  for each pole of  $G(s)$  in the right-half of the complex plane.
- The number of surplus encirclements ( $N + P$  greater than 0) is exactly the number of unstable poles of the closed-loop system.
- However, if the graph happens to pass through the point  $-1+j0$ , then deciding upon even the marginal stability of the system becomes difficult and the only conclusion that can be drawn from the graph is that there exist zeros on the  $j\omega$  axis.

From (6.1.1.1),  $G(s)$  is stable since it has a

single pole at  $s = 0$ . Further, from Fig. 6.1.3, the Nyquist plot does not encircle  $s = -1$ . From Theorem 6.1.5b, we may conclude that the system is stable.

## 6.2 Example

6.2.1. Find the number of encirclements around the point  $-1+j0$  in the complex plane by the Nyquist plot of

$$G(s) = \frac{1-s}{4+2s}. \quad (6.2.1.1)$$

**Solution:** The following code generates the Nyquist plot in Fig. 6.2.1. It is easy to verify that the number of encirclements of  $-1+j0$  is zero.

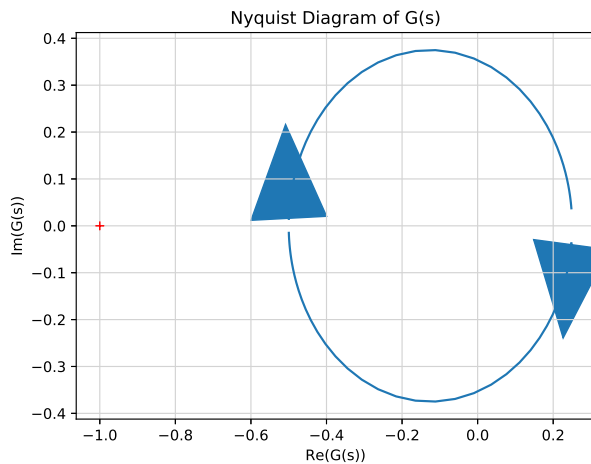


Fig. 6.2.1

## 6.3 Example

6.1. The open loop transfer function of a feedback system is

$$G(s)H(s) = \frac{s+3}{s^2(s-3)} \quad (6.1.1)$$

Find out how many times the Nyquist contour encircles  $-1+j0$  in the clockwise direction.

**Solution:** The following code plots Fig. 6.1

codes/es17btech11009.py

There is only one encirclement in the clockwise direction.

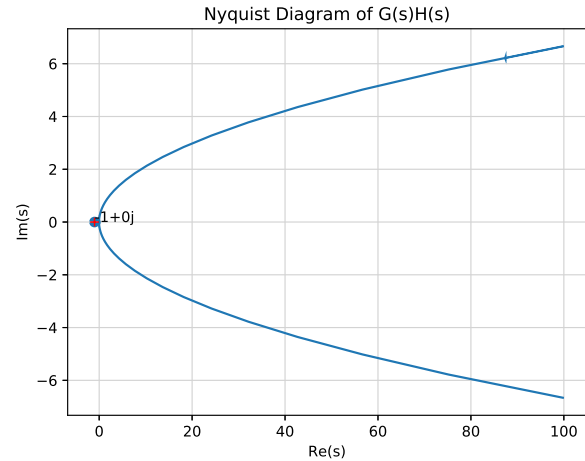


Fig. 6.1

## 7 COMPENSATORS

### 7.1 Phase Lead

7.1.1. Consider a control system with

$$G(s) = \frac{1}{s(3s+1)} \quad (7.1.1.1)$$

Find its phase margin.

**Solution:**

$$G(j\omega) = \frac{1}{(j\omega)(3j\omega+1)} \quad (7.1.1.2)$$

$$\Rightarrow |G(j\omega)| = \frac{1}{\omega(\sqrt{9\omega^2+1})} \quad (7.1.1.3)$$

$$\Rightarrow \angle G(j\omega) = -\tan^{-1}(3\omega) - 90^\circ \quad (7.1.1.4)$$

At Gain Crossover,

$$|G(j\omega)| = 1 \quad (7.1.1.5)$$

$$\Rightarrow \frac{1}{\omega(\sqrt{9\omega^2+1})} = 1 \quad (7.1.1.6)$$

$$\Rightarrow \omega_{gc} = 0.531 \quad (7.1.1.7)$$

$$\Rightarrow \angle G(j\omega) = -147.88^\circ \quad (7.1.1.8)$$

$$\Rightarrow PM = 32.12^\circ \quad (7.1.1.9)$$

7.1.2. The minimum acceptable PM for a control system is  $45^\circ$ . Design a suitable *lead compensator* for (7.1.1.1).

**Solution:** Let the desired compensator be

$$D(s) = \frac{3(s + \frac{1}{3T})}{(s + \frac{1}{T})} \quad (7.1.2.1)$$

Choosing  $T = 1$ ,

$$D(s) = \frac{3(s + \frac{1}{3})}{(s + 1)} \quad (7.1.2.2)$$

By cascading the Compensator and the Open Loop Transfer Function,

$$G_1(s) = D(s)G(s) \quad (7.1.2.3)$$

$$= \frac{1}{s(3s + 1)} \frac{3(s + \frac{1}{3})}{(s + 1)} \quad (7.1.2.4)$$

$$\Rightarrow G_1(s) = \frac{1}{s(s + 1)} \quad (7.1.2.5)$$

$$\Rightarrow G_1(j\omega) = \frac{1}{(j\omega)(j\omega + 1)} \quad (7.1.2.6)$$

$$\Rightarrow |G_1(j\omega)| = \frac{1}{\omega(\sqrt{\omega^2 + 1})} \quad (7.1.2.7)$$

$$\angle G_1(j\omega) = -\tan^{-1}(\omega) - 90^\circ \quad (7.1.2.8)$$

At Gain Crossover,

$$|G_1(j\omega)| = 1 \quad (7.1.2.9)$$

$$\Rightarrow \frac{1}{\omega(\sqrt{\omega^2 + 1})} = 1 \quad (7.1.2.10)$$

$$\Rightarrow \omega_{gc} = 0.786 \quad (7.1.2.11)$$

$$\Rightarrow \angle G(j\omega) = -128.167^\circ \quad (7.1.2.12)$$

$$\Rightarrow PM = 51.83^\circ \quad (7.1.2.13)$$

7.1.3. Verify the above improvement in Phase Margin with the help of a Python Code

**Solution:** The following code generates Fig. 7.1.3

codes/ee18btech11021.py

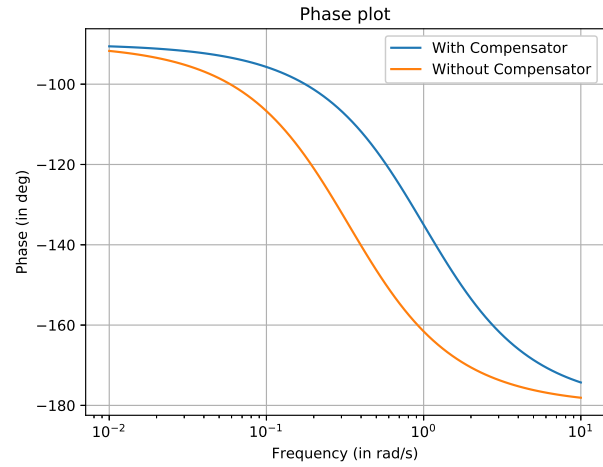


Fig. 7.1.3

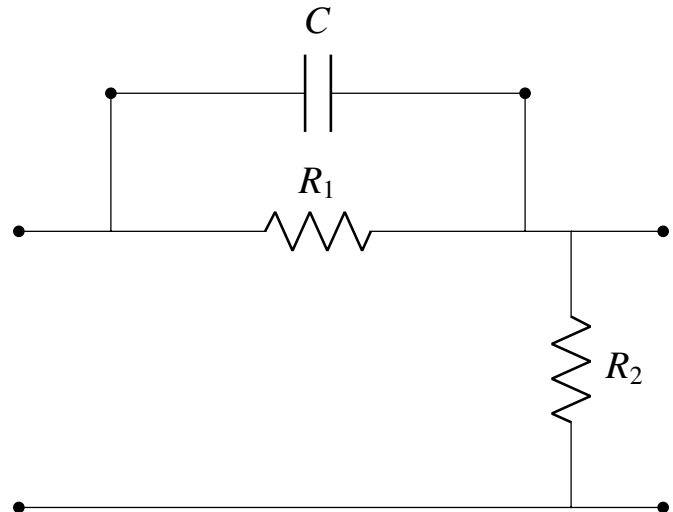


Fig. 7.2.1

where

$$\alpha = \frac{R_2}{R_1 + R_2} \quad (7.2.1.4)$$

$$\tau = R_1 C$$

## 7.2 Lead Circuit

7.2.1. A lead Compensator network includes a parallel combination of R and C in feed-forward path as shown in Fig. 7.2.1. Find the gain of 7.2.2. If the transfer function of the compensator is the compensator.

