
SIGNAL PROCESSING

Through GATE

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Contents

| | |
|------------------------------|------------|
| Introduction | iii |
| 1 Harmonics | 1 |
| 2 Filters | 9 |
| 3 Z-transform | 37 |
| 4 Systems | 39 |
| 5 Sequences | 81 |
| 6 Sampling | 89 |
| 7 Contour Integration | 97 |
| 8 Laplace Transform | 101 |
| 9 Fourier transform | 159 |
| 10 FFT | 183 |
| 11 Filter Design | 189 |

Introduction

This book provides solutions to signal processing problems in GATE.

Chapter 1

Harmonics

- 1.1 Let $y(t)=x(4t)$, where $x(t)$ is a continuous-time periodic signal of 100s. the fundamental period of $y(t)$ is (**rounded off to the nearest integer**) (GATE IN 2023)

Solution:

| Symbol | Value | Description |
|------------|--------------------|---------------------------------|
| T | 100 | fundamental period of $x(t)$ |
| T_1 | | fundamental period of $y(t)$ |
| ω_0 | $\frac{8\pi}{100}$ | fundamental frequency of $y(t)$ |

Table 1: input parameters

From Table 1

Applying Fourier series:

$$x(t) = \sum_{n=-\infty}^{\infty} c_n e^{\frac{j 2\pi n t}{100}} \quad (1.1)$$

$$y(t) = x(4t) \quad (1.2)$$

$$y(t) = \sum_{n=-\infty}^{\infty} c_n e^{\frac{j 2\pi n (4t)}{100}} \quad (1.3)$$

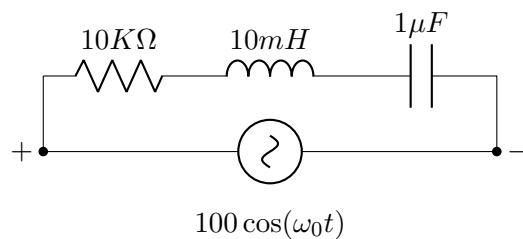
$$= \sum_{n=-\infty}^{\infty} c_n e^{\frac{j 2\pi n t}{25}} \quad (1.4)$$

$$T_1 = 25\text{sec} \quad (1.5)$$



Figure 1: plot $y(t)$ v/s t

- 1.2 In the circuit shown below, it is observed that the amplitude of voltage across the resistor is the same as the amplitude of the source voltage. What is the angular frequency ω_0 (in rad/s)?



(GATE BM 2023) **Solution:**

- 1.3 For a regular sinusoidal wave propagating in deep water having wave height of 3.5 m and wave period of 9 s, the wave steepness is _____ (round off to three decimal places). Gate 2023 NM 33

Solution:

| Symbol | Value | Description |
|-----------|-------|----------------------------|
| H | 3.5m | wave height |
| T | 9s | wave period |
| S | ? | wave steepness |
| λ | | wave length |
| η | | surface elevation of water |

Table 1.2: Input Parameters

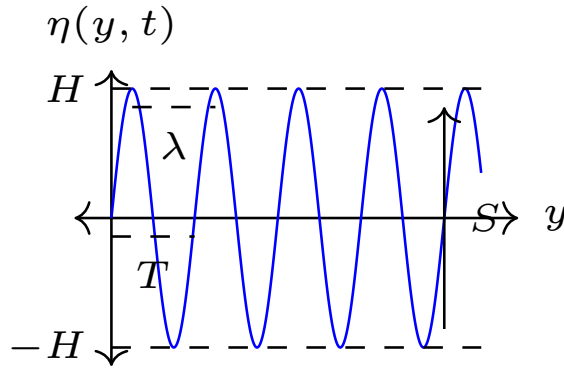


Figure 1.2: Sinusoidal wave

- (a) Deriving the formula for wavelength of deep water wave:

$$S = \frac{H}{\lambda} \quad (1.6)$$

Let's start with the linearized shallow water wave equation.

$$\frac{\partial^2 \eta}{\partial t^2} = g \frac{\partial \eta}{\partial y} \quad (1.7)$$

$$\eta = A \sin(ky - \omega t) \quad (1.8)$$

$$\frac{\partial^2 \eta}{\partial t^2} = -(\omega)^2 A \sin(ky - \omega t) \quad (1.9)$$

For deep water waves:

$$\frac{\partial \eta}{\partial y} \approx -k\eta \quad (1.10)$$

Using the equation (1.7).

$$\frac{\partial^2 \eta}{\partial t^2} = -gk\eta \quad (1.11)$$

$$= -gkA \sin(ky - \omega t) \quad (1.12)$$

where, k is wave number.

Comparing equations (1.9) and (1.12),

$$\omega^2 = gk \quad (1.13)$$

$$\omega = \frac{2\pi}{T} \quad (1.14)$$

$$k = \frac{2\pi}{\lambda} \quad (1.15)$$

$$\lambda = \frac{g \cdot T^2}{2\pi} \quad (1.16)$$

(b) Numerical computation:

$$\lambda = \frac{g \cdot T^2}{2\pi} \tag{1.17}$$

$$= \frac{9.81 \, (9)^2}{2\pi} \tag{1.18}$$

$$= 126.53m \tag{1.19}$$

Using the equation (1.6).

$$S = \frac{3.5}{126.53} \tag{1.20}$$

$$= 0.028 \tag{1.21}$$

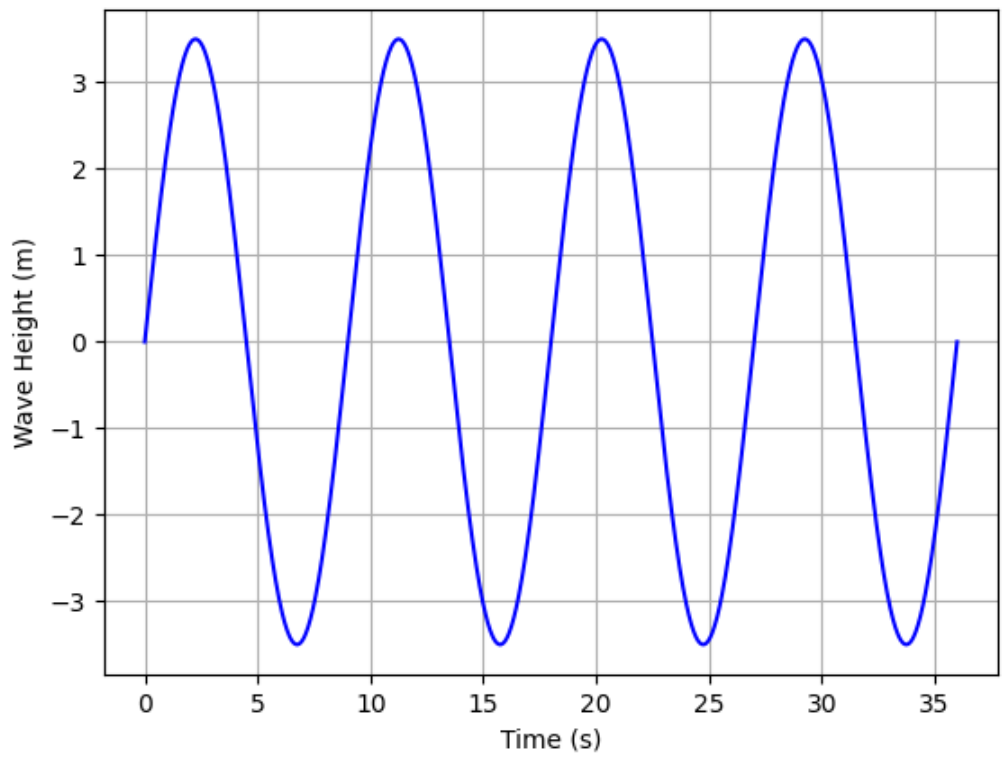
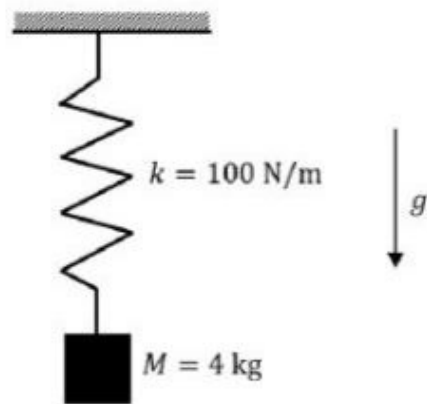


Figure 1.3: Sinusoidal wave

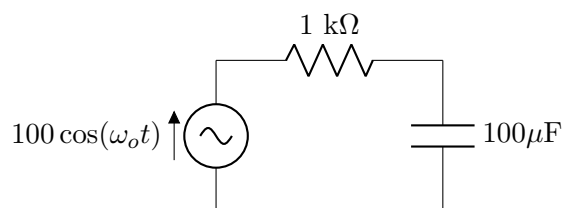
1.4 A spring mass system is shown in the figure . Take the value of acceleration due to gravity as $g = 9.81m/s^2$.The static deflection due to weight and the time period of the oscillations,respectively,are

(GATE 2023 XE)

Solution:



- 1.5 In the circuit shown below, the amplitudes of the voltage across the resistor and the capacitor are equal. What is the value of the angular frequency ω_o (in rad/s)? (Round off the answer to one decimal place.) (GATE BM 32 2023)



Solution:

Chapter 2

Filters

2.1 For the circuit given below, choose the angular frequency ω_0 at which voltage across capacitor has maximum amplitude?

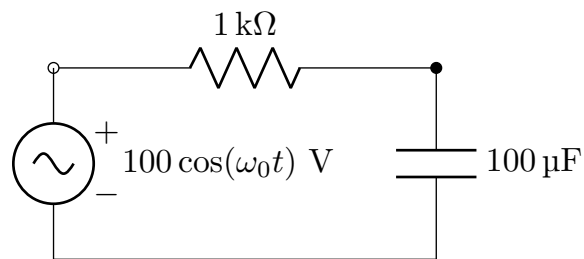


Figure 2.1: circuit

- (A) 1000
- (B) 100
- (C) 1
- (D) 0

(GATE BM 2023 Question 16)

Solution:

| Parameter | Description | Value |
|----------------|---------------------------------------|-------------------------|
| $V_i(j\omega)$ | Input voltage | 100 |
| $v_c(t)$ | Potential difference across Capacitor | ? |
| $V_c(s)$ | Potential difference across Capacitor | $V_c(s)$ |
| $H(s)$ | Transfer function | $\frac{V_c(s)}{V_i(s)}$ |
| V_o | Amplitude of input voltage | 100 V |
| R | Resistance in circuit | 1 k Ω |
| C | Capacitance in circuit | 100 μ F |
| ω_o | Angular frequency of input voltage | ω_o |

Table 2.1: input values

$$V_c(s) = \frac{V_i(s) \frac{1}{sC}}{R + \frac{1}{sC}} \quad (2.1)$$

$$\Rightarrow H(s) = \frac{1}{1 + sRC} \quad (2.2)$$

$$\Rightarrow H(j\omega) = \frac{1}{1 + j\omega RC} \quad (2.3)$$

$$|H(j\omega)| = \frac{1}{\sqrt{1 + (\omega RC)^2}} \quad (2.4)$$

$$v_c(t) = \frac{100}{\sqrt{1 + (\omega_o RC)^2}} \left(\cos \omega_o t + \arctan \left(\frac{1}{\omega_o RC} \right) \right) \quad (2.5)$$

Maximum amplitude of $v_c(t)$ occurs at $\omega_o = 0$

$$\therefore \omega_o = 0 \quad (2.6)$$

\therefore maximum value of $v_c(t)$ at steady state is 100 Volts.

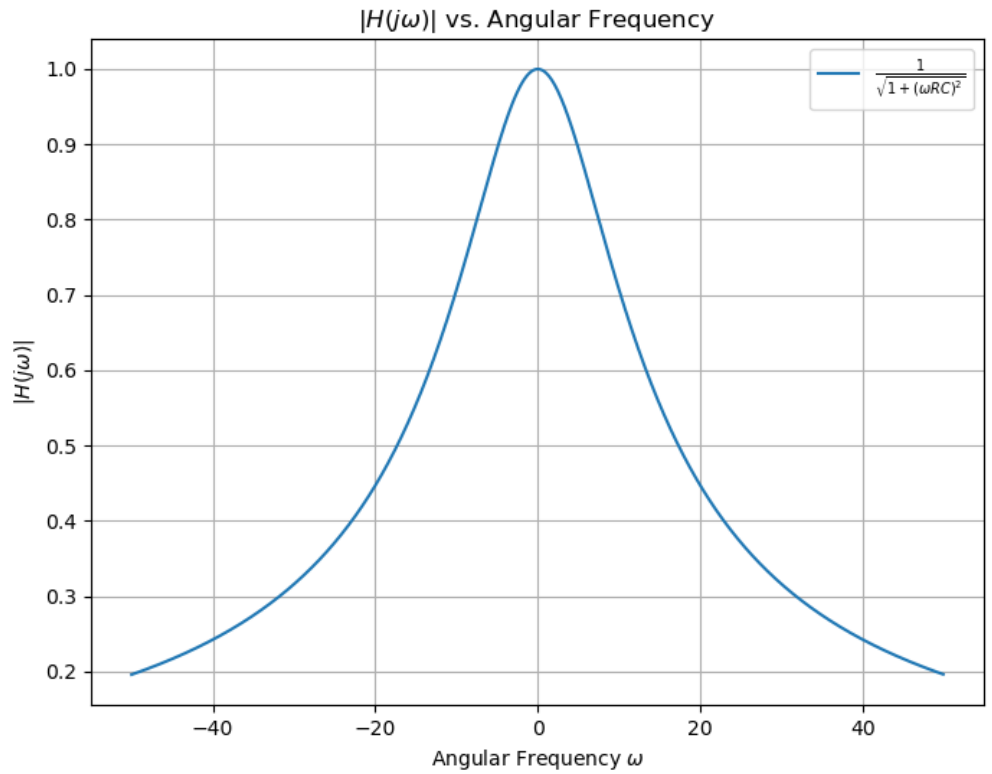


Figure 2.2: $|H(j\omega)|$

2.2 In the following circuit, the switch S is open for $t < 0$ and closed for $t \geq 0$. What is the steady state voltage (in Volts) across the capacitor when the switch is closed?

(GATE BM 2023 Question 30)

2.3 A finite impulse response (FIR) filter has only two non-zero samples in its impulse response $h[n]$, namely $h[0] = h[1] = 1$. The Discrete Time Fourier Transform (DTFT) of $h[n]$ equals $H(e^{j\omega})$, as a function of the normalized angular frequency ω . For the range $|\omega| \leq \pi$, $|H(e^{j\omega})|$ is equal to

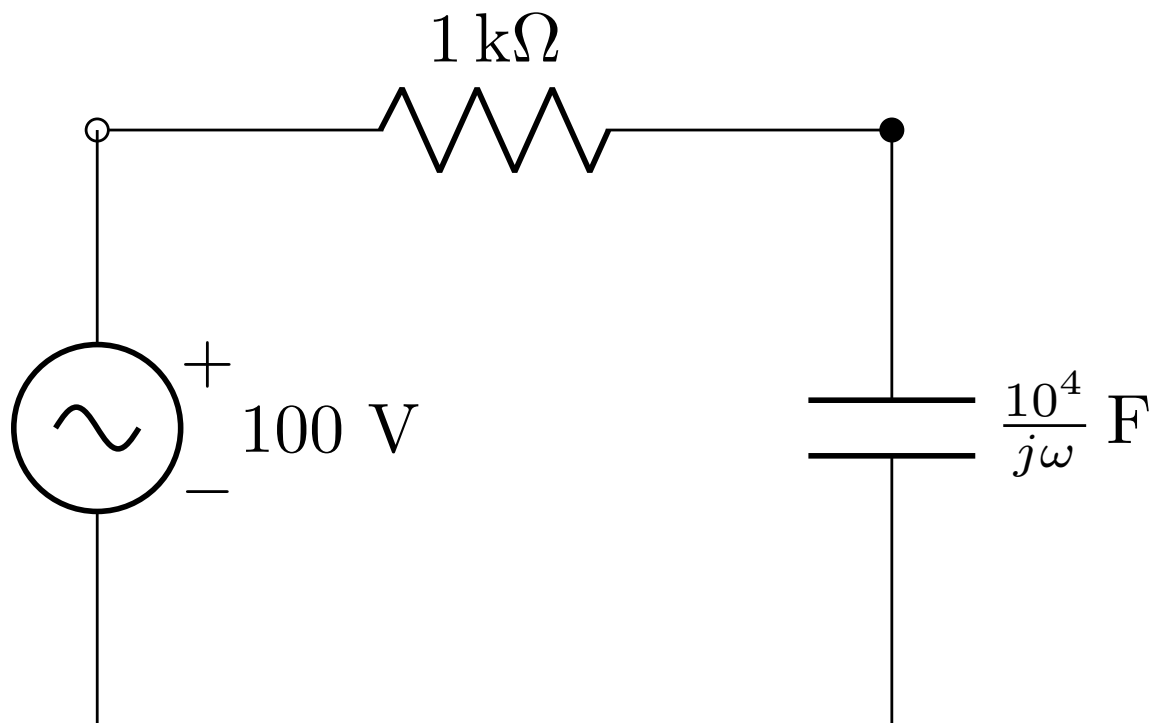


Figure 2.3: circuit in ω -domain

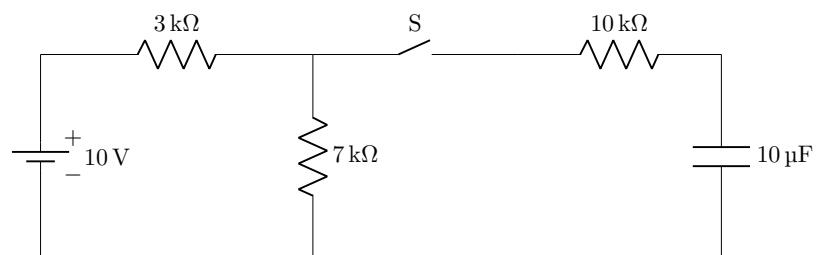


Figure 2.4: circuit

(A) $2|\cos(\omega)|$

(B) $2|\sin(\omega)|$

(C) $2\left|\cos\left(\frac{\omega}{2}\right)\right|$

(D) $2\left|\sin\left(\frac{\omega}{2}\right)\right|$

(GATE BM 2023 Question 17)

Solution:

| Parameter | Value | Description |
|------------------|----------------------------------|-----------------------------|
| $h[n]$ | - | impulse response |
| $h[0]$ | 1 | impulse response at $n = 0$ |
| $h[1]$ | 1 | impulse response at $n = 1$ |
| ω | $-\pi \leq \omega \leq \pi$ | normalized frequency |
| $H(e^{j\omega})$ | $\sum_{n=0}^M h[n]e^{-jn\omega}$ | frequency response |

Table 2.2: Input Parameters Table

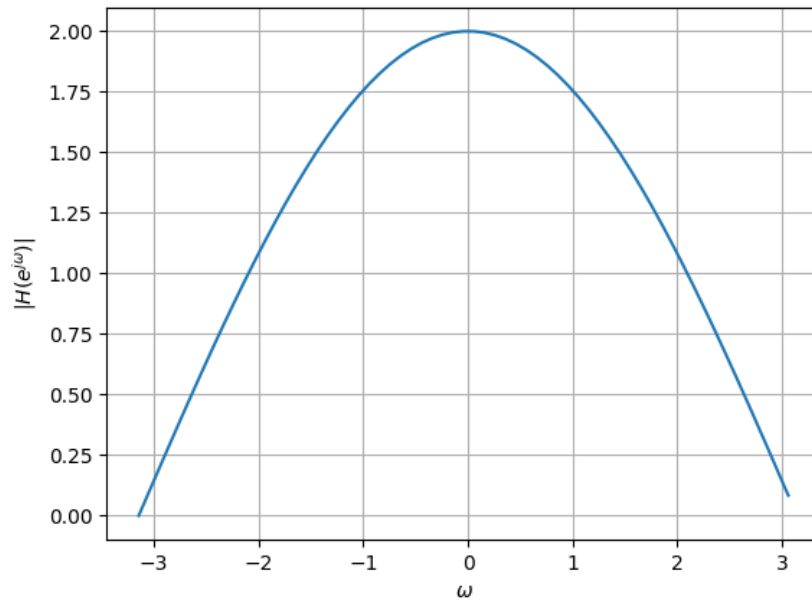
From Table 2.2,

$$H(e^{j\omega}) = 1 + e^{-j\omega} \quad (2.7)$$

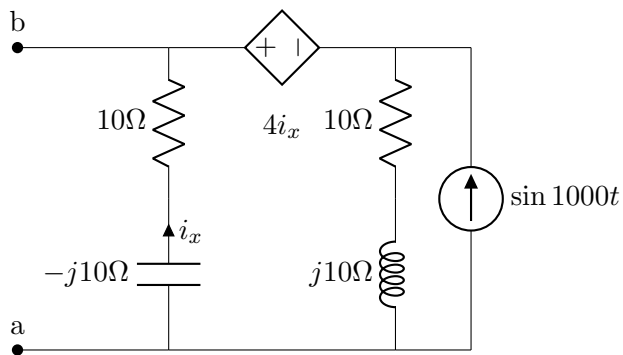
$$= e^{-\frac{j\omega}{2}} \left(e^{\frac{j\omega}{2}} + e^{-\frac{j\omega}{2}} \right) \quad (2.8)$$

$$= e^{-\frac{j\omega}{2}} \left(2 \cos \left(\frac{\omega}{2} \right) \right) \quad (2.9)$$

$$|H(e^{j\omega})| = 2 \left| \cos \left(\frac{\omega}{2} \right) \right| \quad (2.10)$$

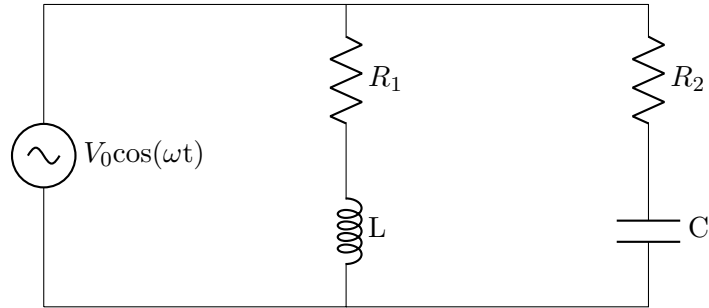


2.4 For the circuit shown, if $i = \sin 1000t$, the instantaneous value of the Thevenin's voltage (in volts) across the terminals a and b at time $t=5\text{ms}$ is



(GATE EE 2023 Question 51)

- 2.5 In the circuit shown , $\omega = 100\pi\text{rads/s}$, $R_1=R_2=2.2\Omega$ and $L=7\text{mH}$. the capacitance C for which Y_{in} is purely real is mF



(GATE IN 2023 Q46)

Solution:

| variable | value | description | formulae |
|------------|-----------------------|---------------------------|---|
| Y_{in} | - | Admittance of circuit | $\frac{R_1 - Ls}{R_1^2 - (Ls)^2} + \frac{R_2 - \frac{1}{sC}}{R_2^2 - (\frac{1}{sC})^2}$ |
| X_L | $7s\Omega$ | Inductive reactance | sL |
| X_C | $\frac{1}{sC}\Omega$ | Capacitive reactance | $\frac{1}{sC}$ |
| s | $100\pi j$ | Laplace complex frequency | $j\omega$ |
| ω | $100\pi\text{rads/s}$ | Angular frequency | - |
| V | $V_0 \cos(\omega t)$ | voltage of source | - |
| R_1, R_2 | 2.2Ω | resistance of resistors | - |

Table 2.3: Table: Input Parameters

From *Table 2.3*

$$Y_{in} = \frac{R_1 - Ls}{R_1^2 - (Ls)^2} + \frac{R_2 - \frac{1}{sC}}{R_2^2 - (\frac{1}{sC})^2} \quad (2.11)$$

$$Im(Y_{in}) = \frac{-Ls}{R_1^2 - (Ls)^2} + \frac{-\frac{1}{sC}}{R_2^2 - (\frac{1}{sC})^2} \quad (2.12)$$

According to the question given, Y_{in} is purely real , so imaginary part should be equal

to zero

Take the values from *Table 2.3*

$$\frac{-1}{4.4} + \frac{\frac{1}{(100\pi)C}}{(2.2)^2 + \left(\frac{1}{(100\pi)C}\right)^2} = 0 \quad (2.13)$$

$$\frac{\frac{1}{(100\pi)C}}{(2.2)^2 + \left(\frac{1}{(100\pi)C}\right)^2} = \frac{1}{4.4} \quad (2.14)$$

$$(2.2)^2 - \frac{4.4}{(100\pi)C} + \left(\frac{1}{(100\pi)C}\right)^2 = 0 \quad (2.15)$$

$$\left(2.2 - \frac{1}{(100\pi)C}\right)^2 = 0 \quad (2.16)$$

$$\frac{1}{(100\pi)C} = 2.2 \quad (2.17)$$

$$C = \frac{700}{484}\text{mF} \quad (2.18)$$

$$C = 1.446281\text{mF} \quad (2.19)$$

The capacitance of capacitor C is 1.45mF

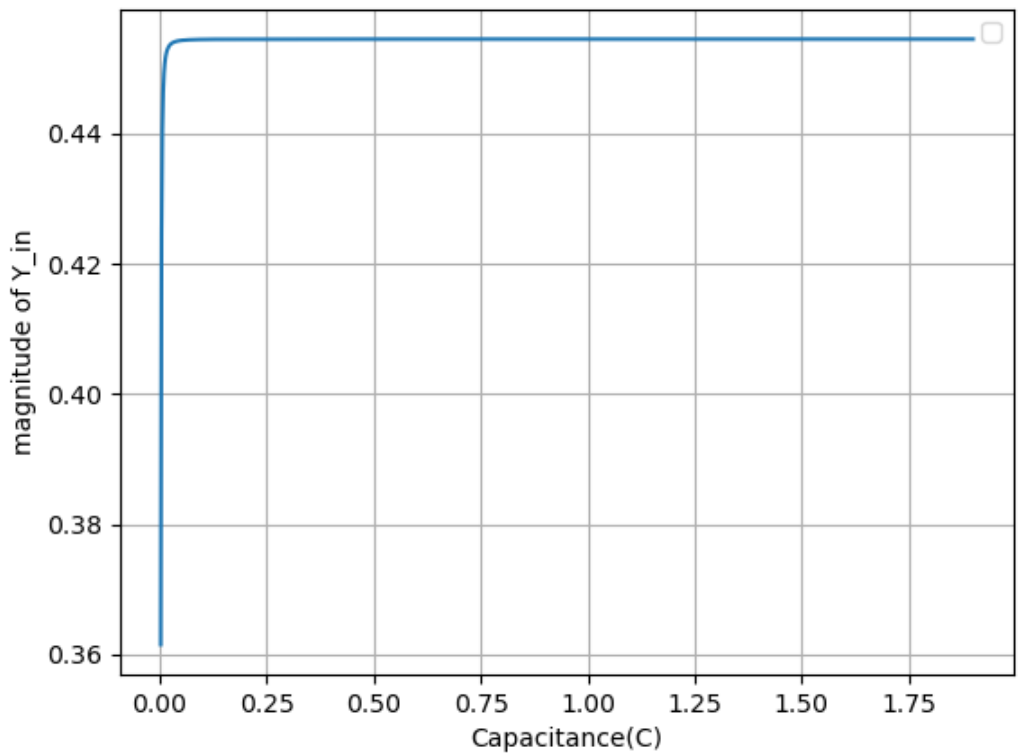


Figure 2.5: the plot of capacitance vs magnitude of Y_{in}

2.6 An input voltage in the form of a square wave of frequency 1 kHz is given to a circuit, which results in the output shown schematically below. Which one of the following options is the CORRECT representation of the circuit? (GATE PH 2023 Q37)

- (a)
- (b)
- (c)
- (d)

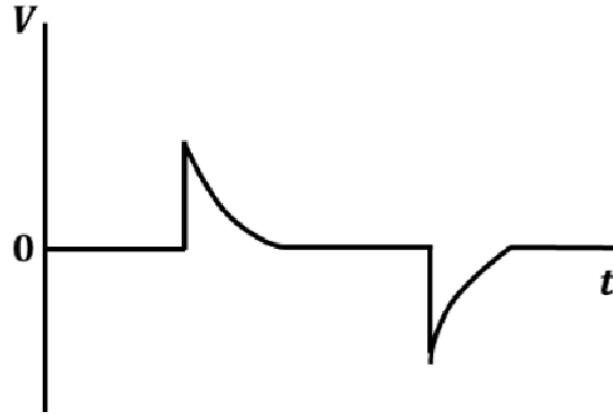
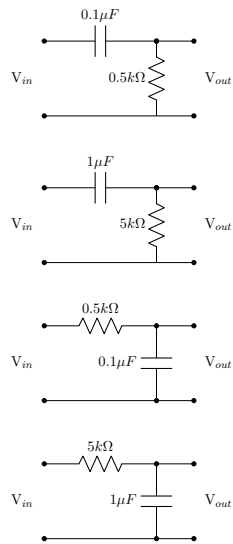


Figure 2.6:



(GATE 2023 PH 37)

Solution:

Input waveform is a square wave (Fig. 2.7), so we take its Fourier Transform

$$V_{in}(t) = 2 \left(2 \left[\frac{(t - \frac{T}{4})}{T} \right] - \left[\frac{2(t - \frac{T}{4})}{T} \right] \right) + 1 \quad (2.20)$$

| Symbol | Value | Description |
|------------------------------|----------------------------------|-----------------------------------|
| $V_{in}(t)$ | | Input Voltage |
| $\mathcal{V}_{in}(j\omega)$ | | Fourier Transform of $V_{in}(t)$ |
| $V_{out}(t)$ | | Output Voltage |
| $\mathcal{V}_{out}(j\omega)$ | | Fourier Transform of $V_{out}(t)$ |
| f | $\frac{\omega}{2\pi} = 1000Hz$ | Input Wave Frequency |
| T | $\frac{2\pi}{\omega} = 10^{-3}s$ | Input Wave Time Period |
| R | (a) $0.5k\Omega$ | Resistance |
| | (b) $5k\Omega$ | |
| C | (a) $0.1\mu F$ | Capacitance |
| | (b) $1\mu F$ | |
| τ | RC | Time Constant |
| Z | $R + \frac{1}{j\omega C}$ | Impedance |
| $H(j\omega)$ | $\frac{V_{out}}{V_{in}}$ | General Transfer Function |
| $H_R(j\omega)$ | $\frac{V_{R,out}}{V_{in}}$ | Transfer Function for Resistor |
| $H_C(j\omega)$ | $\frac{V_{C,out}}{V_{in}}$ | Transfer Function for Capacitor |

Table 2.4: Given Parameters

Fourier Series Coefficient:

$$c_k = \frac{1}{T} \int_T V_{in}(t) e^{-jk\omega t} dt \quad (2.21)$$

As square wave is even, $\sin(k\omega t)$ terms become zero. Cosine coefficients are:

$$a_n = \frac{2}{T} \int_T V_{in}(t) \cos\left(\frac{2\pi nt}{T}\right) dt \quad (2.22)$$

$$= \frac{4}{n\pi} \sin\left(\frac{n\pi}{2}\right) \cos(n\pi) \quad (2.23)$$

Fourier Series of $V_{in}(t)$:

$$V_{in}(t) = \sum_{n=1}^{\infty} a_n \cos\left(\frac{2\pi nt}{T}\right) \quad (2.24)$$

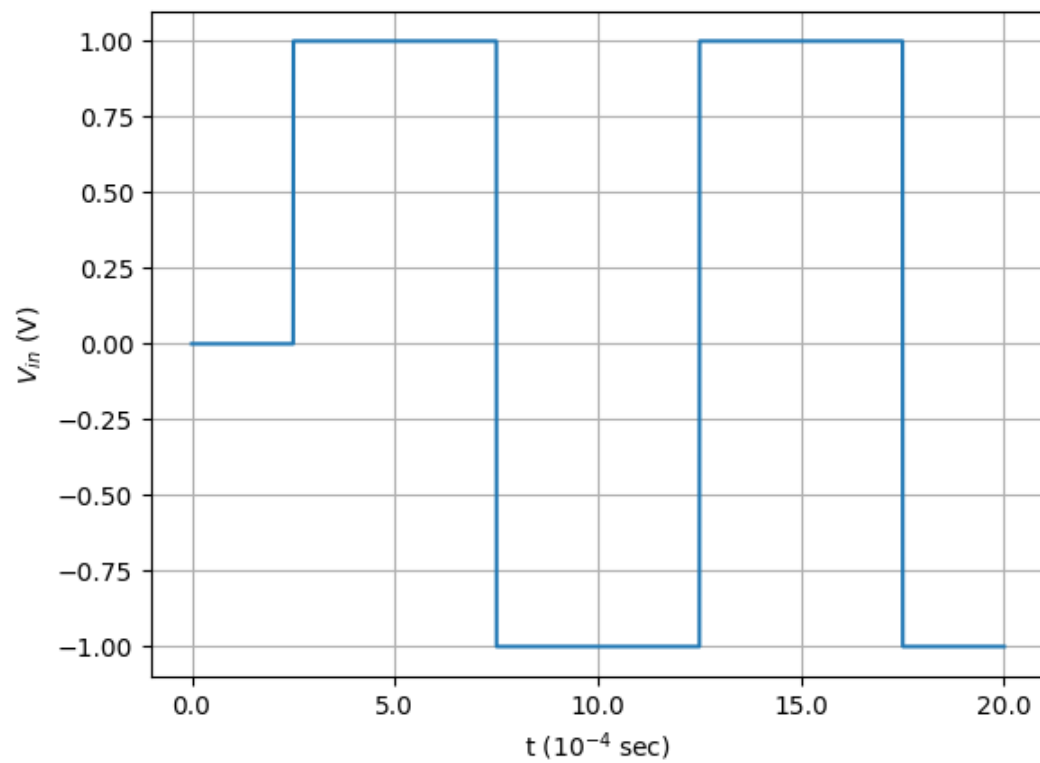


Figure 2.7: Input Square Waveform ($V_{in}(t)$)

Taking Fourier Transform of $V_{in}(t)$:

$$V_{in}(t) \xleftrightarrow{\mathcal{F}} V_{in}(j\omega) \quad (2.25)$$

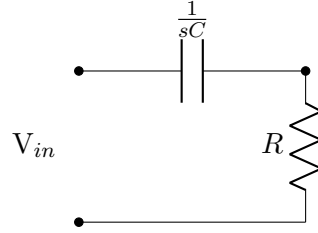


Figure 2.8: Series RC Circuit in s-domain

$$s = j\omega \quad (2.26)$$

$$\Rightarrow Z = R + \frac{1}{sC} \quad (2.27)$$

$$= R + \frac{1}{j\omega C} \quad (2.28)$$

$\mathcal{V}_{in}(j\omega)$ was input into all four circuits and $V_{out}(t)$ was calculated using the Transfer Functions of the RC Filters.

Transfer Function:

$$H(j\omega) = \frac{V_{out}}{V_{in}} \quad (2.29)$$

(a) Option A

$$H_R(j\omega) = \frac{R}{R + \frac{1}{j\omega C}} \quad (2.30)$$

$$= \frac{j\omega RC}{1 + j\omega RC} \quad (2.31)$$

$$= \left(\frac{\omega RC}{\sqrt{1 + (\omega RC)^2}} \right) e^{j \tan^{-1}(\frac{1}{\omega RC})} \quad (2.32)$$

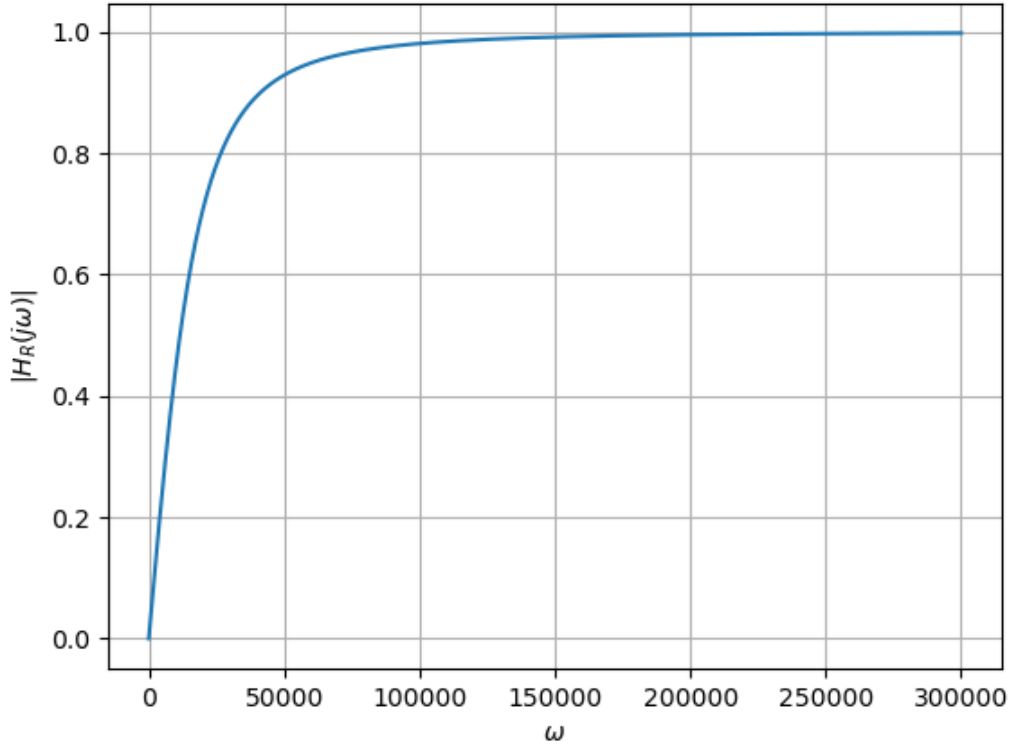


Figure 2.9: $|H_R(j\omega)|$ vs ω for $R = 0.5k\Omega$, $C = 0.1\mu F$

$$\implies \mathcal{V}_{out}(j\omega) = H_R(j\omega)\mathcal{V}_{in}(j\omega) \quad (2.33)$$

$$(2.34)$$

Using (2.24) and (2.32),

$$V_{out}(t) = \sum_{n=1}^{\infty} \left(\frac{n\omega RC}{\sqrt{1 + (n\omega RC)^2}} \right) a_n \cos \left(n\omega t + \tan^{-1} \left(\frac{1}{n\omega RC} \right) \right) \quad (2.35)$$