**Solution:** The transfer function is

$$T(s) = \frac{V_o}{V_i} \quad (7.2.1.1)$$

$$= \frac{R_2}{\frac{1}{sC} R_1 + R_2} \quad (7.2.1.2)$$

$$= \frac{s + \frac{1}{\tau}}{s + \frac{1}{\tau\alpha}} \quad (7.2.1.3)$$

, find the value of RC.

**Solution:** From (7.2.2.1), (7.2.1.3) and (7.2.1.4)

$$G_c(s) = \frac{s + 2}{s + 4} \quad (7.2.2.1)$$

$$\tau = R_1 C = 0.5 \quad (7.2.2.2)$$

7.2.3. Find the value of RC for the compensator in

Section 7.1.

**Solution:** The compensator gain in this case is

$$T(s) = \frac{(s + \frac{1}{3})}{s + 1} \quad (7.2.3.1)$$

From (7.2.3.1), (7.2.1.3) and (7.2.1.4),

$$\tau = 3 \quad (7.2.3.2)$$

$$\Rightarrow R_1 C = 3 \quad (7.2.3.3)$$

### 7.3 Lag Lead

7.1. Write the general expression for the transfer function of a Phase lag-lead compensator. **So-**

**lution:** The Transfer Function of the Phase lag-lead compensator is

$$H(s) = \frac{(1 + \alpha s T_1)(1 + \beta s T_2)}{(1 + T_1 s)(1 + T_2 s)} \quad (7.1.1)$$

$\alpha$  and  $\beta$  are generally chosen in such a way that

$$\alpha\beta = 1 \quad (7.1.2)$$

7.2. Write the expression for phase introduced by phase lag-lead compensator. **Solution:**

$$\phi = \tan^{-1}\left(\frac{\omega T_1}{\beta}\right) + \tan^{-1}(\beta\omega T_2) - \tan^{-1}(\omega T_1) - \tan^{-1}(\omega T_2) \quad (7.2.1)$$

7.3. Consider the Transfer function of a phase lag-lead compensator

$$C(s) = \frac{(1 + \frac{s}{0.1})(1 + \frac{s}{100})}{(1 + \frac{s}{1})(1 + \frac{s}{10})} \quad (7.3.1)$$

Find the frequency range in which the phase (lead) introduced by the compensator reaches the maximum

**Solution:** From (7.1.1) and (7.3.1),

$$\alpha = 10, T_1 = 1, \quad (7.3.2)$$

$$\beta = 0.1, T_2 = 0.1. \quad (7.3.3)$$

Thus,

$$\angle C(j\omega) = \underbrace{\tan^{-1}(10\omega) - \tan^{-1}(\omega)}_{\text{lead}} + \underbrace{\tan^{-1}(0.01\omega) - \tan^{-1}(0.1\omega)}_{\text{lag}} \quad (7.3.4)$$

As we are trying to find the range of frequencies in which phase lead introduced by

the compensator is maximum, the phase introduced by the lag part of compensator will be close to zero. Hence, the problem can be expressed as

$$\min_{\omega} \tan^{-1}(10\omega) - \tan^{-1}(\omega) \quad (7.3.5)$$

which can be obtained by

$$\frac{d}{d\omega} [\tan^{-1}(10\omega) - \tan^{-1}(\omega)] = 0 \quad (7.3.6)$$

$$\Rightarrow \frac{10}{1 + 100\omega^2} - \frac{1}{1 + \omega^2} = 0 \quad (7.3.7)$$

$$\text{or, } \omega = \frac{1}{\sqrt{10}} \quad (7.3.8)$$

7.4. Verify your result using a python plot.

**Solution:** The following code

codes/ee18btech11044.py

generates Fig. 7.4.

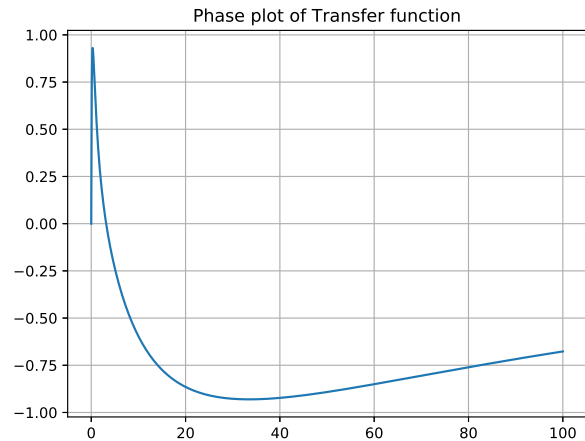


Fig. 7.4

### 7.4 Example

7.1. Consider the system in Section 7.1.

$$G(s) = \frac{1}{s(3s + 1)} \quad (7.1.1)$$

Find the step response for the system in Fig. 7.3.



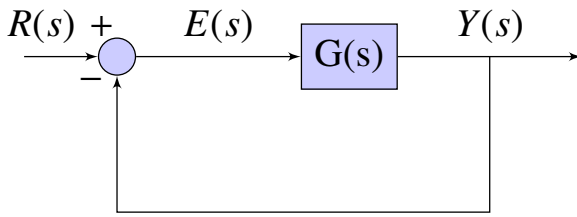


Fig. 7.1

**Solution:** The step response is

$$Y(s) = \frac{G(s)}{1 + G(s)} \frac{1}{s} \quad (7.1.2)$$

$$= \frac{1}{(s)(3s^2 + s + 1)} \quad (7.1.3)$$

$$= \frac{-3s - 1}{3s^2 + s + 1} + \frac{1}{s} \quad (7.1.4)$$

$$\Rightarrow y(t) = \left[ 1 - e^{-\frac{t}{6}} \left\{ \cos\left(\frac{\sqrt{11}t}{6}\right) - \frac{1}{\sqrt{11}} \sin\left(\frac{\sqrt{11}t}{6}\right) \right\} \right] u(t) \quad (7.1.5)$$

7.2. Find the step response for the system shown in Fig. 7.2 that is obtained by adding the lead compensator to the system in Fig. 7.1

$$D(s) = \frac{3(s + \frac{1}{3})}{(s + 1)} \quad (7.2.1)$$

**Solution:** The step response is given by

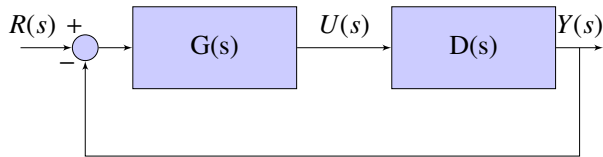


Fig. 7.2

$$Y_1(s) = \frac{G_1(s)}{1 + G_1(s)} \frac{1}{s} \quad (7.2.2)$$

$$= \frac{1}{s(s^2 + s + 1)} \quad (7.2.3)$$

where

$$G_1(s) = G(s)D(s) = \frac{1}{s(s + 1)} \quad (7.2.4)$$

$$\Rightarrow y(t) = \left[ 1 - e^{-\frac{t}{2}} \left\{ \cos\left(\frac{\sqrt{3}t}{2}\right) - \frac{1}{\sqrt{3}} \sin\left(\frac{\sqrt{3}t}{2}\right) \right\} \right] u(t) \quad (7.2.5)$$

7.3. Show that the lead compensator reduces the settling time.

**Solution:** The following code generates Fig. 7.3 which is self-explanatory.

codes/ee18btech11027.py

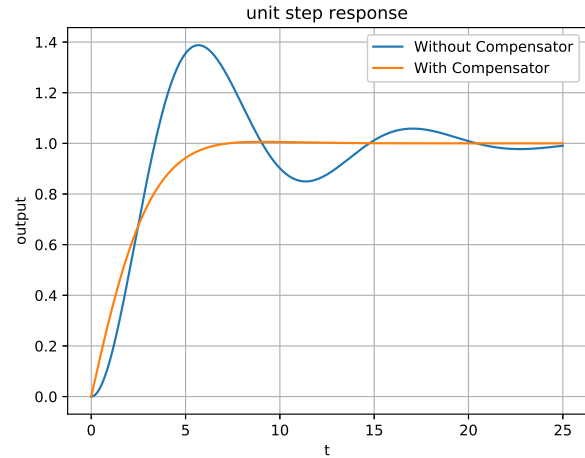


Fig. 7.3

## 8 GAIN MARGIN

### 8.1 Introduction

8.1.1. The open loop transfer function of a feedback control system is

$$G(s) = \frac{1}{s(1 + 2s)(1 + s)} \quad (8.1.1.1)$$

Find the magnitude and phase of  $|G(j\omega)|$ .

**Solution:**

$$G(j\omega) = \frac{1}{j\omega(1+2j\omega)(1+j\omega)} \quad (8.1.1.2)$$

$$= \frac{1}{j\omega(1+3j\omega-2\omega^2)} \quad (8.1.1.3)$$

$$= \frac{1}{j\omega - 3\omega^2 - 2j\omega^3} \quad (8.1.1.4)$$

$$= \frac{1}{-3\omega^2 + j\omega(1-2\omega^2)} \quad (8.1.1.5)$$

$$\Rightarrow \angle G(j\omega) = -\tan^{-1} \left( \frac{\omega(1-2\omega^2)}{-3\omega^2} \right) \quad (8.1.1.6)$$

8.1.2. The frequency at which the phase of open-loop transfer function reaches  $-180^\circ$  or  $+180^\circ$  depending upon the range of tan inverse function) is defined to be the phase crossover frequency. Find the phase crossover frequency for (8.1.1.1). **Solution:** From (8.1.1.6), at  $\omega = \omega_{pc}$

$$\omega(1-2\omega^2) = 0 \quad (8.1.2.1)$$

$$\Rightarrow \omega_{pc} = \frac{1}{\sqrt{2}} \quad (8.1.2.2)$$

8.1.3. The gain Margin is given by,

$$GM = -20 \log_{10} |G(j\omega_{pc})| = 20 \log_{10} k_g \quad (8.1.3.1)$$

where

$$k_g = \frac{1}{|G(j\omega_{pc})|} \quad (8.1.3.2)$$

Find the GM for (8.1.1.6).

**Solution:**

$$|G(j\omega_{pc})| = \frac{1}{\left(\frac{3}{2}\right)} \Rightarrow k_g = \frac{1}{|G(j\omega_{pc})|} = \frac{3}{2} 3.5dB \quad (8.1.3.3)$$

The greater the Gain Margin (GM), the greater the stability of the system. The gain margin refers to the amount of gain, which can be increased or decreased without making the system unstable. It is usually expressed as a magnitude in dB.

8.1.4. Obtain the GM from the Bode plot.

**Solution:** The following code

codes/ee18btech11016.py

plots the amplitude and phase of (8.1.1.1) in Fig. 8.1.4. From Fig. 8.1.4,

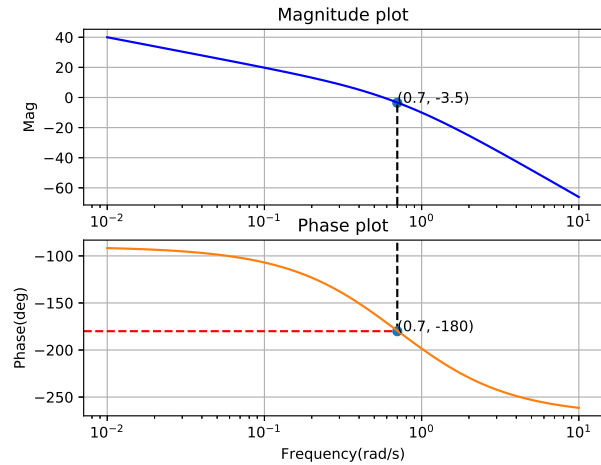


Fig. 8.1.4

$$20 \log_{10} |G(j\omega_{pc})| = -3.5dB, \quad \omega_{pc} = -180^\circ \quad (8.1.4.1)$$

$$\Rightarrow GM = +3.5dB. \quad (8.1.4.2)$$

8.1.5. A positive GM indicates closed loop stability with unity feedback. Verify this for (8.1.1.1).

**Solution:** The characteristic equation is

$$1 + G(s) = 0 \Rightarrow 2s^3 + 3s^2 + s + 1 = 0 \quad (8.1.5.1)$$

Constructing the routh array

$$\begin{array}{c|ccc} s^3 & 2 & 1 & 0 \\ s^2 & 3 & 1 & 0 \\ s & (1/3) & 0 & 0 \end{array} \quad (8.1.5.2)$$

$$\begin{array}{c|ccc} s^3 & 2 & 1 & 0 \\ s^2 & 3 & 1 & 0 \\ s & (1/3) & 0 & 0 \\ s^0 & 1 & 0 & 0 \end{array} \quad (8.1.5.3)$$

There are no sign changes in the first column of the routh array.  $\therefore$  the system is stable.

8.1.6. Instead of unity feedback, consider a system with

$$H(s) = \frac{1}{s+1} \quad (8.1.6.1)$$

Find the magnitude and phase of  $|G(j\omega)H(j\omega)|$

**Solution:**

$$\therefore G(s)H(s) = \frac{1}{s(1+2s)(s+1)^2}, \quad (8.1.6.2)$$

$$G(j\omega)H(j\omega) = \frac{1}{(2\omega^4 - 4\omega^2) + j(\omega - 5\omega^3)} \quad (8.1.6.3)$$

$$\Rightarrow \angle G(j\omega)H(j\omega) = -\tan^{-1}\left(\frac{\omega - 5\omega^3}{2\omega^4 - 4\omega^2}\right) \quad (8.1.6.4)$$

8.1.7. Compute the open loop gain margin for this system.

**Solution:** For  $\omega = \omega_{pc}$

$$\text{Im}\{G(j\omega)H(j\omega)\} = 0. \quad (8.1.7.1)$$

$$\Rightarrow \omega(1 - 5\omega^2) = 0 \quad (8.1.7.2)$$

$$\Rightarrow \omega_{pc} = \frac{1}{\sqrt{5}} \quad (8.1.7.3)$$

Hence,

$$GM = -20 \log_{10} |G(j\omega_{pc})H(j\omega_{pc})| = 20 \log_{10} k_g \quad (8.1.7.4)$$

where

$$k_g = \frac{1}{|G(j\omega_{pc})H(j\omega_{pc})|} \quad (8.1.7.5)$$

$$= \frac{18}{25} = 2.853 \text{ dB}. \quad (8.1.7.6)$$

Hence  $GM < 0$  and the system is unstable.