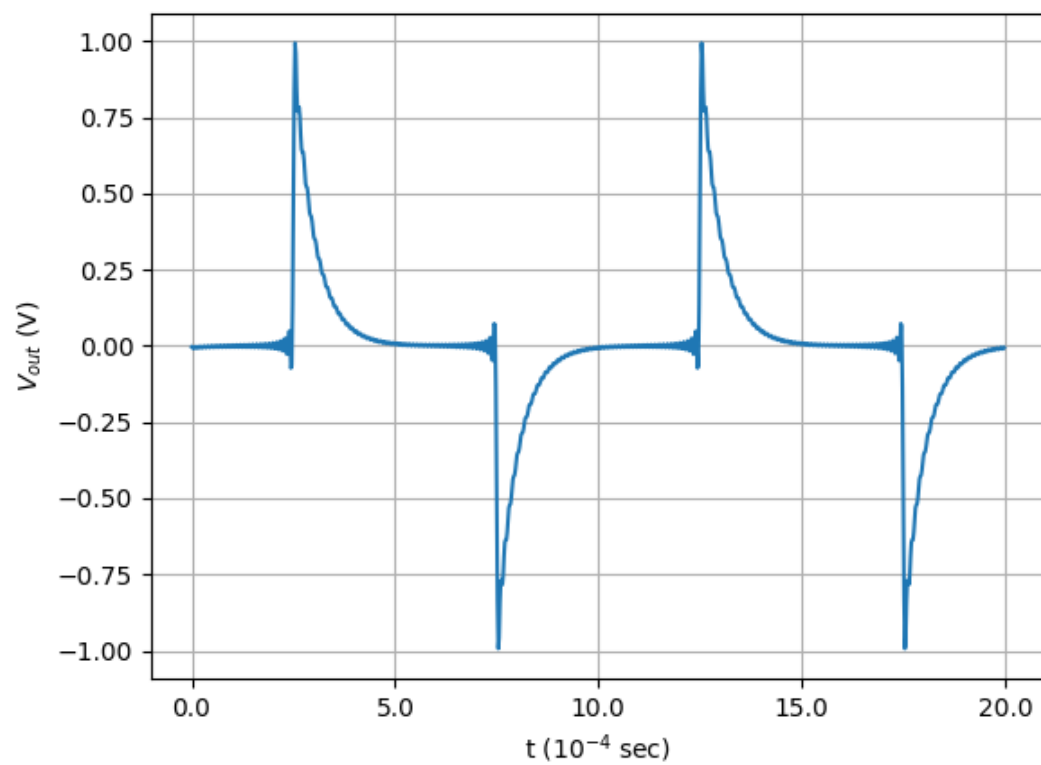


Figure 2.10: Opt A: $V_{out}(t)$ vs t

(b) Option B

$$H_R(j\omega) = \frac{R}{R + \frac{1}{j\omega C}} \quad (2.36)$$

$$= \frac{j\omega RC}{1 + j\omega RC} \quad (2.37)$$

$$= \left(\frac{\omega RC}{\sqrt{1 + (\omega RC)^2}} \right) e^{j \tan^{-1}(\frac{1}{\omega RC})} \quad (2.38)$$

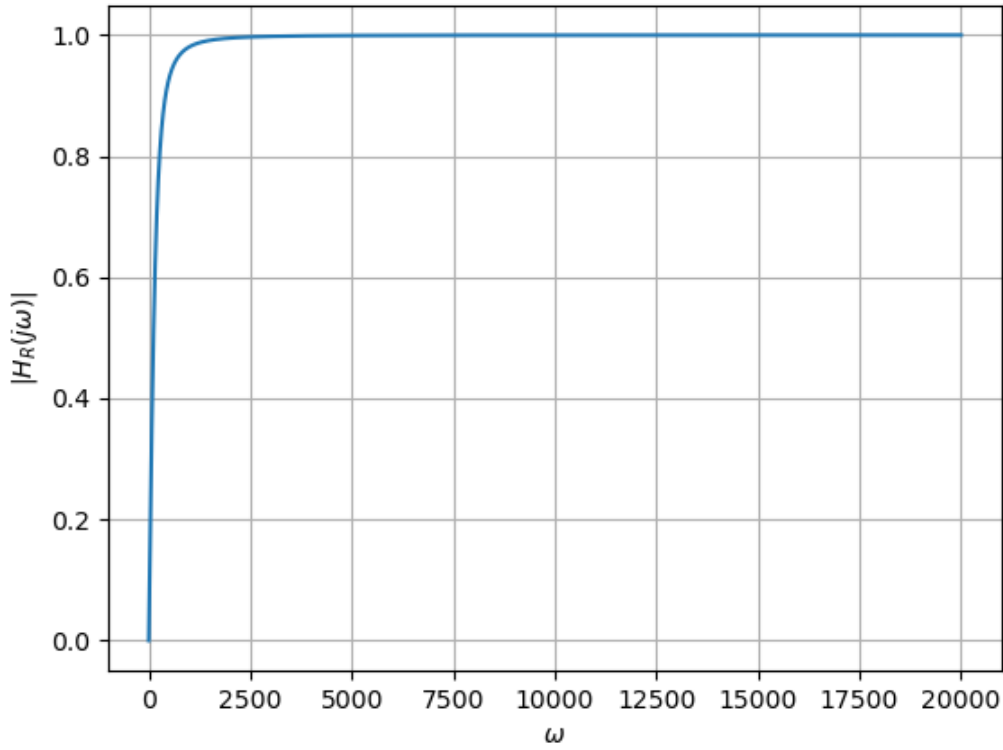


Figure 2.11: $|H_R(j\omega)|$ vs ω for $R = 5k\Omega$, $C = 1\mu F$

$$\implies \mathcal{V}_{out}(j\omega) = H_R(j\omega)\mathcal{V}_{in}(j\omega) \quad (2.39)$$

Using (2.24) and (2.38),

$$V_{out}(t) = \sum_{n=1}^{\infty} \left(\frac{n\omega RC}{\sqrt{1 + (n\omega RC)^2}} \right) a_n \cos \left(n\omega t + \tan^{-1} \left(\frac{1}{n\omega RC} \right) \right) \quad (2.40)$$

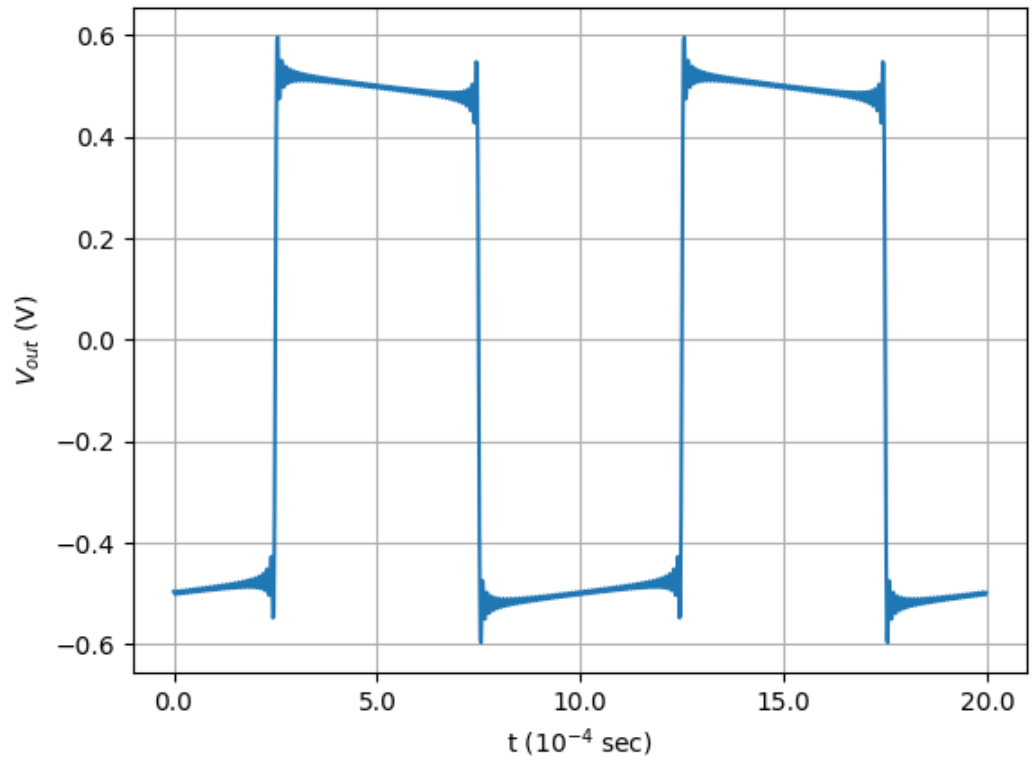


Figure 2.12: Opt B: $V_{out}(t)$ vs t

(c) Option C

$$H_C(j\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \quad (2.41)$$

$$= \frac{1}{1 + j\omega RC} \quad (2.42)$$

$$= \left(\frac{1}{\sqrt{1 + (\omega RC)^2}} \right) e^{-j \tan^{-1}(\omega RC)} \quad (2.43)$$

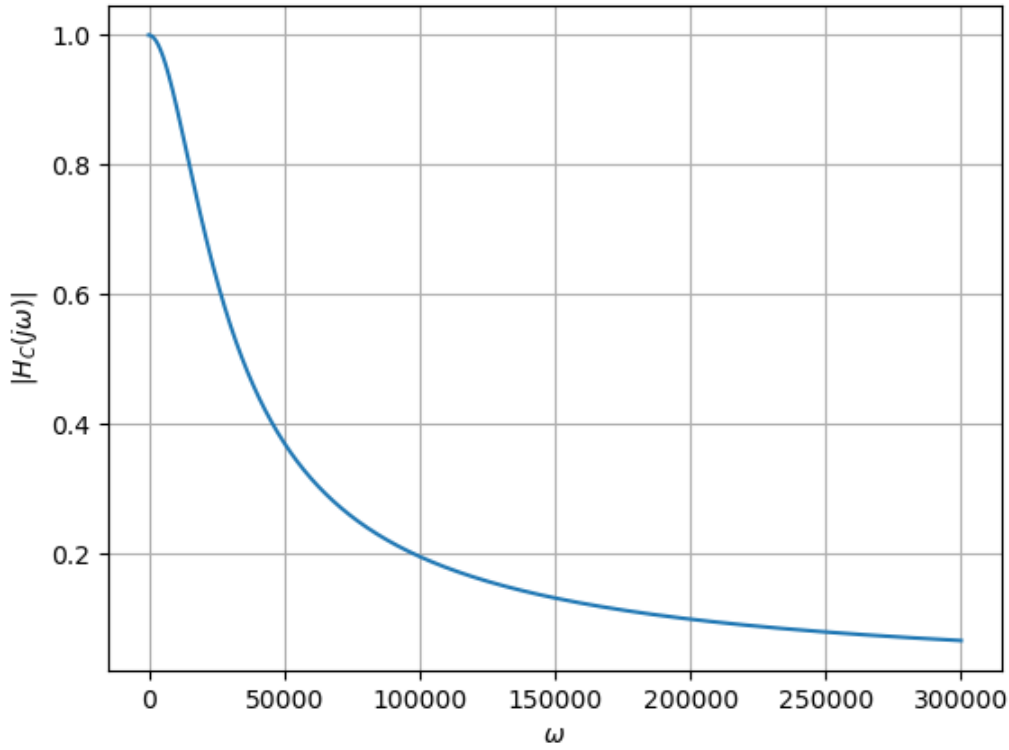


Figure 2.13: $|H_C(j\omega)|$ vs ω for $R = 0.5k\Omega$, $C = 0.1\mu F$

$$\implies \mathcal{V}_{out}(j\omega) = H_C(j\omega)\mathcal{V}_{in}(j\omega) \quad (2.44)$$

Using (2.24) and (2.43),

$$V_{out}(t) = \sum_{n=1}^{\infty} \left(\frac{1}{\sqrt{1 + (n\omega RC)^2}} \right) a_n \cos(n\omega t - \tan^{-1}(n\omega RC)) \quad (2.45)$$

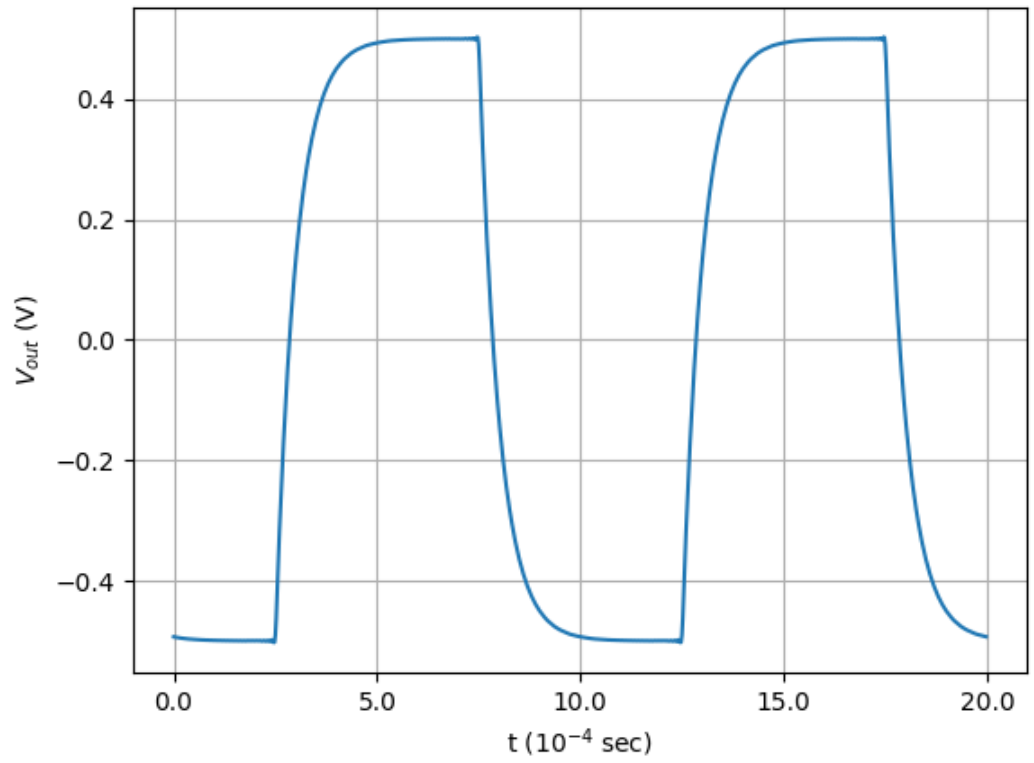


Figure 2.14: Opt C: $V_{out}(t)$ vs t

(d) Option D

$$H_C(j\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \quad (2.46)$$

$$= \frac{1}{1 + j\omega RC} \quad (2.47)$$

$$= \left(\frac{1}{\sqrt{1 + (\omega RC)^2}} \right) e^{-j \tan^{-1}(\omega RC)} \quad (2.48)$$

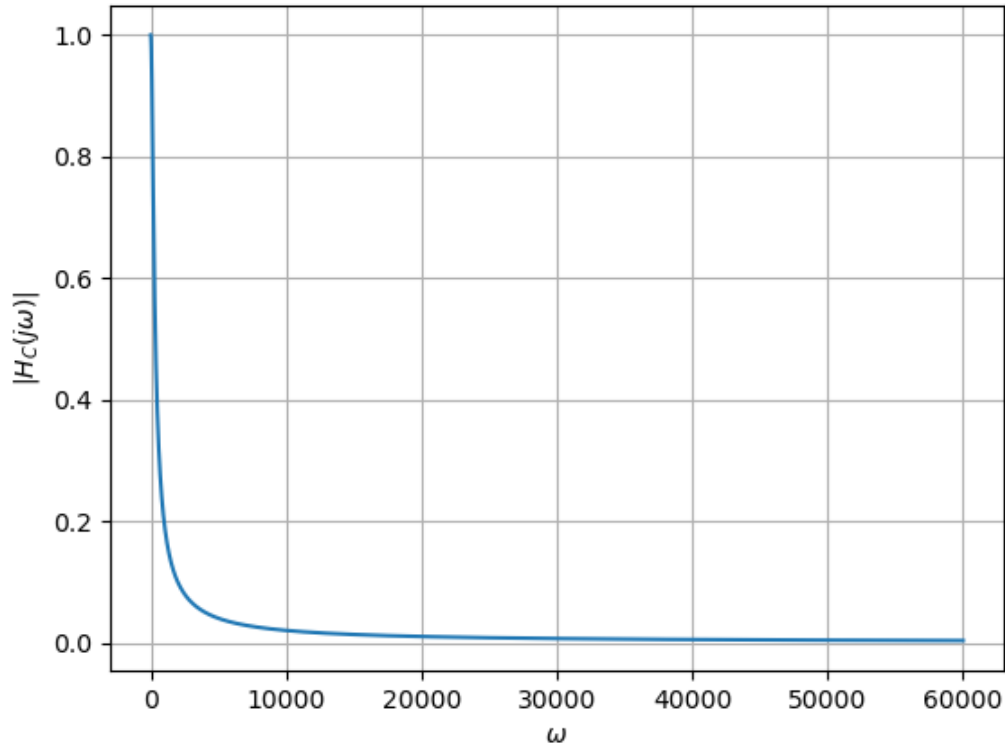


Figure 2.15: $|H_C(j\omega)|$ vs ω for $R = 5k\Omega$, $C = 1\mu F$

$$\implies \mathcal{V}_{out}(j\omega) = H_C(j\omega)\mathcal{V}_{in}(j\omega) \quad (2.49)$$

Using (2.24) and (2.48),

$$V_{out}(t) = \sum_{n=1}^{\infty} \left(\frac{1}{\sqrt{1 + (n\omega RC)^2}} \right) a_n \cos(n\omega t - \tan^{-1}(n\omega RC)) \quad (2.50)$$

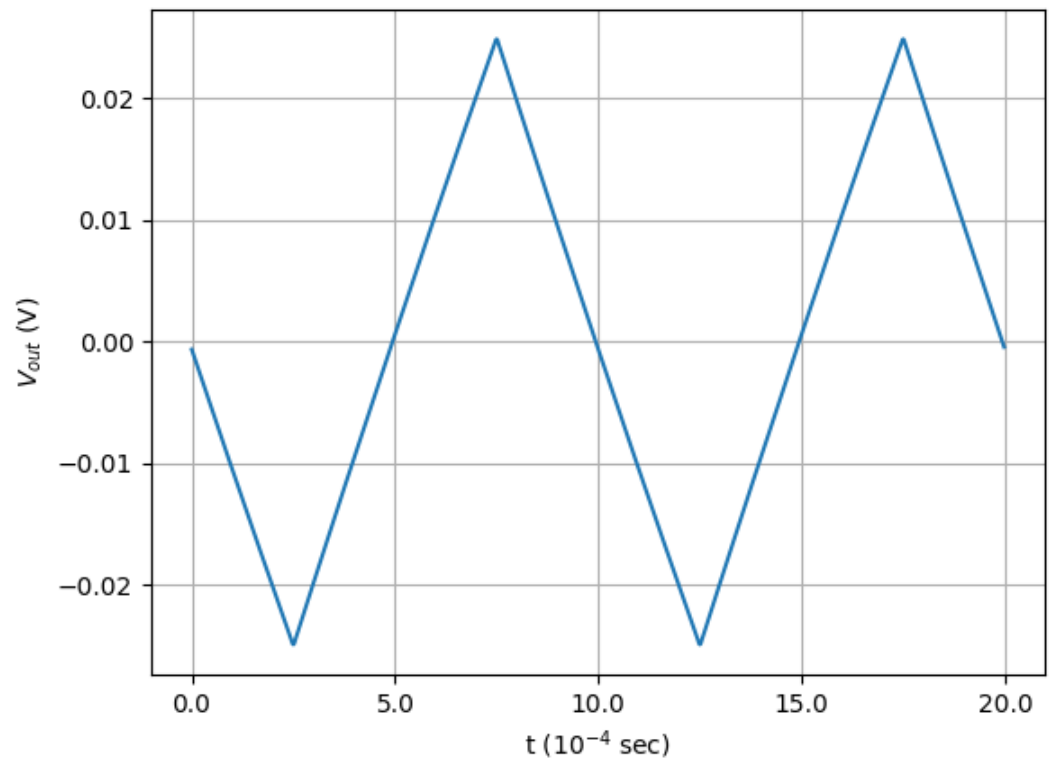


Figure 2.16: Opt D: $V_{out}(t)$ vs t

2.7 In the circuit shown below, switch S was closed for long time. If the switch is opened at $t = 0$, the maximum magnitude of the voltage V_R , in volts is (rounded off to the nearest integer) (GATE 2023 EC 35)