8.1.8. Obtain the GM from the Bode plot.

**Solution:** The following code

```
codes/ee18btech11016_2.py
```

plots the amplitude and phase of (8.1.1.1) in Fig. 8.1.8.

8.1.9. Show that the closed loop transfer function

$$T(s) = \frac{1}{1 + (s(1+2s)(1+s)^2)} \quad (8.1.9.1)$$

is unstable using the Routh Hurwitz criterion.

**Solution:** The characteristics equation is

$$2s^4 + 5s^3 + 4s^2 + s + 1 = 0 \quad (8.1.9.2)$$

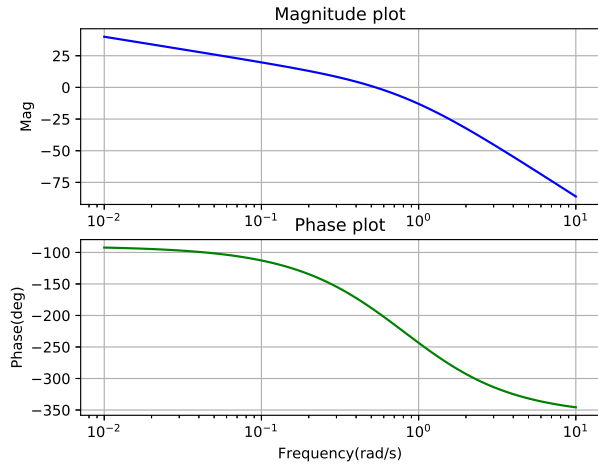


Fig. 8.1.8

Constructing routh array for the above,

$$\begin{array}{c|ccc} s^4 & 2 & 4 & 1 \\ s^3 & 5 & 1 & 0 \\ s^2 & (18/5) & 1 & 0 \end{array} \quad (8.1.9.3)$$

$$\begin{array}{c|ccc} s^4 & 2 & 1 & 0 \\ s^3 & 3 & 1 & 0 \\ s^2 & (18/5) & 1 & 0 \\ s & (-7/18) & 0 & 0 \end{array} \quad (8.1.9.4)$$

$$\begin{array}{c|ccc} s^4 & 2 & 1 & 0 \\ s^3 & 3 & 1 & 0 \\ s^2 & (18/5) & 1 & 0 \\ s & (-7/18) & 0 & 0 \\ s^0 & 1 & 0 & 0 \end{array} \quad (8.1.9.5)$$

There are 2 sign changes in the first column of the routh array. So, 2 poles lie on right half of s-plane. Therefore, the system is unstable.

## 8.2 Example

8.2.1. Fig. 8.2.1.1 shows the Bode magnitude and phase plots of

$$G(s) = \frac{n_0}{s^3 + d_2s^2 + d_1s + d} \quad (8.2.1.1)$$

Find  $|G(j\omega_{pc})|$ .

**Solution:** From Fig. 8.2.1.1,

$$\angle G(j\omega_{pc}) = 180^\circ \quad (8.2.1.2)$$

$$\Rightarrow 20 \log |G(j\omega_{pc})| = 20 \quad (8.2.1.3)$$

8.2.2. Consider the negative unity feedback configuration with gain  $k$  in the feed forward path as

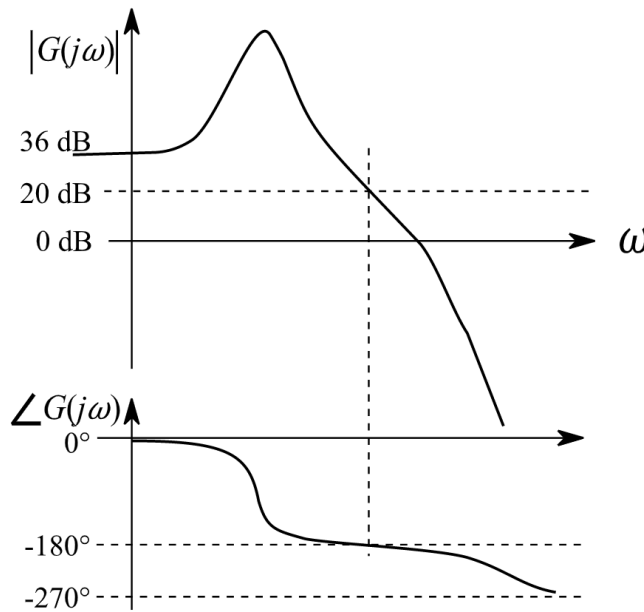


Fig. 8.2.1.1

shown in Fig. 8.2.2.1. Find the condition for the closed loop system to be stable.

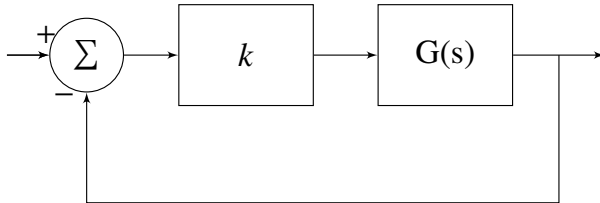


Fig. 8.2.2.1

**Solution:** The open loop gain for the system in Fig. 8.2.2.1 is

$$G_1(s) = kG(s) \quad (8.2.2.1)$$

$$\Rightarrow \angle G_1(j\omega_{pc}) = \angle G(j\omega_{pc}) \quad (8.2.2.2)$$

$$= 180^\circ \quad \text{and} \quad (8.2.2.3)$$

$$20 \log |G_1(j\omega_{pc})| = 20 \log |k| + 20 \log |G(j\omega_{pc})| \quad (8.2.2.4)$$

$$= 20(1 + \log |k|) \quad (8.2.2.5)$$

from (8.2.1.3). From (8.1.3.1) and (8.2.2.5), the GM of  $G_1(s)$  is

$$-20 \log |G_1(j\omega_{pc})| = -20(1 + \log |k|) \quad (8.2.2.6)$$

For stability,  $GM > 0$

$$\Rightarrow -20(1 + \log |k|) > 0 \quad (8.2.2.7)$$

$$\Rightarrow |k| < 0.1 \quad (8.2.2.8)$$

### 8.3 Example

8.3.1. Consider the unity feedback control system in Fig. 8.3.2.1. Find the value of  $K$  such that  $PM = 30^\circ$ .

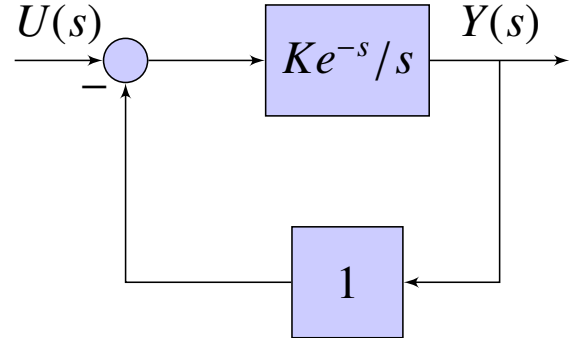


Fig. 8.3.1.1

**Solution:** From Fig. 8.3.2.1,

$$G(s) = \frac{Ke^{-s}}{s} \quad (8.3.1.1)$$

$$H(s) = 1 \quad (8.3.1.2)$$

$$\Rightarrow \quad (8.3.1.3)$$

$$|G(j\omega_{gc})H(j\omega_{gc})| = 1 \quad (8.3.1.4)$$

$$\Rightarrow \omega_{gc} = K \quad (8.3.1.5)$$

Thus,

$$\angle G(j\omega_{gc})H(j\omega_{gc}) = \angle \frac{Ke^{-jK}}{jK} \quad (8.3.1.6)$$

$$= -90^\circ - K \left( \frac{180}{\pi} \right) \quad (8.3.1.7)$$

$$\Rightarrow PM = 180^\circ - 90^\circ - K \left( \frac{180}{\pi} \right) \quad (8.3.1.8)$$

$$= 30^\circ \quad (8.3.1.9)$$

$$\Rightarrow K = \frac{\pi}{3} \quad (8.3.1.10)$$

8.3.2. Verify your result by plotting the gain and phase plots of  $G(j\omega)$

**Solution:** The following code plots Fig. 8.3.2.1

codes/ee18btech11038.py

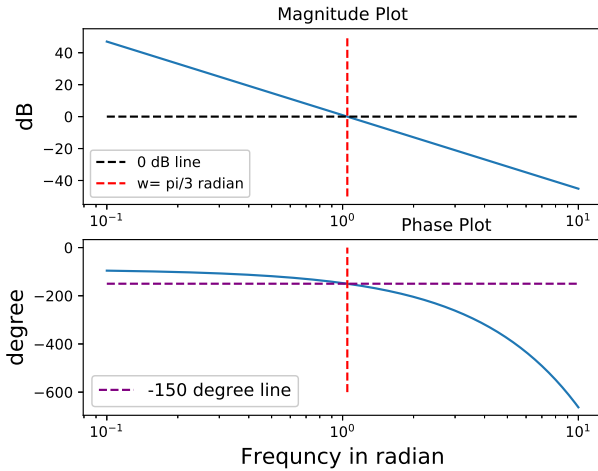


Fig. 8.3.2.1

## 9 PHASE MARGIN

### 9.1 Introduction

9.1. The open loop transfer function of a system is

$$G(s) = \frac{2}{(s+1)(s+2)} \quad (9.1.1)$$

Find its magnitude and phase response.

**Solution:** Substituting  $s = j\omega$  in (9.1.1),

$$G(j\omega) = \frac{1}{(j\omega+1)(j\omega+2)} \quad (9.1.2)$$

$$\Rightarrow |G(j\omega)| = \frac{2}{(\sqrt{\omega^2+1})(\sqrt{\omega^2+4})} \quad (9.1.3)$$

$$\angle G(j\omega) = -\tan^{-1}(\omega) - \tan^{-1}\left(\frac{\omega}{2}\right) \quad (9.1.4)$$

9.2. Find  $\omega$  for which the gain of (9.1.1) first becomes 1.

**Solution:** From (9.1.3)

$$|G(j\omega)| = 1 \quad (9.2.1)$$

$$\Rightarrow \frac{2}{(\sqrt{\omega^2+1})(\sqrt{\omega^2+4})} = 1 \quad (9.2.2)$$

$$\Rightarrow \omega_{gc} = 0 \quad (9.2.3)$$

which is the desired frequency.

9.3. Find  $\angle G(j\omega_{gc}) + 180^\circ$ . This is known as the *phase margin*(PM)

**Solution:** From (9.1.4),

$$\angle G(j\omega) = 0^\circ \Rightarrow PM = 180^\circ \quad (9.3.1)$$

9.4. Verify your result by plotting the gain and phase plots of  $G(j\omega)$ .

**Solution:** The following code plots Fig. 9.4.1

codes/ee18btech11017.py

The Phase plot is as shown,

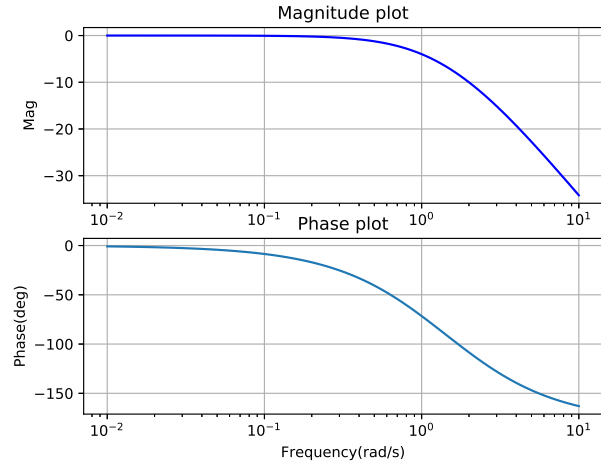


Fig. 9.4.1

9.5. A positive phase margin for the open loop system indicates a stable closed loop system. (9.3.1) indicates that  $G(s)$  with unity feedback is stable. Show that the roots of  $1 + G(s)$  lie in the left half plane proving closed loop stability.

**Solution:** Let the closed loop transfer function

$$T(s) = \frac{G(s)}{1 + G(s)} \quad (9.5.1)$$

Then

$$1 + G(s) = 0 \quad (9.5.2)$$

$$\Rightarrow s^2 + 3s + 4 = 0 \quad (9.5.3)$$

$$\text{or } s = -1.5 + 1.3j, -1.5 - 1.3j \quad (9.5.4)$$

Since the roots are in the left half plane, the system is stable.

9.6. Instead of unity feedback, consider a system with

$$H(s) = \frac{50}{s+1} \quad (9.6.1)$$

Compute the open loop phase margin for this system.

**Solution:**

$$\therefore G(s)H(s) = \frac{100}{(s+1)^2(s+2)}, \quad (9.6.2)$$

the magnitude and phase are

$$|G(j\omega)H(j\omega)| = \frac{10^2}{\sqrt{(\omega^2+1)^2} \sqrt{\omega^2+4}} \quad (9.6.3)$$

$$\angle G(j\omega)H(j\omega) = -\tan^{-1} \frac{\omega}{2} - 2 \tan^{-1}(\omega) \quad (9.6.4)$$

The gain crossover frequency is given by

$$\frac{10^2}{\sqrt{\omega_{gc}^2+4} \sqrt{(\omega_{gc}^2+1)^2}} = 1 \quad (9.6.5)$$

$$(9.6.6)$$

$$\omega_{gc}^6 + 6\omega_{gc}^4 + 9\omega_{gc}^2 - 9996 = 0 \quad (9.6.7)$$

$$\Rightarrow \omega_{gc} = 4.42 \quad (9.6.8)$$

From (9.6.4) and (9.6.8), the phase margin is

$$PM = 180^\circ - 2 \tan^{-1}(\omega_{gc}) - \tan^{-1}\left(\frac{\omega_{gc}}{2}\right) \quad (9.6.9)$$

$$\Rightarrow PM = -40.15^\circ \quad (9.6.10)$$

9.7. Verify your result through the magnitude and phase plot.

**Solution:** The following code plots Fig. 9.7.1

codes/ee18btech11017\_2.py

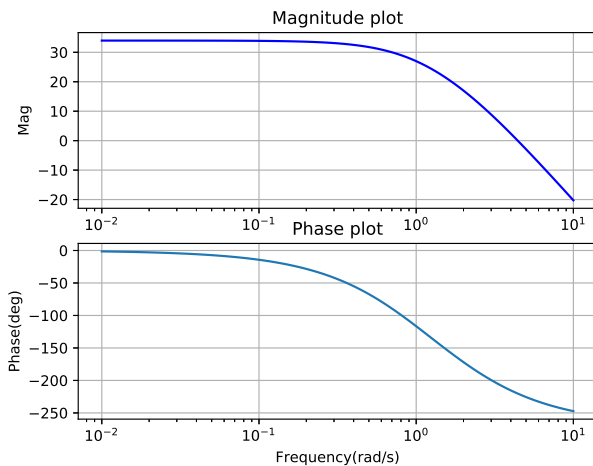


Fig. 9.7.1

9.8. Since the PM in (9.6.10) is negative, the closed loop system is unstable. Verify this using the

Routh-Hurwitz criterion.

**Solution:** The characteristic equation is

$$1 + G(s)H(s) = 0 \quad (9.8.1)$$

$$\Rightarrow s^3 + 4s^2 + 5s + 102 = 0 \quad (9.8.2)$$

Constructing the routh array for (9.8.2),

$$\begin{array}{c|ccc} s^3 & 1 & 5 & 0 \\ s^2 & 4 & 102 & 0 \\ s & -20.5 & 0 & 0 \end{array} \quad (9.8.3)$$

$$\begin{array}{c|ccc} s^3 & 1 & 5 & 0 \\ s^2 & 4 & 102 & 0 \\ s & -20.5 & 0 & 0 \\ s^0 & 102 & 0 & 0 \end{array} \quad (9.8.4)$$

$\therefore$  there are two sign changes in the first column of the routh array, two poles lie on right half of s-plane. Therefore, the system is unstable.