Solution:

$$At, t = 0^- \quad (2.51)$$

inductor acts as wire

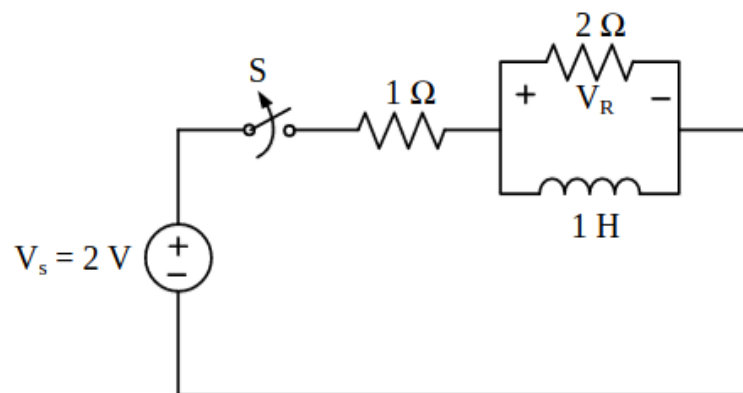


Figure 2.17:

| parameter | description | value |
|-----------|-------------------------------------|--------------------|
| $i(0^-)$ | current at $t < 0$ | $2A$ |
| $V_R(t)$ | voltage across 2Ω | $-2i(t)u(t)$ |
| L | inductance | $1H$ |
| $i(t)$ | current in small loop after $t = 0$ | $\frac{V_R(t)}{2}$ |
| $I(s)$ | $i(t)$ in laplace | $-$ |

Table 2.5: input parameters

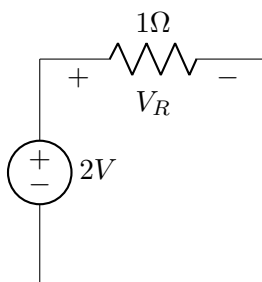


Figure 2.18: steady state circuit

apply KVL

$$-2 + 1i(0^-) = 0 \quad (2.52)$$

$$i(0^-) = 2A \quad (2.53)$$

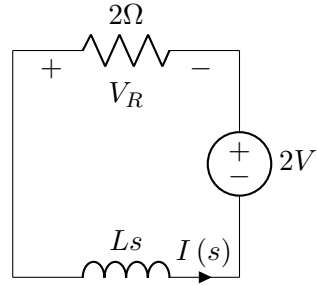


Figure 2.19: s domain circuit for $t > 0$

$$2I(s) - 2V + LsI(s) = 0 \quad (2.54)$$

$$\implies I(s) = \frac{2}{s+2} A \quad (2.55)$$

applying inverse laplace transform

$$i(t) = 2e^{-2t}u(t) A \quad (2.56)$$

$$V_R(t) = -2i(t) \quad (2.57)$$

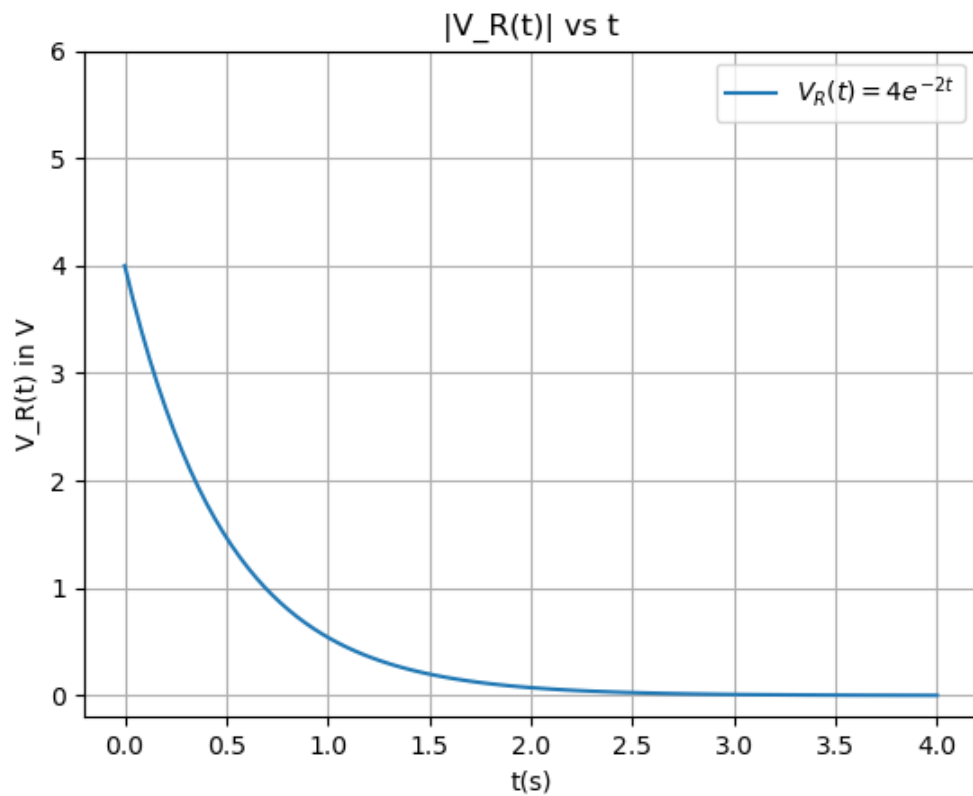
$$\implies V_R(t) = -4e^{-2t}u(t) V \quad (2.58)$$

As,

$$t \rightarrow 0 \quad (2.59)$$

$$\implies e^{-2t} \rightarrow 1 \quad (2.60)$$

$$|V_R(max)| = 4V \quad (2.61)$$



2.8 A signal $x(t) = 2 \cos(180\pi t) \cos(60\pi t)$ is sampled at 200 Hz and then passed through an ideal low pass filter having cut-off frequency of 100 Hz.

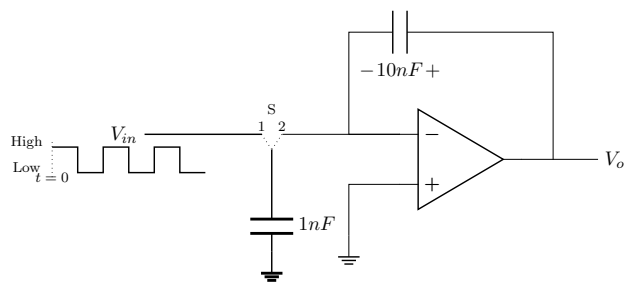
The maximum Frequency present in the filtered signal in Hz is _____ (Round off to the nearest integer.)

(GATE 2023 EE) **Solution:**

2.9 In the circuit shown, the input voltage $V_{in} = 100mV$. The switch and the opamp are ideal. At time $t = 0$, the initial charge stored in the $10nF$ capacitor is $1nC$, with the polarity as indicated in the figure. The switch S is controlled using a $1KHz$ square-wave voltage signal V_s as shown. Whenever V_s is 'High', S is in position '1' and when V_s is 'Low', S is in position '2'.

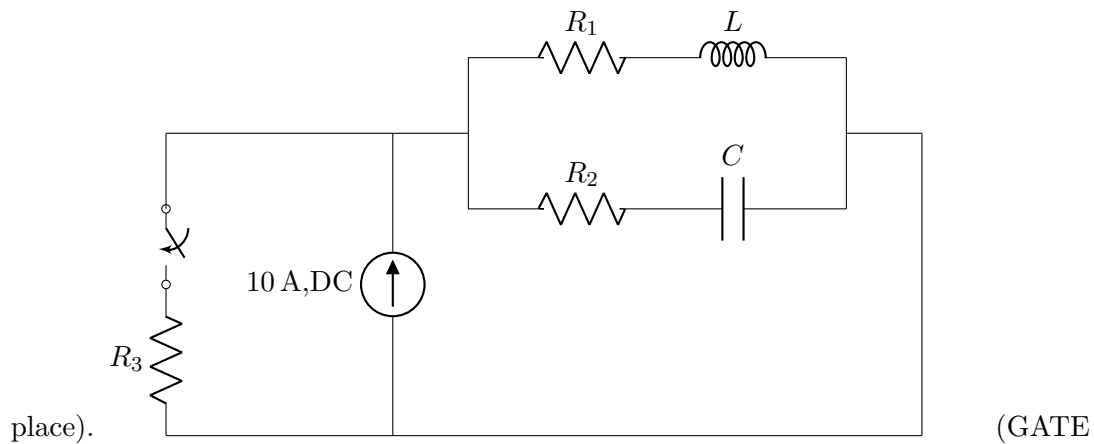
At $t = 20ms$, the magnitude of the voltage V_o will be

(GATE IN 2023)



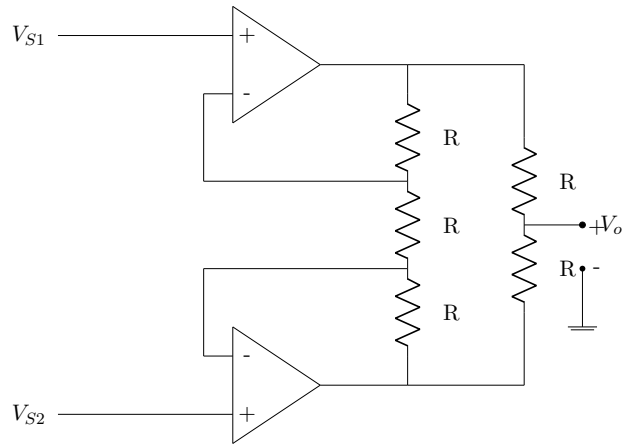
Solution:

2.10 The value of parameters of the circuit shown in the figure are $R_1 = 2\Omega, R_2 = 2\Omega, R_3 = 3\Omega, L = 10\text{mH}, C = 100\mu\text{F}$. For time $t < 0$, the circuit is at steady state with the switch ' K ' in closed condition. If the switch is opened at $t = 0$, the value of the voltage across the inductor (V_L) at $t = 0^+$ in Volts is _____ (Round off to 1 decimal



place). (GATE 2023 EE 29Q) **Solution:**

- 2.11 The op amps in the circuit are ideal. The input signals are $V_{S1} = 3 + 0.10 \sin(300t)$, V and $V_{S2} = -2 + 0.11 \sin(300t)$ V. The average value of the voltage V_0 is _____ volts (rounded off to two decimal places). (GATE IN 2023)



Chapter 3

Z-transform

Chapter 4

Systems

- 4.1 Consider a unity-gain negative feedback system consisting of the plant $G(s)$ and a proportional-integral controller. Let the proportional gain and integral gain be 3 and 1, respectively. For a unit step reference input, the final values of the controller output and the plant output, respectively, are

$$G(s) = \frac{1}{(s-1)}$$

(GATE EE 2023)

Solution:

| Parameter | Description | Value |
|-----------|-------------------|---------------|
| K_p | Proportional Gain | 3 |
| K_i | Integral Gain | 1 |
| $r(t)$ | Reference Input | $u(t)$ |
| $w(t)$ | Controller Output | ? |
| $y(t)$ | Plant Output | ? |
| $e(t)$ | Error Input | $r(t) - y(t)$ |

Table 1: Parameter Table

From the Fig. 4.1:

$$E(s) = U(s) - Y(s) \quad (4.1)$$

$$W(s) = 3E(s) + \frac{1}{s}E(s) \quad (4.2)$$

$$Y(s) = G(s)W(s) \quad (4.3)$$

Some results:

$$tx(t) \xleftrightarrow{\mathcal{L}} -\frac{dX(s)}{ds} \quad (4.4)$$

$$e^{-at}x(t) \xleftrightarrow{\mathcal{L}} X(s+a) \quad (4.5)$$

By using (4.4) and (4.5):

$$e^{-t}u(t) \xleftrightarrow{\mathcal{L}} \frac{1}{s+1}, \text{Re}(s) > -1 \quad (4.6)$$

$$te^{-t}u(t) \xleftrightarrow{\mathcal{L}} \frac{1}{(s+1)^2}, \text{Re}(s) > -1 \quad (4.7)$$



Figure 4.1: Block Diagram of System

(a) **Plant Output:**

From (4.1) , (4.2) and (4.3):

$$Y(s) = \frac{3s+1}{s(s+1)^2}, \text{Re}(s) > -1 \quad (4.8)$$

Final Value Theorem:

$$\lim_{t \rightarrow \infty} x(t) = \lim_{s \rightarrow 0} sX(s) \quad (4.9)$$

Using (4.9) on Y(s):

$$\lim_{t \rightarrow \infty} y(t) = \lim_{s \rightarrow 0} sY(s) \quad (4.10)$$

$$= 1 \quad (4.11)$$

Taking partial fraction of (4.8) :

$$Y(s) = \frac{1}{s} + \frac{2}{(s+1)^2} - \frac{1}{s+1} \quad (4.12)$$

Using (4.6) and (4.7):

$$\therefore y(t) = u(t) + 2te^{-t}u(t) - e^{-t}u(t) \quad (4.13)$$

(b) **Controller Output:**

From (4.2)

$$W(s) = \frac{3}{s} + \frac{1}{s^2} - Y(s) \left(3 + \frac{1}{s} \right) \quad (4.14)$$

Substituting (4.8)

$$W(s) = \frac{(s-1)(3s+1)}{s(s+1)^2}, \operatorname{Re}(s) > -1 \quad (4.15)$$

Using (4.9) on $W(s)$

$$\lim_{t \rightarrow \infty} w(t) = \lim_{s \rightarrow 0} sW(s) \quad (4.16)$$

$$= -1 \quad (4.17)$$

Taking partial fraction of equation(4.15) :

$$W(s) = -\frac{1}{s} - \frac{4}{(s+1)^2} + \frac{4}{s+1} \quad (4.18)$$

Using equations (4.6) and (4.7) and taking inverse lapalace transform:

$$w(t) = -u(t) - 4te^{-t}u(t) + 4e^{-t}u(t) \quad (4.19)$$



Figure 4.2: $w(t)$ converges at -1.



Figure 4.3: $y(t)$ converges at +1

4.2 Level (h) in a steam boiler is controlled by manipulating the flow rate (F) of the break-up(fresh) water using a proportional (P) controller. The transfer function between the output and the manipulated input is

$$\frac{h(s)}{F(s)} = \frac{0.25(1-s)}{s(2s+1)}$$

The measurement and the valve transfer functions are both equal to 1. A process engineer wants to tune the controller so that the closed loop response gives the decaying oscillations under the servo mode. Which one of the following is the CORRECT value of the controller gain to be used by the engineer?

- (a) 0.25
- (b) 2
- (c) 4
- (d) 6

GATE CH 2023

Solution:

Closed loop signal transfer function of the above block diagram can be given by,

$$T(s) = \frac{G(s)}{1 + G(s)H(s)} \quad (4.20)$$

From Fig. 4.4 and Table 4.2 for a unit impulse, $X(s) = 1$

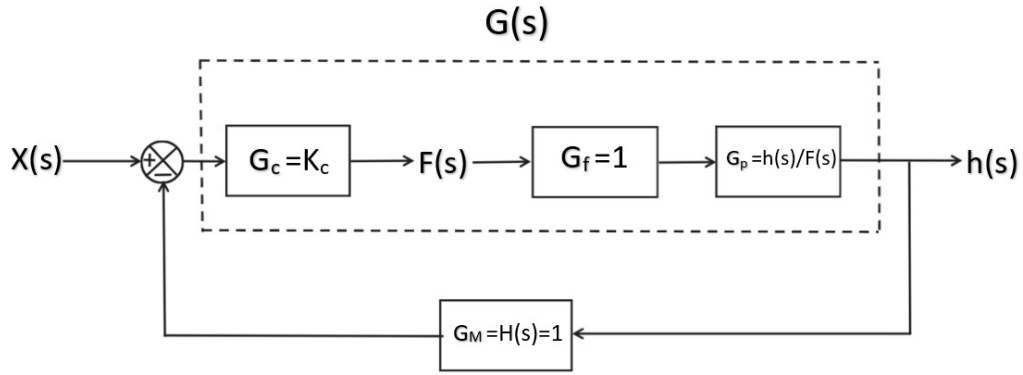


Figure 4.4: Closed loop Block diagram

$$h(s) = T(s) \times X(s) \quad (4.21)$$

$$h(s) = \frac{(1-s)K_c}{8s^2 + (4-K_c)s + K_c} \quad (4.22)$$

$$\Rightarrow h(s) = \frac{(1-s)K_c}{8(s-s_1)(s-s_2)} \quad (4.23)$$

Where,

$$s_1 = \frac{(K_c - 4)}{16} + \sqrt{\left(\frac{K_c - 4}{16}\right)^2 - \frac{K_c}{8}} \quad (4.24)$$

$$s_2 = \frac{(K_c - 4)}{16} - \sqrt{\left(\frac{K_c - 4}{16}\right)^2 - \frac{K_c}{8}} \quad (4.25)$$

From (4.23) we get,

$$h(s) = \frac{K_c}{8(s_1 - s_2)} \left(\frac{1 - s_1}{s - s_1} - \frac{1 - s_2}{s - s_2} \right) \quad (4.26)$$

Now taking the inverse laplace transform we have,

$$h(t) = \frac{K_c}{8(s_1 - s_2)} [(1 - s_1)e^{s_1 t} - (1 - s_2)e^{s_2 t}] u(t) \quad (4.27)$$

$$\Rightarrow h(t) = e^{\frac{K_c - 4}{16}} \left(A_1 e^{\sqrt{\left(\frac{K_c - 4}{16}\right)^2 - \frac{K_c}{8}}} - A_2 e^{-\sqrt{\left(\frac{K_c - 4}{16}\right)^2 - \frac{K_c}{8}}} \right) u(t) \quad (4.28)$$

Where,

$$A_1 = \frac{K_c}{8} \left(\frac{1 - s_1}{s_1 - s_2} \right) \quad (4.29)$$

$$A_2 = \frac{K_c}{8} \left(\frac{1 - s_2}{s_1 - s_2} \right) \quad (4.30)$$

Now applying the condition for underdamped oscillations,

$$\left(\frac{K_c - 4}{16} \right)^2 - \frac{K_c}{8} < 0 \quad (4.31)$$

$$\Rightarrow K_c \in (20 - \sqrt{384}, 20 + \sqrt{384}) \quad (4.32)$$

For the system to be stable,

$$\frac{K_c - 4}{8} < 0 \quad (4.33)$$

$$\Rightarrow K_c < 4 \quad (4.34)$$

From (4.32) and (4.34)

$$K_c \in (0.4, 4) \quad (4.35)$$

(4.35) represents the $ROC, (Re\{s\} < 0)$

$$\implies K_c = 2 \quad (4.36)$$

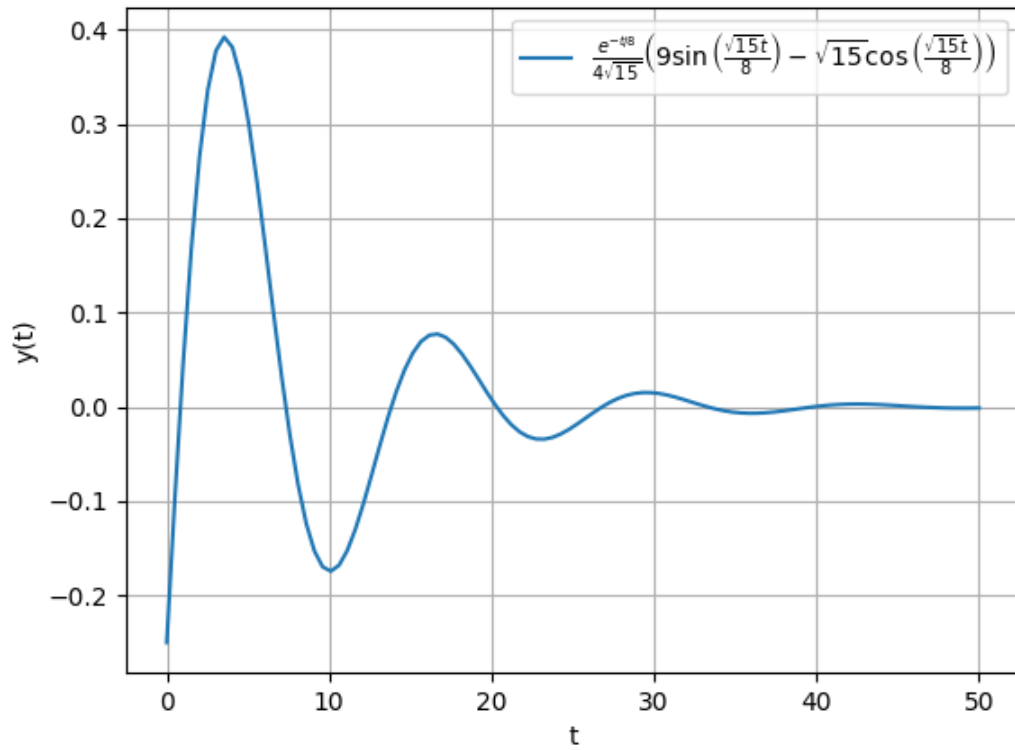
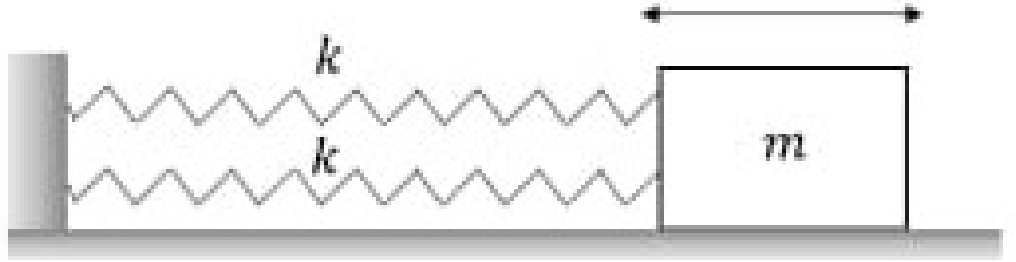


Figure 4.5: $y(t)$ vs t graph

- 4.3 The figure shows a block of mass $m = 20$ kg attached to a pair of identical linear springs, each having a spring constant $k = 1000$ N/m. The block oscillates on a frictionless horizontal surface. Assuming free vibrations, the time taken by the block to complete ten oscillations is _____ seconds . (Rounded off to two decimal places)
Take $\pi = 3.14$.
(GATE ME 2023)



Solution:

$$F = ma \quad (4.37)$$

$$F = -kx \quad (4.38)$$

$$\implies ma + kx = 0 \quad (4.39)$$

$$\therefore m \frac{d^2x}{dt^2} + kx = 0 \quad (4.40)$$

The Laplace transform of the terms is ,

$$x \xrightarrow{\mathcal{L}} X(s) \quad (4.41)$$

$$\frac{d^2x}{dt^2} \xrightarrow{\mathcal{L}} s^2 X(s) - sx(0) - \dot{x}(0) \quad (4.42)$$

Using equation (4.41) and (4.42) in equation (4.40),

$$m (s^2 X (s) - sx (0) - \dot{x} (0)) + kX (s) = 0 \quad (4.43)$$

$$ms^2 X (s) - msA + kX (s) = 0 \quad (4.44)$$

$$X (s) = \frac{msA}{ms^2 + k} \quad (4.45)$$

$$= \frac{sA}{s^2 + \frac{k}{m}} \quad (4.46)$$

The inverse Laplace transform of such terms is given by,

$$\frac{s}{s^2 + a^2} \xleftrightarrow{\mathcal{L}^{-1}} \cos (at) u (t) \quad (4.47)$$

\therefore the inverse Laplace of (4.46) is,

$$x (t) = A \cos \left(\sqrt{\frac{k}{m}} t \right) \quad (4.48)$$

From equation (4.48) and Table 4.3 ,the time to complete one oscillation is,

$$T_n = \frac{2\pi}{\sqrt{\frac{k}{m}}} \quad (4.49)$$

$$= \frac{\pi}{5} \quad (4.50)$$

\therefore the time required for 10 oscillations is ,

$$10T_n = 2\pi \quad (4.51)$$

$$= 6.28s \quad (4.52)$$

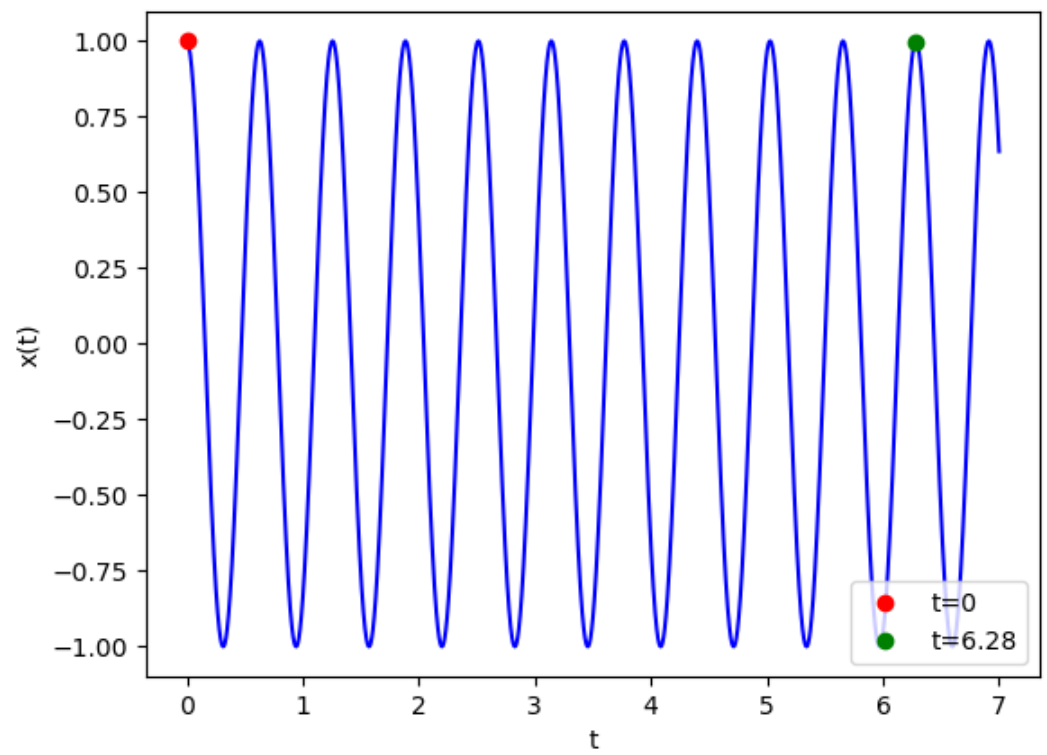


Figure 4.6: Plot of $x(t)$

4.4 A system has transfer function

$$\frac{Y(s)}{X(s)} = \frac{s - \pi}{s + \pi}$$

let $u(t)$ be the unit step function. The input $x(t)$ that results in a steady-state output $y(t) = \sin(\pi t)$ is _____. (GATE IN 2023)

Solution:

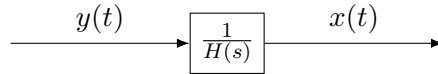


Figure 4.7: Block diagram of the inverse system

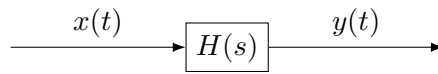


Figure 4.8: Block diagram of the system

$$H(s) = \frac{s - \pi}{s + \pi} \quad (4.53)$$

from Fig. 4.7

$$\frac{1}{H(s)} = \frac{s + \pi}{s - \pi} \quad (4.54)$$

Converting transfer function to frequency response, we get

$$\frac{1}{H(j\omega)} = \frac{j\omega + \pi}{j\omega - \pi} \quad (4.55)$$

from Table 4.4 $\omega = \pi$

$$\frac{1}{H(j\pi)} = \frac{j + 1}{j - 1} = -j = e^{-j\frac{\pi}{2}} \quad (4.56)$$

from (4.56)

$$\left| \frac{1}{H(j\pi)} \right| = 1 \quad \text{and} \quad \arg \left(\frac{1}{H(j\pi)} \right) = -90^\circ \quad (4.57)$$

$$y(t) = \sin(\pi t) \quad (4.58)$$

$$\sin(\pi t) \xleftrightarrow{\mathcal{H}(\omega)} \left| \frac{1}{H(j\omega)} \right| \sin \left(\pi t + \arg \left(\frac{1}{H(j\omega)} \right) \right) \quad (4.59)$$

Therefore, by (4.58) and (4.59), we get

$$x(t) = \sin \left(\pi t - \frac{\pi}{2} \right) \quad (4.60)$$

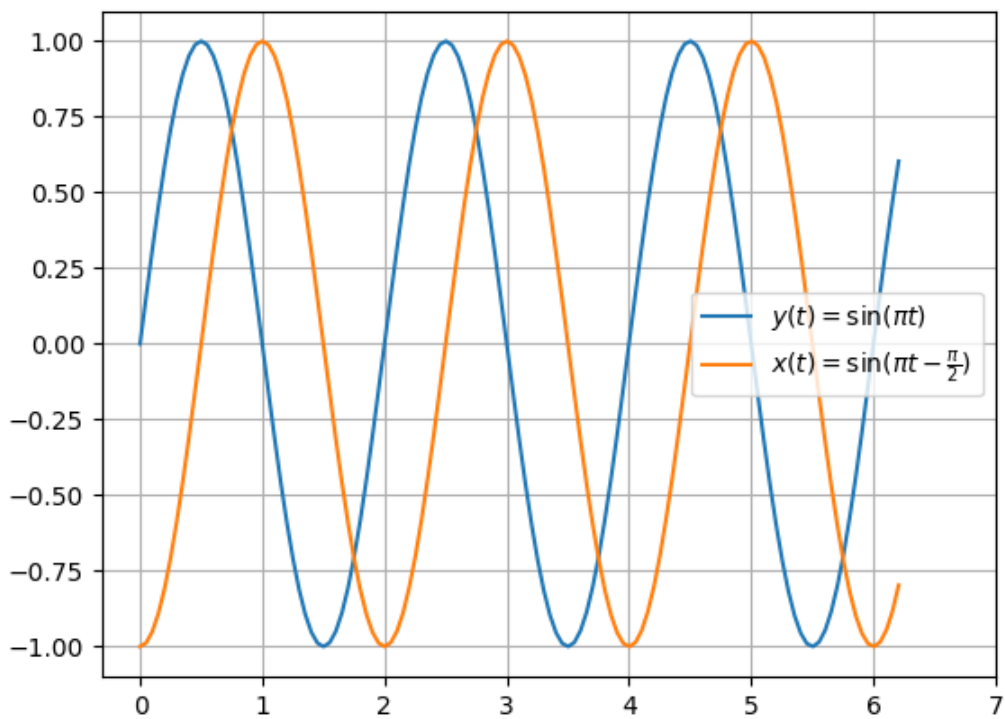


Figure 4.9: Plot of $x(t)$ and $y(t)$ taken from Python

4.5 Consider the complex function

$$f(z) = \frac{z^2 \sin z}{(z - \pi)^4}$$

At $z = \pi$, which of the following options is (are) correct?

(A) The order of the pole is 4

(B) The order of the pole is 3

(C) The residue at the pole is $\frac{\pi}{6}$

(D) The residue at the pole is $\frac{2\pi}{3}$

(GATE PH 2023)

- 4.6 A buoy of virtual mass 30 kg oscillates in a fluid medium as a single degree of freedom system. If the total damping in the system is set as 188.5 N-s/m, such that the oscillation just ceases to occur, then the natural period of the system is _____ s (round off to one decimal place) (GATE MN 2023 question 63)

Solution:

The differential equation of the system is:

$$m \frac{d^2 x(t)}{dt^2} + \lambda \frac{dx(t)}{dt} + m\omega_o^2 x(t) = 0 \quad (4.61)$$

Taking laplace transform:

$$ms^2 X(s) + \lambda s X(s) + m\omega_o^2 X(s) = 0 \quad (4.62)$$

$$\implies ms^2 + s\lambda + m\omega_o^2 = 0 \quad (4.63)$$

$$\therefore s = \frac{-\lambda \pm \sqrt{\lambda^2 - 4m^2\omega_o^2}}{2m} \quad (4.64)$$

where $\sqrt{\lambda^2 - 4m^2\omega_o^2}$ is ω_d .

From Table 4.5,

$$\omega_d = 0 \quad (4.65)$$

$$\implies \lambda = 2\omega_o m \quad (4.66)$$

$$\implies \omega_o \approx \pi \quad (4.67)$$

$$T_i = \frac{2\pi}{\omega_o} \quad (4.68)$$

$$\therefore t_i = 2 \text{ seconds} \quad (4.69)$$

To find $x(t)$, we assume the initial amplitude of oscillations to be 1 meter and it is

situated at extreme position.

$$s^2 X(s) + \lambda s X(s) + \omega_o^2 X(s) = s x(0) + x(0) \quad (4.70)$$

$$\Rightarrow X(s) = \frac{1+s}{s^2 + s \frac{\lambda}{m} + \omega_o^2} \quad (4.71)$$

substituting values from Table 4.5 and ω_o ,

$$X(s) = \frac{1+s}{(s+\pi)^2} \quad (4.72)$$

Taking inverse laplace transform by method of partial fractions,

$$X(s) = \frac{1}{s+\pi} + \frac{1-\pi}{(s+\pi)^2} \quad (4.73)$$

$$\therefore x(t) = (1 + (1-\pi)t) e^{-\pi t} \quad (4.74)$$

4.7 Which of the following statement(s) is/are true?

- (a) If an LTI system is causal, it is stable.
- (b) A discrete time LTI system is causal if and only if its response to a step input $u[n]$ is 0 for $n < 0$.
- (c) If a discrete time LTI system has an impulse response $h[n]$ of finite duration the system is stable.
- (d) If the impulse response $0 < |h[n]| < 1$ for all n , then the LTI system is stable.

(GATE EE 2023 question 27)

Solution:

(a)

$$\text{Assume } h(t) = e^{2t} \cdot u(t) \quad (4.75)$$

$$\mathcal{L}\{e^{2t}\} = \frac{1}{s-2} \quad \text{Re}(s) > 2 \quad (4.76)$$

This system is causal but not stable because ROC does not contain imaginary axis.

Therefore, this statement does not hold true.

- (b) For a causal system, its response to the step input should indeed be zero for $n < 0$, as the system hasn't yet "seen" any input before time $n = 0$.

Mathematically, the output of an LTI system $y[n]$ can be represented as the convolution of the input $u[n]$ with the system's impulse response $h[n]$:

$$y[n] = \sum_{k=-\infty}^{\infty} h[n] u[n-k] \quad (4.77)$$

Now applying step input,

$$y[n] = \sum_{k=0}^{\infty} h[n] u[n-k] \quad (4.78)$$

This is because $u[n-k]$ is zero for $n < k$, hence, the summation only starts from $k = 0$.

For $n < 0$, $u[n-k] = 0$ for all k , because $n-k < 0$ when $n < 0$. Therefore, $y[n] = 0$ for $n < 0$.

Therefore, this statement is true.

(c)

$$\text{Assume } h[n] = \begin{cases} n & \text{if } 0 \leq n \leq N \\ 0 & \text{otherwise} \end{cases} \quad (4.79)$$

$$y[n] = h[n] * u[n] \quad (4.80)$$

$$y[n] = \sum_{k=0}^n h[k] u[n-k] \quad (4.81)$$

$$= \sum_{k=0}^n k \quad (4.82)$$

The input response is finite but the output response is not BIBO stable.

Therefore, this statement does not hold true.

(d)

$$\text{Assume } h[n] = \frac{1}{2}u[n] \quad (4.83)$$

$$g[n] = \sum_{n=0}^{\infty} |h[n]| \quad (4.84)$$

$$= \sum_{n=0}^{\infty} \frac{1}{2} \quad (4.85)$$

$$\Rightarrow \sum_{n=0}^{\infty} |h[n]| \rightarrow \infty \quad (4.86)$$

Hence it is unstable.

Therefore, this statement does not hold true.

So, the answer is option (B).