## 9.2 Example

9.1. For the feedback system in Fig. 9.1.1,

$$G(s) = \frac{1}{(s+1)(s+2)(s+3)}. \quad (9.1.1)$$

Find  $k > 0$  for which the gain margin of system is exactly 0 dB and phase margin of system is exactly 0 degree.

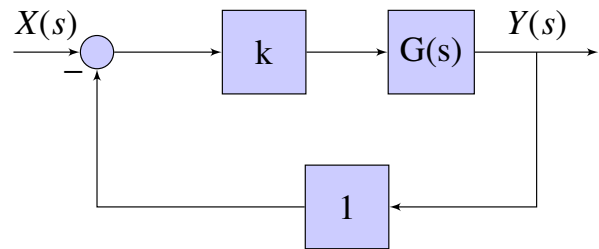


Fig. 9.1.1

**Solution:** From the given information, system can be destabilized with a marginal increase in the gain. Hence the system is marginally stable. The characteristic equation for (9.1.1) is

$$s^3 + 6s^2 + 11s + (6+k) = 0 \quad (9.1.2)$$

and the corresponding Routh array is

$$\begin{array}{c|ccc} s^3 & 1 & 11 & \\ s^2 & 6 & (6+k) & \\ s^1 & \frac{66-(6+k)}{6} & 0 & \\ s^0 & (6+k) & 0 & \end{array} \quad (9.1.3)$$

For the system to be marginally stable,

$$\frac{66 - (6 + K)}{6} > 0 \implies k = 60 \quad (9.1.4)$$

The following code

```
codes/ee18btech11036.py
```

verifies that the system is marginally stable for  $k = 60$ .

## 10 OSCILLATOR

### 10.1 Introduction

10.1.1. A unity feedback control system is characterised by the open-loop transfer function

$$G(s) = \frac{2(s+1)}{s^3 + ks^2 + 2s + 1} \quad (10.1.1.1)$$

Find the value of the  $k$  for which the system oscillates at 2 rad/s. Verify your result through a program.

**Solution:** Fig. 10.1.1.1 models the equivalent closed loop system.

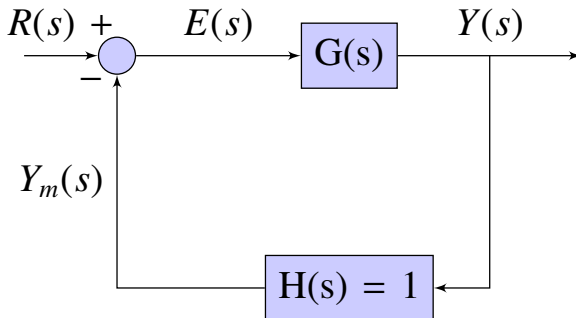


Fig. 10.1.1.1

The characteristic equation is

$$1 + G(s) = 0 \quad (10.1.1.2)$$

$$\implies 1 + \frac{2(s+1)}{s^3 + ks^2 + 2s + 1} = 0 \quad (10.1.1.3)$$

$$\text{or, } s^3 + ks^2 + 4s + 3 = 0 \quad (10.1.1.4)$$

Constructing the routh array for (10.1.1.4)

$$\begin{array}{c|cc} s^3 & 1 & 4 \\ s^2 & k & 3 \\ s^1 & \frac{3-4k}{k} & 0 \\ s^0 & 3 & 0 \end{array} \quad (10.1.1.5)$$

For the system to oscillate, poles should lie on the imaginary axis.

$$\implies \frac{3-4k}{k} = 0, \text{ or, } k = \frac{3}{4} \quad (10.1.1.6)$$

Substituting in (10.1.1.4),

$$s^3 + \frac{3}{4}s^2 + 4s + 3 = 0 \quad (10.1.1.7)$$

$$\implies s = \frac{-3}{4}, \pm 2j \quad (10.1.1.8)$$

The following code verifies the result.

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

10.1.2. Sketch the impulse response of the closed loop system.

**Solution:** The closed loop response

$$G_m(s) = \frac{G(s)}{1 + G(s)} = \frac{2(s+1)}{s^3 + \frac{3}{4}s^2 + 4s + 3} \quad (10.1.2.1)$$

$$= \frac{8}{73(s + \frac{3}{4})} + \frac{-8s + 152}{73(s^2 + 4)} \quad (10.1.2.2)$$

$$\implies g_m(t) = \frac{8}{73}e^{-\frac{3}{4}t}u(t) - \left(\frac{8}{73}\right)\sin(2t) + \left(\frac{152}{73}\right)\cos(2t) \quad (10.1.2.3)$$

The following code

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

plots Fig. 10.1.2.1 . This shows that system

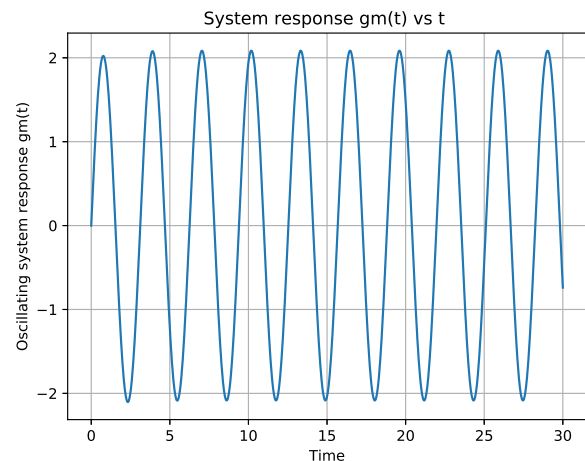


Fig. 10.1.2.1

oscillates at 2 rad/sec.

## 11 Root Locus

### 11.1 Introduction

11.1.1. A feedback control system has the characteristic equation

$$s^2 + 6Ks + 2s + 5 = 0, \quad K > 0. \quad (11.1.1.1)$$

Find the open loop gain.

**Solution:** can be expressed as

$$1 + \frac{6ks}{s^2 + 2s + 5} = 0 \quad (11.1.1.2)$$

$$\Rightarrow 1 + KG(s) = 0 \quad (11.1.1.3)$$

$$\Rightarrow G(s) = \frac{6s}{s^2 + 2s + 5} \quad (11.1.1.4)$$

11.1.2. Find the poles and zeros of  $G(s)$

**Solution:** The poles and zeros are at

$$\begin{aligned} p_1, p_2 &= -1 \pm 2j \\ z &= 0 \end{aligned} \quad (11.1.2.1)$$

11.1.3. Find the number of root locus branches.

**Solution:** For  $G(s)$ , let

- $P$ - No. of finite poles
- $Z$ - No. of finite zeros

The number of root locus branches

$$N = \begin{cases} P & P > Z, \\ Z & P < Z. \end{cases} \quad (11.1.3.1)$$

The root locus branches start at the open loop poles and end at open loop zeros. From (11.1.2.1),

$$P = 2, Z = 1 \Rightarrow N = 2 \quad (11.1.3.2)$$

One branch originates at each pole and ends at zero and the other branch starts from other pole and goes to infinity.

11.1.4. Find the centroid and the angle of asymptotes.

**Solution:** Some of the root locus branches approach infinity when  $P \neq Z$ . Asymptotes give the direction of these root locus branches. The intersection point of asymptotes on the real axis is known as centroid. The ordinate of the centroid is given by

$$\frac{\sum_{i=1}^P p_i - \sum_{j=1}^Z z_j}{P - Z} = \frac{-2 - 0}{2 - 1} \quad (11.1.4.1)$$

$$= -2 \quad (11.1.4.2)$$

after substituting from (11.1.2.1). Thus, the

centroid is at  $(-2, 0)$ . The formula for angle of asymptotes  $\theta$  is

$$\theta = \frac{(2q + 1)\pi}{P - Z}, \quad q = 0, 1, \dots, P - Z - 1 \quad (11.1.4.3)$$

$$= \pi \quad (11.1.4.4)$$

One branch meets the real axis at a breakaway point then goes to zero at origin and other goes to infinity following the asymptote ( $y = 0$ ).