4.8 The outlet concentration C_A of a plug flow reactor (PFR) is controlled by manipulating the inlet concentration C_{A0} . The following transfer function describes the dynamics of this PFR.

$$\frac{C_A(s)}{C_{A0}(s)} = e^{-(\frac{V}{F})(k+s)}$$

In the above question, $V=1m^3$, $F=0.1m^3min^{-1}$ and $k=0.5min^{-1}$. The measurement and valve transfer functions are both equal to 1. The ultimate gain, defined as the proportional controller gain that produces sustained oscillations, for this system is (GATE 2023 CH 61)

Solution:

4.9 For the block diagram shown in the figure, the transfer function $\frac{Y(s)}{R(s)}$ is

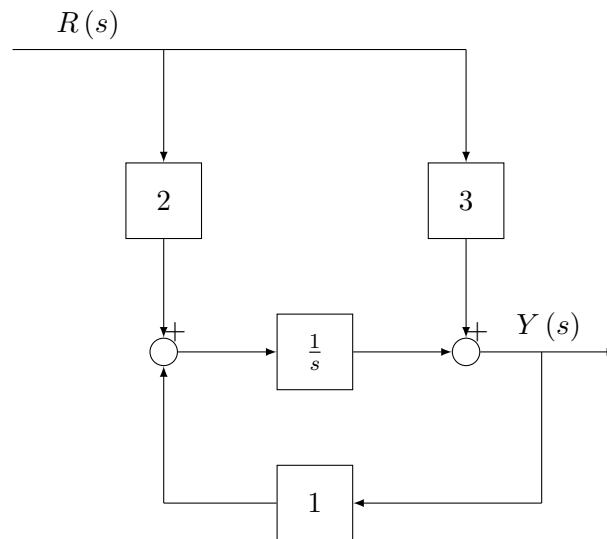


Figure 4.16: Block diagram

(GATE EE 2023)

Solution:

| Parameter | Description | Value |
|---------------------|-----------------------------------|-------------------|
| $Y(s)$ | Output node signal | |
| $R(s)$ | Input node signal | |
| $\frac{Y(s)}{R(s)}$ | Transfer function | ? |
| P_1 | Forward path gain a-b-c | $\frac{2}{s}$ |
| P_2 | Forward path gain a-c | 3 |
| Δ_1 | Determinant of forward path a-b-c | 1 |
| Δ_2 | Determinant of forward path a-c | 1 |
| Δ | Determinant of system | $1 - \frac{1}{s}$ |
| n | Number of forward path | 2 |

Table 4.6: Parameters

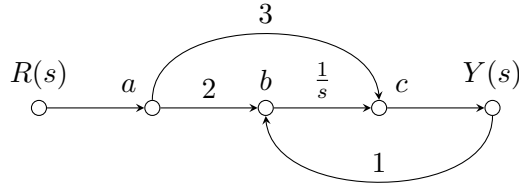


Figure 4.17: signal flow graph

$$P_1 = 2 \left(\frac{1}{s} \right) = \frac{2}{s} \quad (4.87)$$

$$P_2 = 3 \quad (4.88)$$

$$\Delta_1 = 1 - (0) = 1 \quad (4.89)$$

$$\Delta_2 = 1 - (0) = 1 \quad (4.90)$$

$$L_1 = \frac{1}{s} \quad (4.91)$$

$$\Delta = 1 - L_1 = 1 - \frac{1}{s} \quad (4.92)$$

from Fig. 4.17 using Mason's Gain Formula,

$$\frac{Y(s)}{R(s)} = \frac{\sum_{i=1}^n P_i \Delta_i}{\Delta} \quad (4.93)$$

$$= \frac{P_1 \Delta_1 + P_2 \Delta_2}{\Delta} \quad (4.94)$$

$$= \frac{\frac{2}{s} + 3}{1 - \frac{1}{s}} \quad (4.95)$$

$$H(s) = \frac{Y(s)}{R(s)} = \frac{3s + 2}{s - 1} \quad (4.96)$$

$$H(s) = \frac{5}{s - 1} + 3 \quad (4.97)$$

$$H(s) \xLeftrightarrow{-\infty} h(t) \quad (4.98)$$

$$\frac{5}{s - 1} \xLeftrightarrow{-\infty} 5e^t \quad (4.99)$$

$$3 \xLeftrightarrow{-\infty} 3\delta(t) \quad (4.100)$$

using (4.99) and (4.100),

$$h(t) = 5e^t + 3\delta(t) \quad (4.101)$$

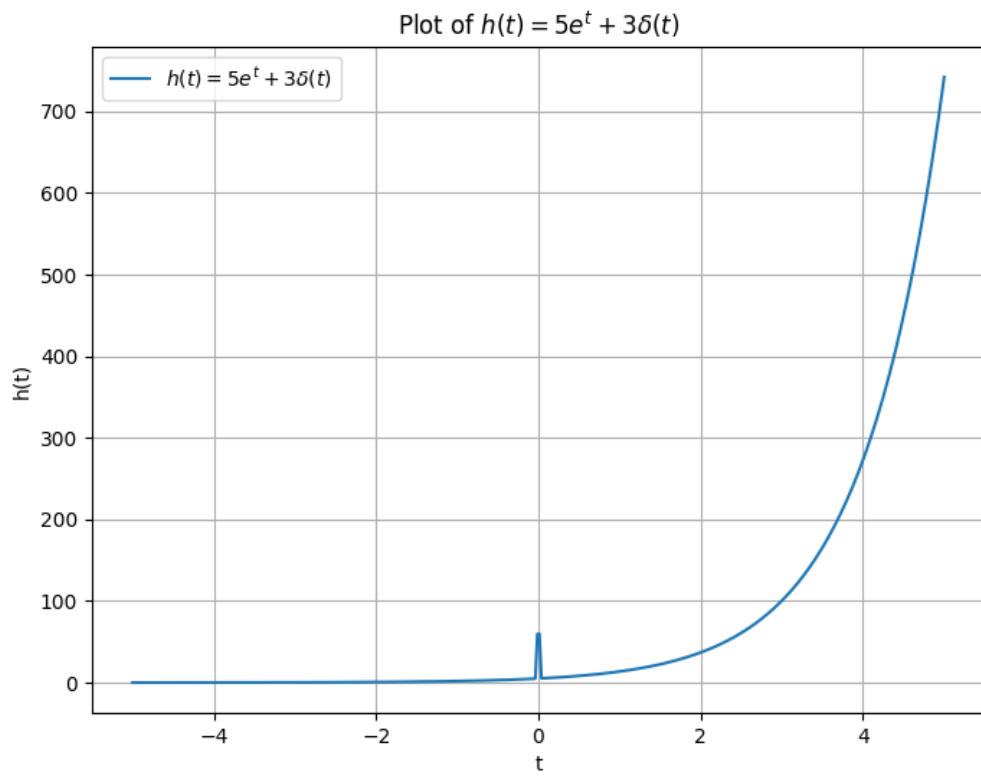


Figure 4.18: Plot of impulse response of the system

4.10 In the following block diagram, $R(s)$ and $D(s)$ are two inputs. The output $Y(s)$ is expressed as $Y(s) = G_1(s)R(s) + G_2(s)D(s)$.

$G_1(s)$ and $G_2(s)$ are given by

GATE 2023 EC Question 42

Solution:

4.11 In the table shown below, match the signal type with its spectral characteristics. GATE

2023 EC

(a) $(i) \rightarrow (a)$, $(ii) \rightarrow (b)$, $(iii) \rightarrow (c)$, $(iv) \rightarrow (d)$

(b) $(i) \rightarrow (a)$, $(ii) \rightarrow (c)$, $(iii) \rightarrow (b)$, $(iv) \rightarrow (d)$

(c) $(i) \rightarrow (d)$, $(ii) \rightarrow (b)$, $(iii) \rightarrow (c)$, $(iv) \rightarrow (a)$

(d) $(i) \rightarrow (a)$, $(ii) \rightarrow (c)$, $(iii) \rightarrow (d)$, $(iv) \rightarrow (b)$

Solution:

4.12 The impulse response of an LTI system is $h(t) = \delta(t) + 0.5\delta(t - 4)$, where $\delta(t)$ is continuous-time unit impulse signal. If the input signal $x(t) = \cos\left(\frac{7\pi t}{4}\right)$, the output is (GATE IN 2023)

Solution:

from Table 4.8

$$y(t) = x(t) * h(t) \quad (4.102)$$

$$= x(t) * (\delta(t) + 0.5\delta(t - 4)) \quad (4.103)$$

$$= x(t) + 0.5x(t - 4) \quad (4.104)$$

$$= \cos\left(\frac{7\pi t}{4}\right) + 0.5 \cos\left(\frac{7\pi(t - 4)}{4}\right) \quad (4.105)$$

$$= \cos\left(\frac{7\pi t}{4}\right) + 0.5 \cos\left(\frac{7\pi t}{4} - 7\pi\right) \quad (4.106)$$

$$= \frac{1}{2} \cos\left(\frac{7\pi t}{4}\right) \quad (4.107)$$

$$= \frac{1}{2} x(t) \quad (4.108)$$

$$Y(f) = X(f) H(f) \quad (4.109)$$

$$= \frac{1}{2} \left[\delta\left(f - \frac{7}{8}\right) + \delta\left(f + \frac{7}{8}\right) \right] [1 + 0.5e^{-j8\pi f}] \quad (4.110)$$

$$Y(f) = \frac{1}{2} \left(1 + 0.5e^{-j8\pi f} \right) \delta \left(f - \frac{7}{8} \right) + \frac{1}{2} \left(1 + 0.5e^{-j8\pi f} \right) \delta \left(f + \frac{7}{8} \right) \quad (4.111)$$

$$= \frac{1}{2} (1 + 0.5(-1)) \delta \left(f - \frac{7}{8} \right) + \frac{1}{2} (1 + 0.5(-1)) \delta \left(f + \frac{7}{8} \right) \quad (4.112)$$

$$= \frac{1}{4} \left[\delta \left(f - \frac{7}{8} \right) + \delta \left(f + \frac{7}{8} \right) \right] \quad (4.113)$$

$$= \frac{1}{2} X(f) \quad (4.114)$$

4.13 Consider the state-space description of an LTI system with matrices

$$A = \begin{bmatrix} 0 & 1 \\ -1 & -2 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad C = \begin{bmatrix} 3 & -2 \end{bmatrix}, \quad D = 1$$

For the input, $\sin(\omega t)$, $\omega > 0$, the value of ω for which the steady-state output of the system will be zero, is _____ (Round off to the nearest integer). (GATE 2023 EE Q46)

Solution:

4.14 A causal, discrete time system is described by the difference equation $y[n] = 0.5y[n - 1] + x[n]$, for all n , where $y[n]$ denotes the output sequence and $x[n]$ denotes the input sequence. Which of the following statements is/are TRUE?

- (a) The system has an impulse response described by $0.5^n u[-n]$ where $u[n]$ is the unit step sequence.
- (b) The system is stable in the bounded input, bounded output sense.
- (c) The system has an infinite number of non-zero samples in its impulse response.
- (d) The system has a finite number of non-zero samples in its impulse response.

(GATE 2023 BM-26)

Solution:

4.15 A closed loop system is shown in the figure where $k > 0$ and $\alpha > 0$. The steady state error due to a ramp input ($R(s) = \alpha s^{-2}$) is given by (GATE 2023 EC 41)

(a) $\frac{2\alpha}{k}$

(b) $\frac{\alpha}{k}$

(c) $\frac{\alpha}{2k}$

(d) $\frac{\alpha}{4k}$

Solution:

| PARAMETER | DESCRIPTION |
|-----------|---|
| G_c | Proportional controller's transfer function |
| G_f | Valve transfer function |
| G_p | Process transfer function |
| G_M | Measurement transfer function |
| $G(s)$ | Open loop transfer function |
| $T(s)$ | Transfer function of system |

Table 4.2: PARAMETER TABLE 1

| Parameter | Description | Value |
|------------|-------------------------------|-------------------------|
| k_i | spring constant | 1000 N/m |
| m | mass of block | 20Kg |
| k | Equivalent spring constant | $k_1 + k_2$ (parallel) |
| ω_n | Natural frequency | $\sqrt{\frac{k}{m}}$ |
| T | Time period of an oscillation | $\frac{2\pi}{\omega_n}$ |
| x | Displacement of block | |
| a | Acceleration of block | $\frac{d^2x}{dt^2}$ |
| F | Force on block | |
| A | Amplitude of oscillation | x(0) |

Table 4.3: Parameter Table

| Variable | Description | Value |
|----------|-------------------|-----------------------|
| $x(t)$ | input function | none |
| $y(t)$ | output function | $\sin(\pi t)$ |
| $H(s)$ | Transfer-function | $\frac{s-\pi}{s+\pi}$ |

Table 4.4: Input parameters

| Parameter | Description | Value |
|------------|---|------------------------|
| $X(s)$ | position in laplace domain | $X(s)$ |
| $x(t)$ | position of buoy w.r.t time | $x(t)$ |
| m | mass of buoy | 30kg |
| λ | damping coefficient of the system | $188.5 \approx 60\pi$ |
| ω_o | natural angular frequency of the system | ? |
| ω_d | damping frequency of the system | 0 rad s^{-1} |

Table 4.5: input values

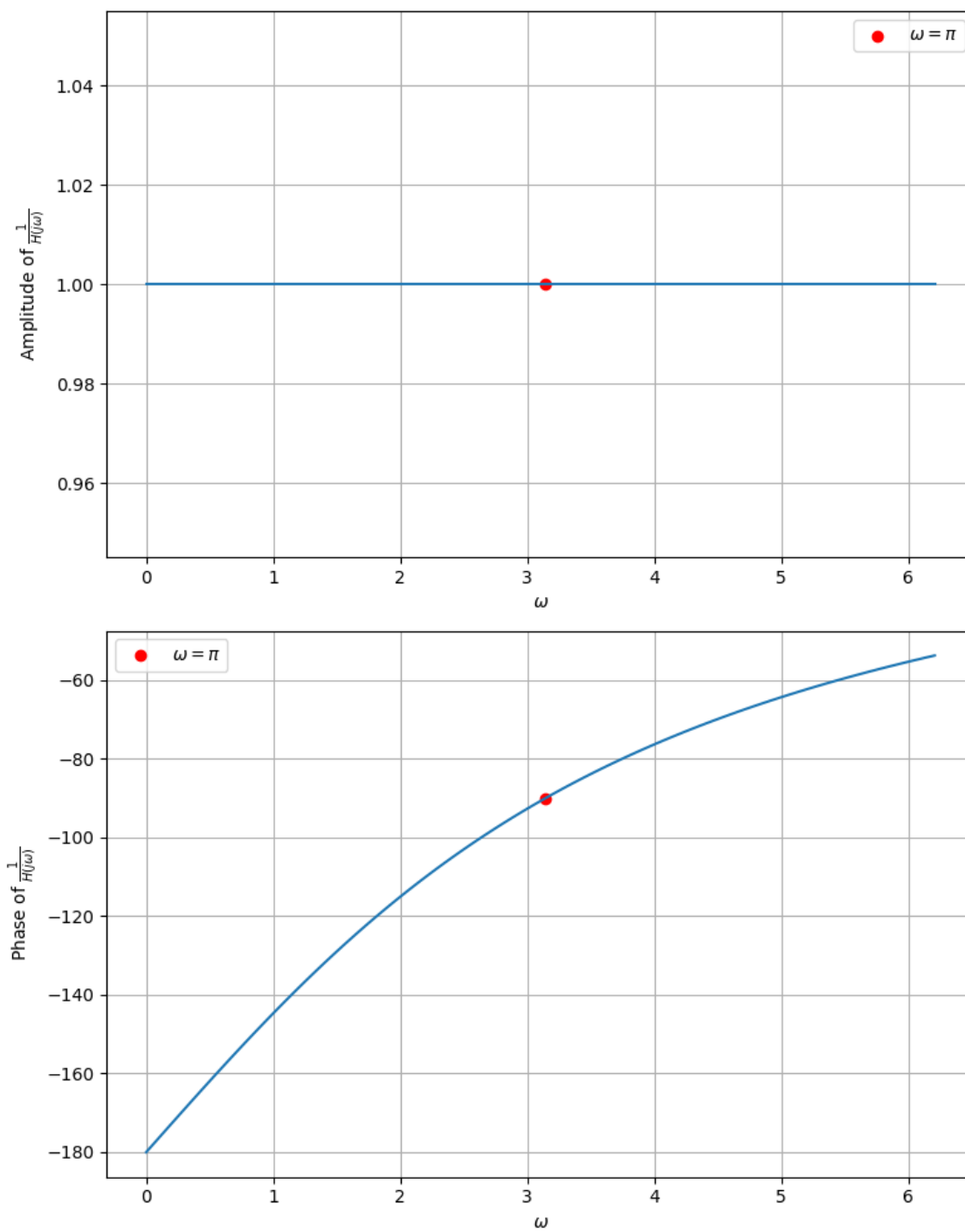


Figure 4.10: Amplitude and phase of $\frac{1}{H(j\omega)}$

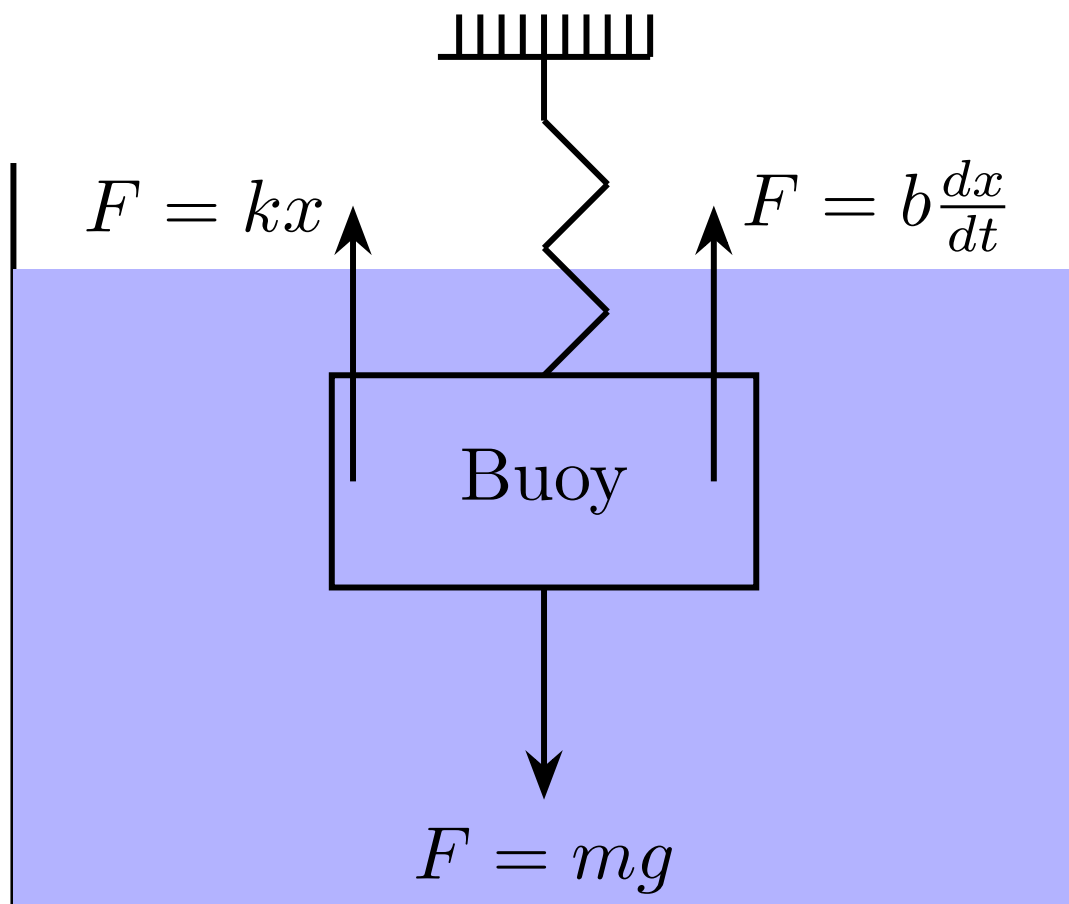


Figure 4.11: Figure given in question

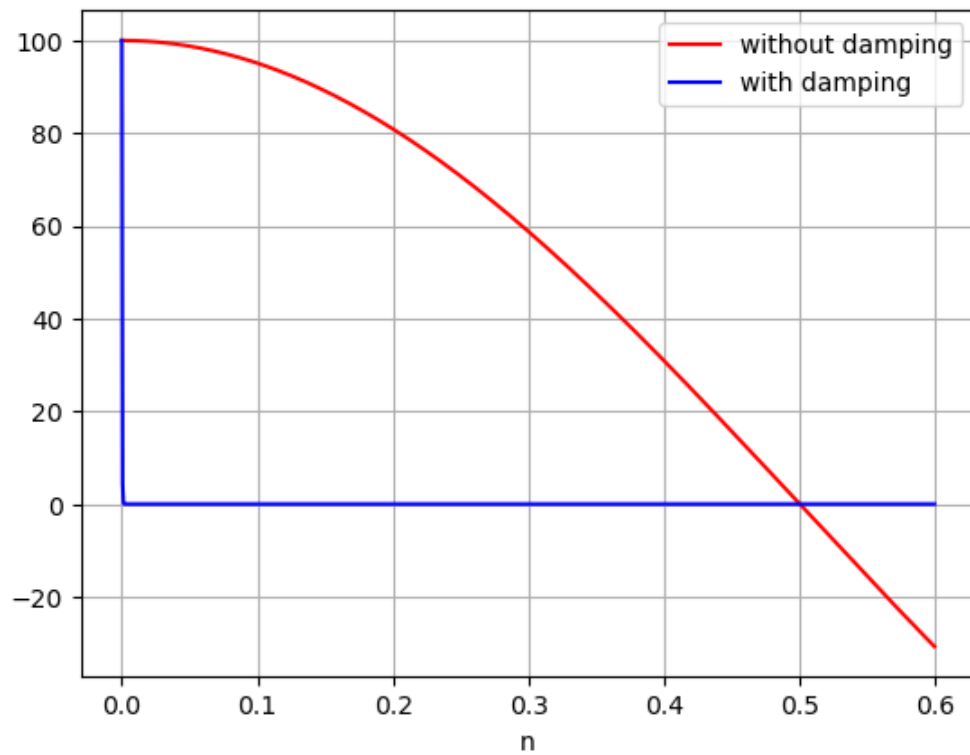


Figure 4.12: $x(t)$ with and with out damping

| Signal Type | Spectral Characteristics |
|---------------------------|---------------------------|
| (i) Continuous, aperiodic | (a) Continuous, aperiodic |
| (ii) Continuous, periodic | (b) Continuous, periodic |
| (iii) Discrete, aperiodic | (c) Discrete, aperiodic |
| (iii) Discrete, periodic | (c) Discrete, periodic |

Table 4.7:

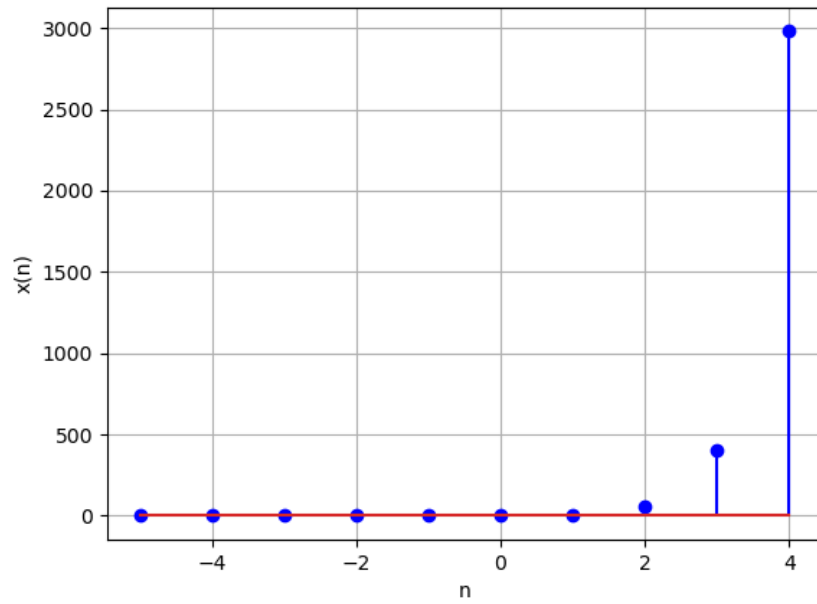


Figure 4.13: graph of $h(t) = e^{2t} \cdot u(t)$

| Variable | Description | value |
|------------------------|--------------------------------|--|
| $\delta(t)$ | Dirac delta function | ∞ if $t=0$; 0 in other cases $\int_{-\infty}^{\infty} \delta(t) dt = 1$ |
| $h(t)$ | impulse response | $\delta(t) + 0.5\delta(t - 4)$ |
| $x(t)$ | input signal | $x(t) = \cos\left(\frac{7\pi t}{4}\right)$ |
| $y(t)$ | output signal | $x(t) * h(t)$ |
| $\mathcal{F}(\cos at)$ | Fourier transform of $\cos at$ | $0.5 \left[\delta\left(f - \frac{a}{2\pi}\right) + \delta\left(f + \frac{a}{2\pi}\right) \right]$ |
| $X(f)$ | Fourier transform of $x(t)$ | $0.5 \left[\delta\left(f - \frac{7}{8}\right) + \delta\left(f + \frac{7}{8}\right) \right]$ |
| $H(f)$ | Fourier transform of $h(t)$ | $1 + 0.5e^{-j8\pi f}$ |
| $Y(f)$ | Fourier transform of $y(t)$ | $X(f)H(f)$ |

Table 4.8: A Table with input parameters

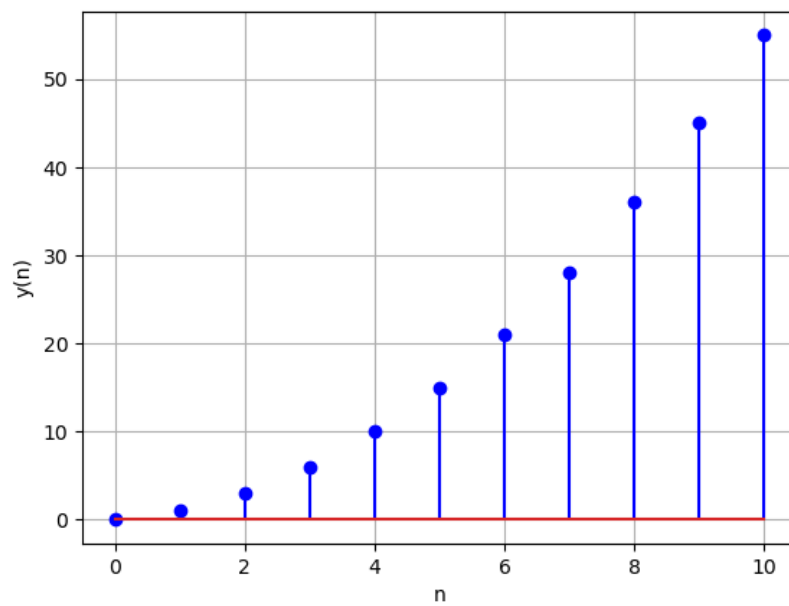


Figure 4.14: graph of $y[n]$

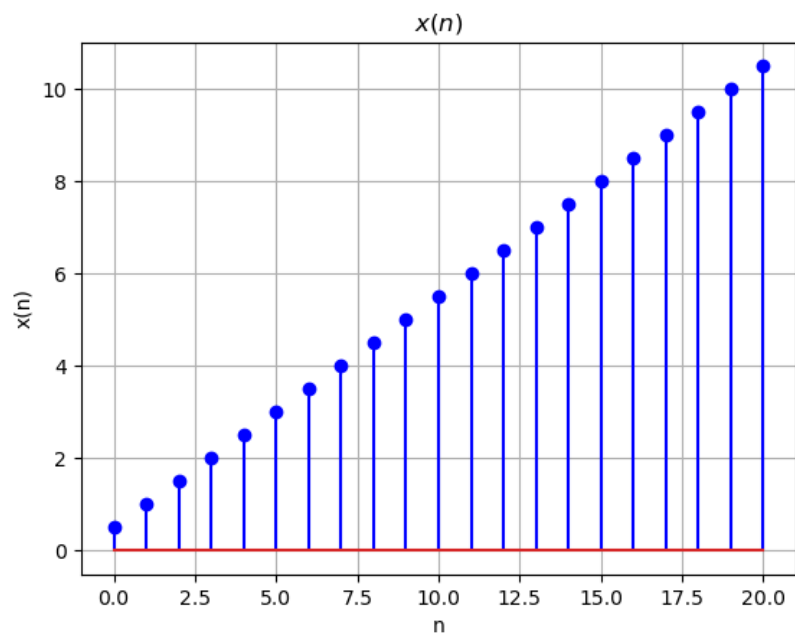
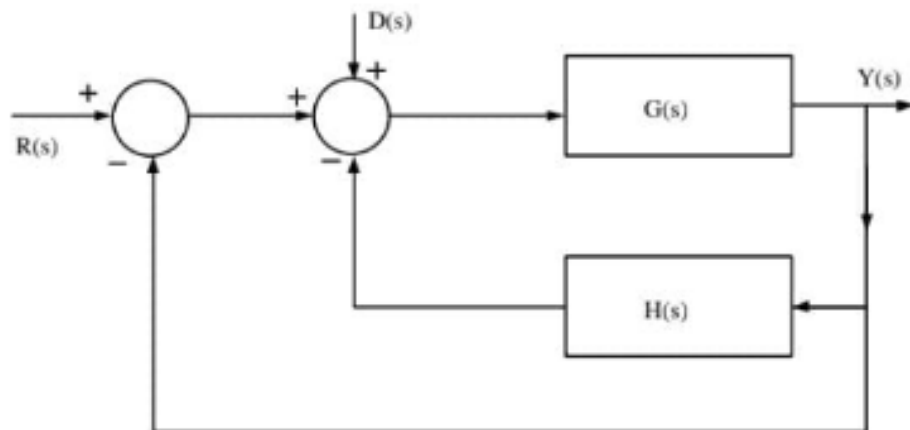


Figure 4.15: graph of $g[n]$



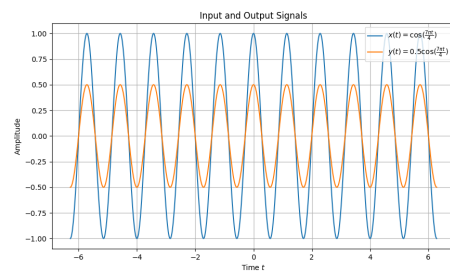
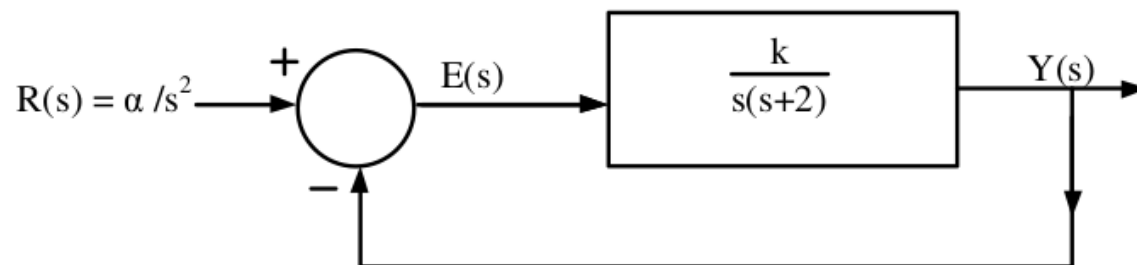


Figure 4.19: Graph showing $x(t)$ and $y(t)$



Chapter 5

Sequences

5.1 Consider the discrete time signal $x[n] = u[-n + 5] - u[n + 3]$, where

$$u[n] = \begin{cases} 1; n \geq 0 \\ 0; n < 0 \end{cases}$$

The smallest n for which $x[n] = 0$ is? (GATE IN 2023)

Solution: From Fig. 1, the minimum value of n is given as

$$n = -3 \tag{5.1}$$



Figure 1: Plot of function $x(n)$ taken from python3

5.2 Two sequences $x_1[n]$ and $x_2[n]$ are described as follows:

$$x_1[0] = x_2[0] = 1 \quad (5.2)$$

$$x_1[1] = x_2[2] = 2 \quad (5.3)$$

$$x_1[2] = x_2[1] = 1 \quad (5.4)$$

$$x_1[n] = x_2[n] = 0 \text{ for all } n < 0 \text{ and } n > 2$$

If $x[n]$ is obtained by convoluting $x_1[n]$ with $x_2[n]$, which of the following equa-

tions is/are TRUE?

(A) $x[2] = x[3]$

(B) $x[1] = 2$

(C) $x[4] = 3$

(D) $x[2] = 5$

(GATE 2023 BM 47) **Solution:** From the data given:

$$x_1 = [1, 2, 1] \tag{5.5}$$

$$x_2 = [1, 1, 2] \tag{5.6}$$

Takin the convolution, we get

$$x = [1, 3, 5, 5, 2] \tag{5.7}$$

$$\tag{5.8}$$

Hence we get:

$$x[0] = 1 \tag{5.9}$$

$$x[1] = 3 \tag{5.10}$$

$$x[2] = 5 \tag{5.11}$$

$$x[3] = 5 \tag{5.12}$$

$$x[4] = 2 \tag{5.13}$$

$$\tag{5.14}$$

Comparing this with the options, we see that options (A) and (D) match

\implies (A), (D)

5.3 A series (S) is given as $S=1+3+5+7+9+\dots$. The sum of the first 50 terms of S is

(GATE 2023 BT 32)

Solution: From the data given:

$$x_1 = [1, 2, 1] \quad (5.15)$$

$$x_2 = [1, 1, 2] \quad (5.16)$$

Takin the convolution, we get

$$x = [1, 3, 5, 5, 2] \quad (5.17)$$

$$(5.18)$$

Hence we get:

$$x[0] = 1 \quad (5.19)$$

$$x[1] = 3 \quad (5.20)$$

$$x[2] = 5 \quad (5.21)$$

$$x[3] = 5 \quad (5.22)$$

$$x[4] = 2 \quad (5.23)$$

$$(5.24)$$

Comparing this with the options, we see that options (A) and (D) match

\implies (A), (D)

5.4 For the signals $x(t)$ and $y(t)$ shown in the figure, $z(t) = x(t) * y(t)$ is maximum at $t = T_1$. Then T_1 in seconds is (Round off to the nearest integer) **Solution:**

5.5 A series of natural numbers $F_1, F_2, F_3, F_4, F_5, F_6, F_7, \dots$ obeys $F_{n+1} = F_n + F_{n-1}$ for all integers $n \geq 2$. If $F_6 = 37$, and $F_7 = 60$, then what is F_1 ?
[GATE CS 2023]

Solution:

5.6 The Lucas sequence L_n is defined by the recurrence relation:

$$L_n = L_{n-1} + L_{n-2}, \text{ for } n \geq 3$$

with $L_1=1$ and $L_2=3$

Which one of the options given is TRUE?

(a) $L_n = \left(\frac{1+\sqrt{5}}{2}\right)^n + \left(\frac{1-\sqrt{5}}{2}\right)^n$

(b) $L_n = \left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{3}\right)^n$

(c) $L_n = \left(\frac{1+\sqrt{5}}{2}\right)^n + \left(\frac{1-\sqrt{5}}{3}\right)^n$

(d) $L_n = \left(\frac{1+\sqrt{5}}{2}\right)^n - \left(\frac{1-\sqrt{5}}{2}\right)^n$

(GATE 2023 CS 15)

Solution:

Chapter 6

Sampling

6.1 An 8 bit ADC converts analog voltage in the range of 0 to $+5\text{ V}$ to the corresponding digital code as per the conversion characteristics shown in figure. For $V_{in} = 1.9922\text{ V}$, which of the following digital output, given in hex, is true?

(a) $64H$

(b) $65H$

(c) $66H$

(d) $67H$

(GATE EE 40)

Solution:



Figure 6.1:

Calculating the step-size:

$$\Delta V_{in} = \frac{V_{max} - V_{min}}{2^n - 1} \quad (6.1)$$

$$= \frac{5 - 0}{2^8 - 1} \quad (6.2)$$

$$= \frac{5}{255} \quad (6.3)$$

$$\Rightarrow V_{out} = \frac{V_{in}}{\Delta V_{in}} \quad (6.4)$$

$$= \frac{1.9922 \times 255}{5} \quad (6.5)$$

$$= 101.59 \quad (6.6)$$

$$\begin{aligned} &90 \\ &\approx 102_{10} \end{aligned} \quad (6.7)$$

| Symbol | Value | Description |
|-----------|---------|------------------------|
| n | 8 | Number of bits of ADC |
| V_{min} | 0V | Minimum Analog Voltage |
| V_{max} | 5V | Maximum Analog Voltage |
| V_{in} | 1.9922V | Input Voltage |
| V_{out} | | Output Voltage |

Table 6.1: Given Parameters

\therefore correct answer is option (c).

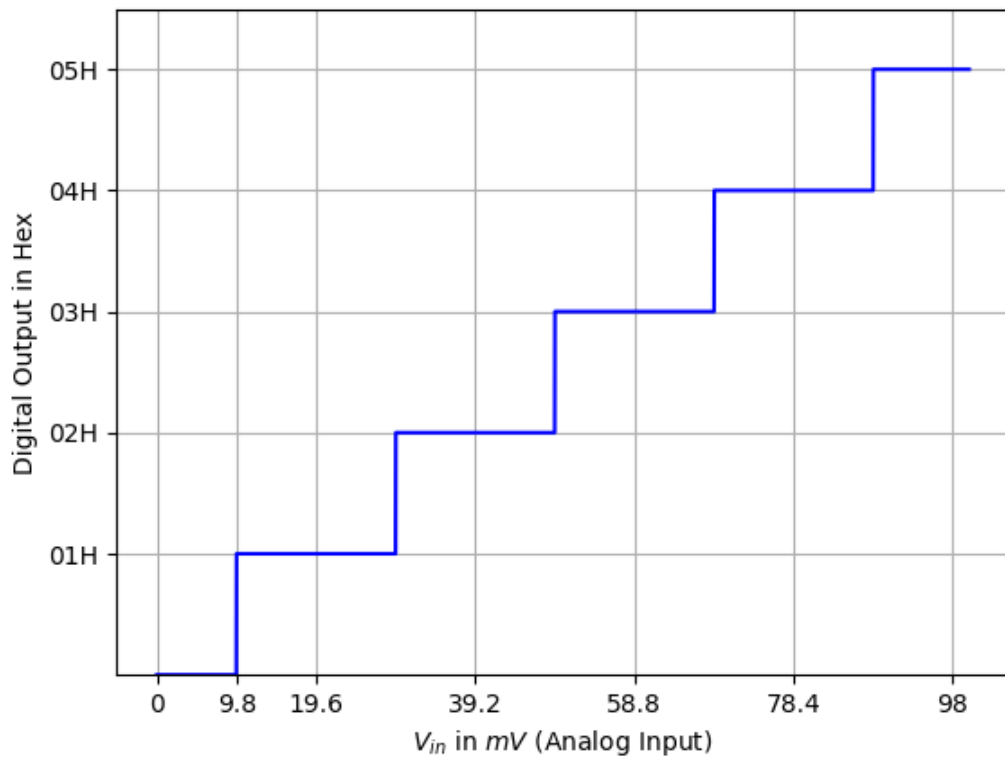
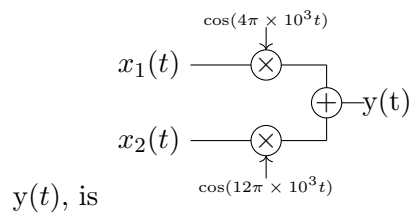


Figure 6.2:

6.2 Let $x_1(t)$ and $x_2(t)$ be two band-limited signals having bandwidth $B = 4\pi \times 10^3$ rad/s each. In the figure below, the Nyquist sampling frequency, in rad/s, required to sample



(a) $20\pi \times 10^3$

(b) $40\pi \times 10^3$

(c) $8\pi \times 10^3$

(d) $32\pi \times 10^3$

(GATE EC 50)

Solution:

6.3 An 8 bit successive approximation Analog to Digital Converter (ADC) has a clock frequency of 1 MHz. Assume that the start conversion and end conversion signals occupy one clock cycle each. Among the following options, what is the maximum frequency that this ADC can sample without aliasing?