11.1.5. Find the intersection points of root locus branches with the imaginary axis.

**Solution:** Using the Routh array method,

11.1.6. Find the angle of departure with respect to the pole  $p_k$ .

**Solution:** The angle of departure with respect to the  $k$ th (complex) pole is defined as

$$\phi_k^d = \begin{cases} \pi - \phi_k, & \text{Im}(p_k) \neq 0 \\ 0 & \text{Im}(p_k) = 0 \end{cases} \quad (11.1.6.1)$$

where,

$$\phi_k = \sum_{i=1}^P \angle p_k - p_i - \sum_{j=1}^Z \angle p_k - z_j \quad (11.1.6.2)$$

For  $p_1 = -1 + 2j$ ,

$$\phi_1 = \angle -1 + 2j - (-1 - 2j) - \angle -1 + 2j - 0 \quad (11.1.6.3)$$

$$\Rightarrow = \frac{\pi}{2} + (\pi - \tan^{-1} 2) = \frac{3\pi}{2} - \tan^{-1} 2 \quad (11.1.6.4)$$

11.1.7. Find the angle of arrival with respect to the zero  $z_k$

**Solution:** The angle of arrival with respect to the  $k$ th (complex) zero is defined as

$$\phi_k^a = \begin{cases} \pi - \phi_k, & \text{Im}(z_k) \neq 0 \\ 0 & \text{Im}(z_k) = 0 \end{cases} \quad (11.1.7.1)$$

where,

$$\phi_k = \sum_{i=1}^P \angle z_k - p_i - \sum_{j=1}^Z \angle z_k - z_j \quad (11.1.7.2)$$

Since there are no complex zeros there is no angle of arrival.

11.1.8. Find the breakaway point for the root locus.



**Solution:** From (11.1.1) and (11.1.1.4),

$$K = \frac{-(s^2 + 2s + 5)}{6s}, \quad (11.1.8.1)$$

$$\frac{dK}{ds} = 0 \Rightarrow \left[ 1 - \frac{5}{s^2} \right] = 0 \quad (11.1.8.2)$$

$$\Rightarrow s = -\sqrt{5} \quad (11.1.8.3)$$

which is the breakaway point that lies only in the left half plane. Some information on the breakaway point is available below.

- While varying  $K$ , the point where the Root Locus enters the real axis is called the breakaway point.
- It is the point on a real axis segment of the root locus between two real poles where the two real closed-loop poles meet and diverge to become complex conjugates.
- As the root locus is symmetric about the real axis there will be two roots at the breakaway point.

#### 11.1.9. Plot the Root Locus.

**Solution:** The following code generates the desired plot in Fig. 11.1.9.1.

```
codes/ee18btech11046.py
```

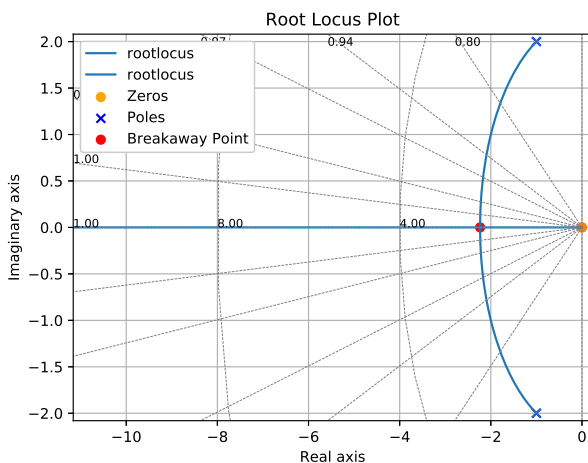


Fig. 11.1.9.1

### 11.2 Example

11.1. A unity negative feedback system has the open loop transfer function

$$G(s) = \frac{K}{s(s+1)(s+3)} \quad (11.1.1)$$

Find the value of the gain  $K$  ( $>0$ ) at which the root locus crosses the imaginary axis.

**Solution:** From , the characteristic function of the control system is

$$s^3 + 4s^2 + 3s + K = 0 \quad (11.1.2)$$

If all elements of any row of the Routh array table are zero, then the root locus branch intersects the imaginary axis. The Routh array is

$$\begin{array}{c|cc} s^3 & 1 & 3 \\ s^2 & 4 & K \\ s^1 & (12-K)/4 & 0 \\ s^0 & K & \end{array} \quad (11.1.3)$$

$$\Rightarrow \frac{12-K}{4} = 0 \quad (11.1.4)$$

$$\text{or, } K = 12. \quad (11.1.5)$$

The following code plots the root locus in Fig. 11.2.1

```
codes/ee18btech11050.py
```

#### 11.2. Root Locus plot

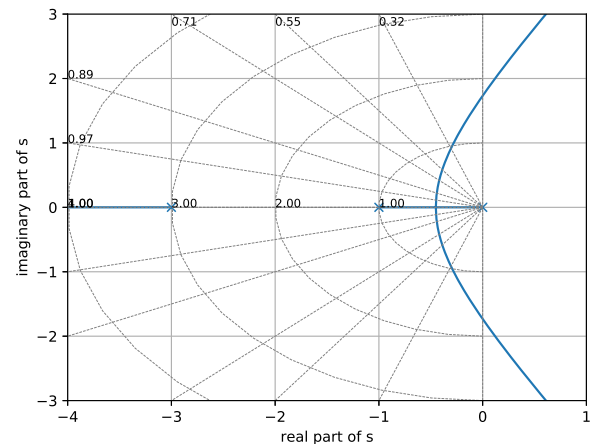


Fig. 11.2.1

### 11.3 Example

11.3.1. The open-loop transfer function of a plant in a unity feedback configuration is given as

$$G(s) = \frac{K(s+4)}{(s+8)(s^2-9)} \quad (11.3.1.1)$$

Find the value of the gain  $K > 0$  for which  $-1 + j2$  lies on the root locus.

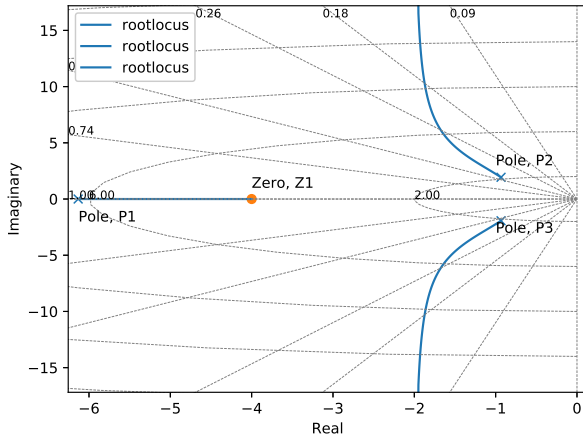


Fig. 11.3.1.1

**Solution:** The closed loop transfer function for a negative feed back system is:

$$F(s) = \frac{G(s)}{1 + G(s)H(s)} \quad (11.3.1.2)$$

From the characteristic equation Since it is a unity feed back system,  $H(s) = 1$ , and now using the characteristic align at  $s_1 = -1 + j2$

$$1 + G(s_1)H(s_1) = 0 \quad (11.3.1.3)$$

$$\Rightarrow |G(s_1)| = \frac{K\sqrt{13}}{\sqrt{51}\sqrt{8}\sqrt{20}} = 1 \quad (11.3.1.4)$$

$$\Rightarrow K = 25.05 \quad (11.3.1.5)$$

$$\text{or, } F(s) = \frac{25.05(s+4)}{s^3 + 8s^2 + 16.05s + 28.2} \quad (11.3.1.6)$$

The following code plots the root locus in Fig. 11.3.1.1.

codes/ee18btech11052.py

## 12 POLAR PLOT

### 12.1 Introduction

12.1. Sketch the polar plot for the transfer function

$$G(s) = \frac{10(s+1)}{10+s} \quad (12.1.1)$$

for

$0 \leq \omega < \infty$ . Which quadrant does it lie in?

**Solution:** Substituting  $s = j\omega$  in (12.1.1),

$$G(j\omega) = \frac{10(1+j\omega)}{(10+j\omega)} \quad (12.1.2)$$

$$= 10 \underbrace{\sqrt{\frac{1+\omega^2}{100+\omega^2}}}_r \times \exp \left\{ j \underbrace{\left( \tan^{-1}(\omega) - \tan^{-1}\left(\frac{\omega}{10}\right) \right)}_{\theta} \right\} \quad (12.1.3)$$

$$\therefore \frac{d}{d\omega} \tan^{-1}(\omega) = \frac{1}{1+\omega^2}, \omega > 0, \quad (12.1.4)$$

$\tan^{-1}(\omega)$  is an increasing funtion. Hence,

$$\tan^{-1}(\omega) \geq \tan^{-1}\left(\frac{\omega}{10}\right). \quad (12.1.5)$$

$\therefore 0 < \theta < \frac{\pi}{2}$  in (12.1.3), the polar plot of  $G(s)$  lies in the first quadrant. The following code generates the polar plot in Fig. 12.1.1.

codes/ee18btech11051.py

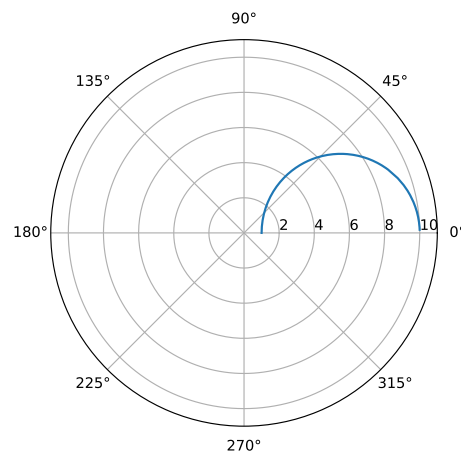


Fig. 12.1.1

## 13 PID CONTROLLER

### 13.1 Introduction

13.1. The plant transfer given by

$$G(s) = \left( K_P + \frac{K_I}{s} \right) \left( \frac{1}{s(s+2)} \right) \quad (13.1.1)$$

and shown in Figs. 13.2 and 13.2 is known as a PI controller.

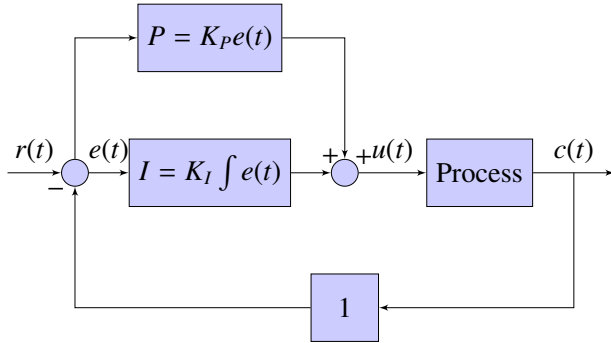


Fig. 13.1.1

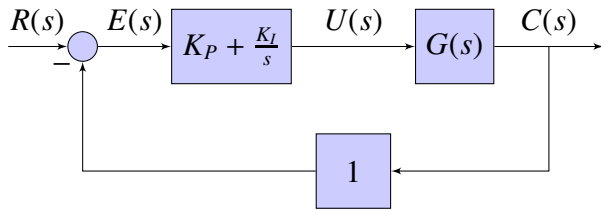


Fig. 13.1.2

When the plant operates in a unity feedback configuration, find the condition for the stability of the closed loop system

**Solution:** The closed Loop Transfer function for unity feedback is

$$\frac{G(s)}{(1 + G(s))} = \frac{(K_P s + K_I)}{s^2(s+2) + (K_P s + K_I)} \quad (13.1.2)$$

$$= \frac{(K_P s + K_I)}{s^3 + 2s^2 + K_P s + K_I} \quad (13.1.3)$$

Using the Routh Hurwitz tabular form

$$\begin{vmatrix} s^3 & 1 & K_P \\ s^2 & 2 & K_I \\ s^1 & \frac{2K_P - K_I}{2} & 0 \\ s^0 & K_P & \end{vmatrix} \quad (13.1.4)$$

The sufficient condition for stability is that all the elements of the first column of the Routh array should have the same sign. Hence,

$$K_P > 0 \quad (13.1.5)$$

$$2K_P - K_I > 0 \quad (13.1.6)$$

$$\Rightarrow K_P > \frac{K_I}{2} > 0 \quad (13.1.7)$$

is the required condition for system to be stable.

13.2. Verify your result by plotting the gain and phase plots of (13.1.3) for different values of  $K_P$  and  $K_I$ .

**Solution:** For a system to be stable Gain Margin should be greater than 1 and Phase Margin Should be Positive.

The following code plots for  $K_P = 1$  and  $K_I = 0.5$  Fig. 13.2

codes/ee17btech11031\_1.py

- The Phase margin: 73.07475039260186
- The Gain Margin:  $\infty$

The Phase plot is as shown,

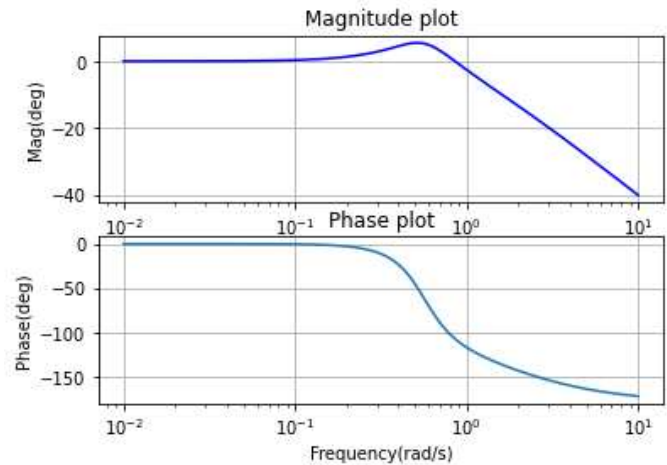


Fig. 13.2

For  $K_P = -1$  and  $K_I = 0.5$  Fig. 13.2

codes/ee17btech11031\_2.py

- The Phase margin: -128.18015255977565
- The Gain Margin:  $\infty$

The Phase plot is as shown,

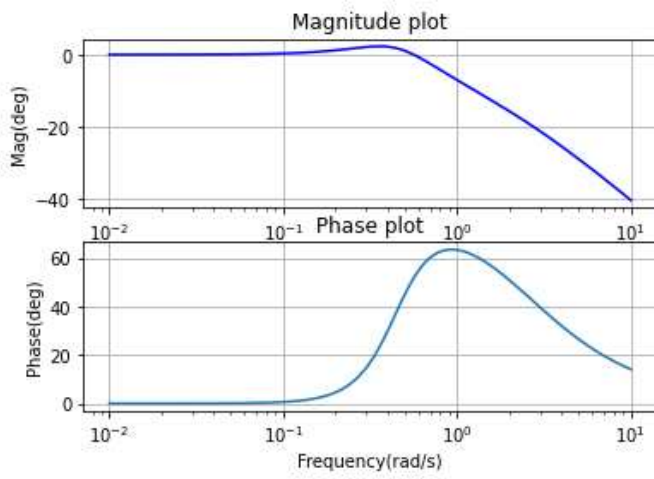


Fig. 13.2