- a) 0.9 kHz
- b) 9.9 kHz
- c) 49.9 kHz
- d) 99.9 kHz

(GATE BM 2023)

Solution:

6.4 The period of the discrete-time signal $x[n]$ described by the equation below is $N =$
(Round off to the nearest integer).

$$x[n] = 1 + 3 \sin \left(\frac{15\pi}{8}n + \frac{3\pi}{4} \right) - 5 \sin \left(\frac{\pi}{3}n - \frac{\pi}{4} \right)$$

(GATE 2023 EE) **Solution:**

Chapter 7

Contour Integration

7.1 The value of the contour integral, $\oint_C \frac{z+2}{z^2+2z+2} dz$, where the contour C is $\{z : |z+1-\frac{3}{2}i| = 1\}$, taken in the counter clockwise direction, is

(A) $-\pi(1+j)$

(B) $\pi(1+j)$

(C) $\pi(1-j)$

(D) $-\pi(1-j)$

(GATE EC 2023)

Solution:

$$I = \oint_C \frac{z+2}{z^2+2z+2} dz; \quad C = \left| z+1-\frac{3}{2}i \right| = 1 \quad (7.1)$$

The poles are given by $(z+1)^2 + 1 = 0$

$$z+1 = \pm\sqrt{-1} \quad (7.2)$$

$$z = -1 + j, z = -1 - j$$

where $-1 - i$ lies outside C and $z = (-1, 1)$ lies inside C , by the Residue Theorem:

$$\oint_C f(z) dz = 2\pi i \operatorname{Res}(f(z), z = -1 + j) \quad (7.3)$$

$$= 2\pi i \left(\frac{z+2}{2(z+1)} \right) \Big|_{z=-1+i} \quad (7.4)$$

$$= 2\pi i \left(\frac{-1+j+2}{2(-1+j+1)} \right) \quad (7.5)$$

$$= \pi(1+j). \quad (7.6)$$

Therefore, the correct answer is option (B).

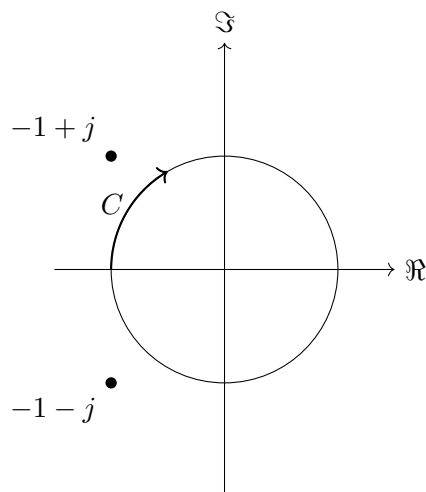


Figure 7.1: Contour C and poles

7.2 The function $f(Z) = \frac{1}{Z-1}$ of a complex variable Z is integrated on a closed contour in an anti-clockwise direction. For which of the following contours, does this integral have a non-zero value?

(A) $|z - 2| = 0.01$

(B) $|z - 1| = 0.1$

(C) $|z - 3| = 5$

(D) $|z| = 2$

(GATE 2023 BM)

Solution:

7.3 Consider the contour integral $\oint \frac{dz}{z^4+z^3-2z^2}$, along the curve $|z| = 3$ oriented in the counterclockwise direction. If $\text{Res}[f, z_0]$ denotes the residue of $f(z)$ at the point z_0 , then which of the following are TRUE?

- (A) $\text{Res}[f, 0] = -\frac{1}{4}$
- (B) $\text{Res}[f, 1] = \frac{1}{3}$
- (C) $\text{Res}[f, -2] = -\frac{1}{12}$
- (D) $\text{Res}[f, 2] = -1$

(GATE NM 2023)

Solution:

Chapter 8

Laplace Transform

8.1 The number of zeroes of the polynomial $P(s) = s^3 + 2s^2 + 5s + 80$ in the right side of the plane? (GATE IN 2023)

Solution: The table below shows the Routh array of the n^{th} - order characteristic polynomial :

$$a_0s^n + a_1s^{n-1} + \dots + a_{n-1}s^1 + a_ns^0 \quad (8.1)$$

| | | | | |
|-----------|-------------------------------------|-------------------------------------|-------|-----|
| s^n | a_0 | a_2 | a_4 | ... |
| s^{n-1} | a_1 | a_3 | a_5 | ... |
| s^{n-2} | $b_1 = \frac{a_1a_2 - a_3a_0}{a_1}$ | $b_2 = \frac{a_1a_4 - a_5a_0}{a_1}$ | ... | .. |
| s^{n-3} | $c_1 = \frac{b_1a_3 - b_2a_1}{b_1}$ | \vdots | | |
| \vdots | \vdots | \vdots | | |
| s^1 | \vdots | \vdots | | |
| s^0 | a_n | | | |

Table 8.1: Routh Array

Characteristic Equation:

$$s^3 + 2s^2 + 5s + 80 = 0 \quad (8.2)$$

From Table 8.1:

| | | |
|-------|--|----|
| s^3 | 1 | 5 |
| s^2 | 2 | 80 |
| s^1 | $\frac{2 \times 5 - 80 \times 1}{2} = -35$ | |
| s^0 | $\frac{-35 \times 80}{-35} = 80$ | |

Table 8.2:

From Table 8.2:

Since there are 2 sign changes in the first column of the Routh tabulation. So, the number of zeros in the right half of the s-plane will be 2.

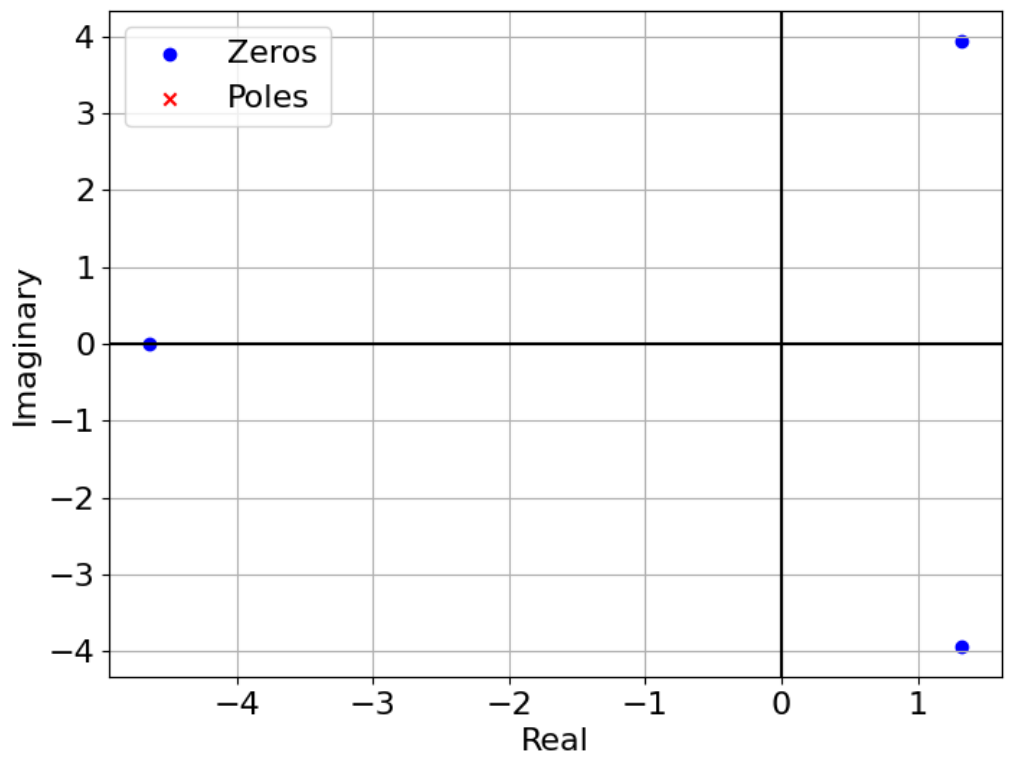
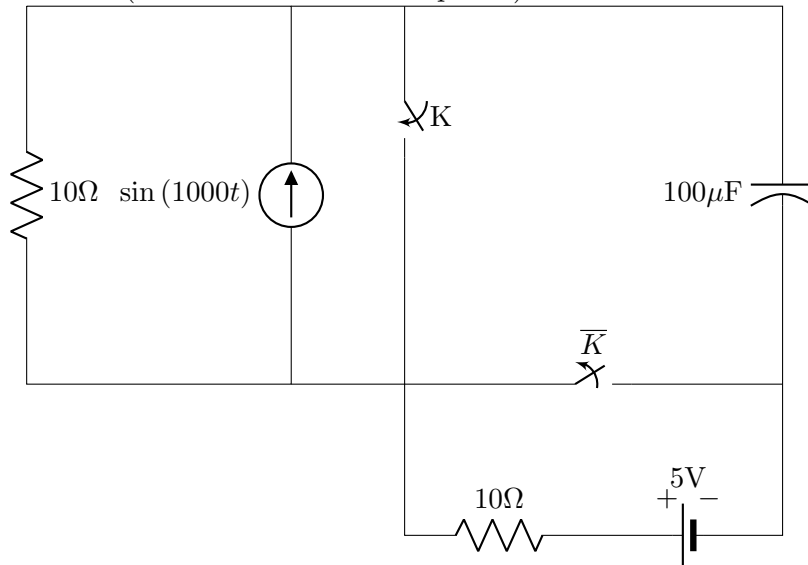


Figure 8.1:

8.2 The circuit shown in the figure is initially in the steady state with the switch K in open condition and \overline{K} in closed condition. The switch K is closed and \overline{K} is opened simultaneously at the instant $t = t_1$, where $t_1 > 0$. The minimum value of t_1 in milliseconds such that there is no transient in the voltage across the $100\ \mu\text{F}$ capacitor, is ____ (Round off to 2 decimal places) (GATE EE 2023)



Solution:

(a) Switch K is open and \overline{K} is closed.

Using Current divider rule,

$$I_1(j\omega) = \frac{10}{10 + \frac{1}{j\omega C}} \quad (8.3)$$

$$V_1(j\omega) = \frac{10}{1 + 10j\omega C} \quad (8.4)$$

$$|V_1(j\omega)| = 5\sqrt{2} \quad (8.5)$$

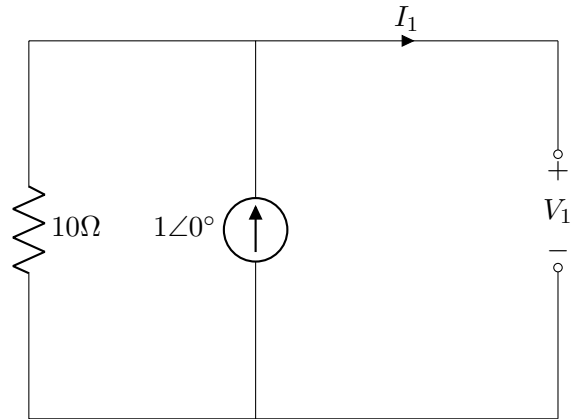


Figure 8.2: K is open and \overline{K} is closed

From Table 8.3

$$V_1(t) = 5\sqrt{2} \sin\left(\omega t - \frac{\pi}{4}\right) \quad (8.6)$$

(b) Switch K is closed and \overline{K} is open.

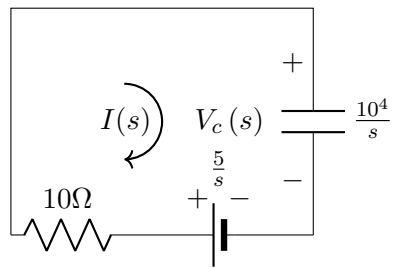


Figure 8.3: K is closed and \overline{K} is open

The capacitor is charged. Thus, acts as a voltage source.

From eq(8.6) and Table 8.4

$$V_1(s) = \frac{5000 - 5s}{s^2 + 10^6} \quad (8.7)$$

$$I(s) = \frac{\frac{5}{s} - V_1(s)}{10 + \frac{10^4}{s}} \quad (8.8)$$

$$V_c(s) = \frac{5}{s} - 10 \left(\frac{5 - V_1(s)}{1 + 10^{-3}s} \right) \quad (8.9)$$

For transient analysis,

$$\frac{5 - V_1(s)}{1 + 10^{-3}s} = 0 \quad (8.10)$$

$$\implies V_1(s) = 5 \quad (8.11)$$

$$\frac{10^7}{(s^2 + 10^6)(s + 10^3)} = \frac{5}{s} \quad (8.12)$$

$$\frac{5}{s + 10^3} + \frac{10^3 - s}{s^2 + 10^6} = \frac{5}{s} \quad (8.13)$$

$$\frac{-s}{s^2 + 10^6} + \frac{10^3}{s^2 + 10^6} + \frac{1}{s + 10^3} = \frac{1}{s} \quad (8.14)$$

From Table 8.4

$$-\cos(1000t_1) + \sin(1000t_1) + e^{-10^3 t_1} = 1 \quad (8.15)$$

$$\implies t_1 \approx 1.57 \text{msec} \quad (8.16)$$

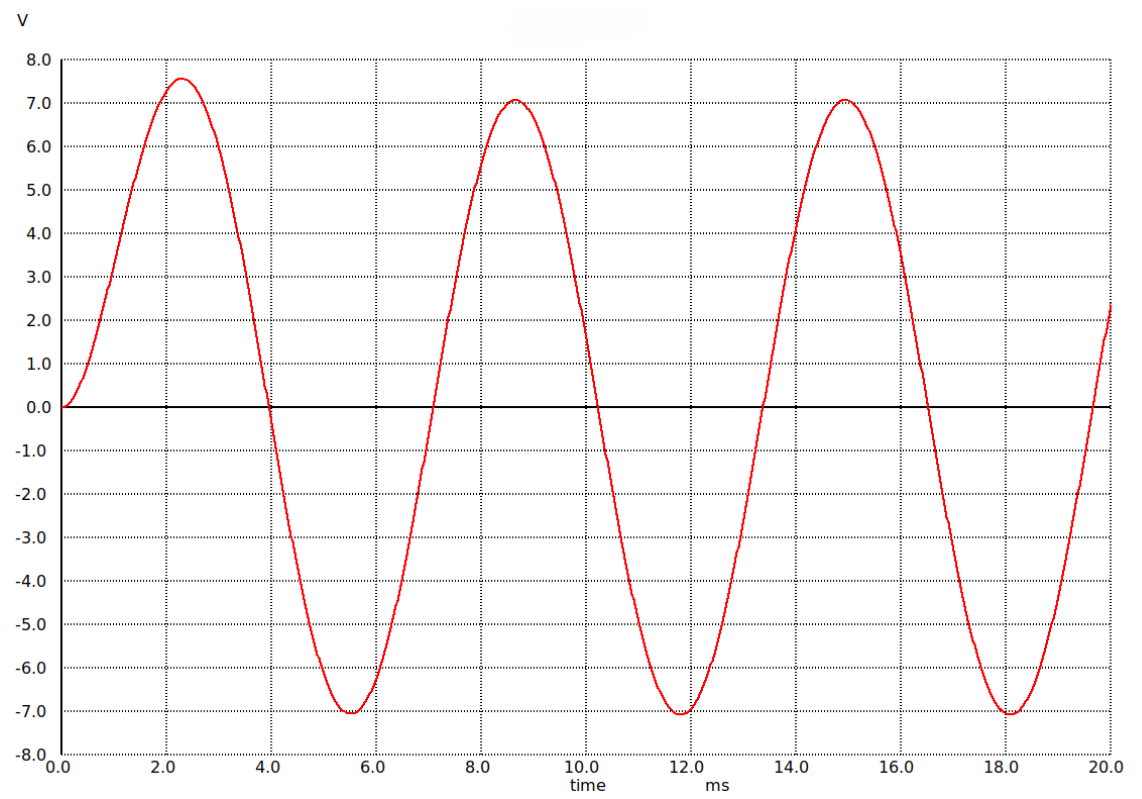


Figure 8.4: plot of V_1 vs time

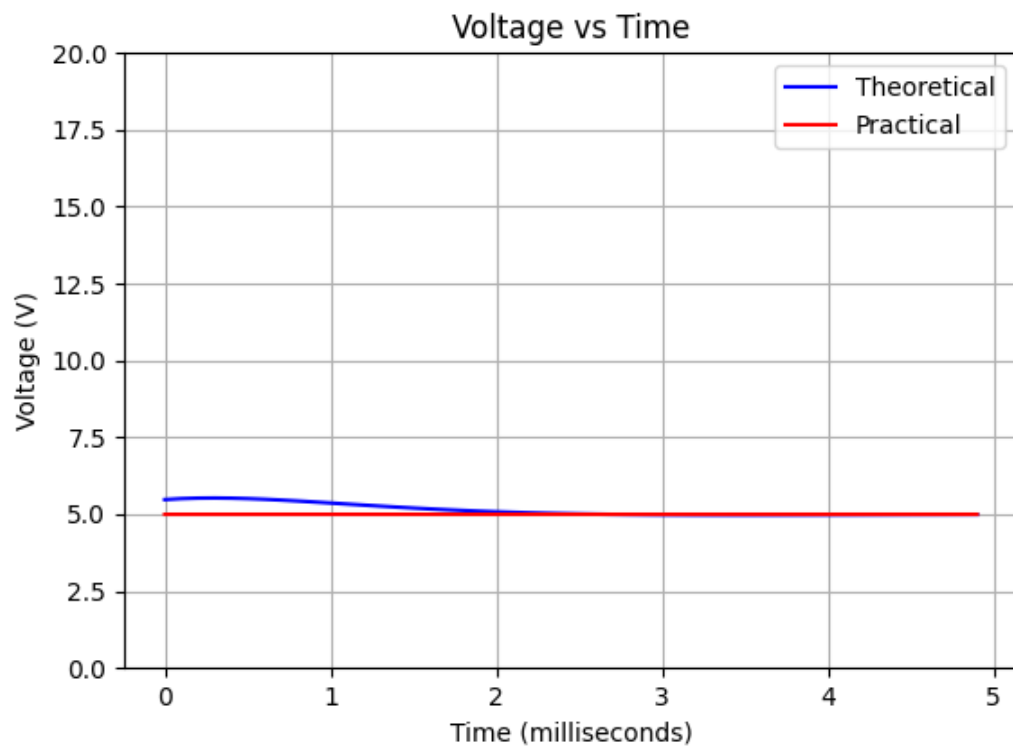


Figure 8.5: plot of V_c vs time

| Parameter | Description | Remarks |
|-----------------------|--------------------------|---|
| ω | frequency of sine-wave | 1000 rad s^{-1} |
| $V_1(t)$ | Voltage across capacitor | $ V_1(j\omega) \sin(\omega t - \angle V_1(j\omega))$ |
| $\angle V_1(j\omega)$ | phase of $V_1(j\omega)$ | $\frac{-\pi}{4}$ |
| C | Capacitance | $100\mu\text{F}$ |

Table 8.3: Parameters

| S Domain | Time Domain |
|----------------------|-------------|
| $\frac{1}{s}$ | $u(t)$ |
| $\frac{-s}{a^2+s^2}$ | $-\cos(at)$ |
| $\frac{a}{a^2+s^2}$ | $\sin(at)$ |
| $\frac{1}{s+a}$ | e^{-at} |

Table 8.4: Laplace transforms

8.3 $y = e^{mx} + e^{-mx}$ is the solution of which differential equation?

1. $\frac{dy}{dx} - my = 0$
2. $\frac{dy}{dx} + my = 0$
3. $\frac{d^2y}{dx^2} + m^2y = 0$
4. $\frac{d^2y}{dx^2} - m^2y = 0$

(GATE AG 2023) **Solution:**

8.4 A cascade control strategy is shown in the figure below. The transfer function between the output (y) and the secondary disturbance (d_2) is defined as

$$G_{d2}(s) = \frac{y(s)}{d_2(s)}$$

. Which one of the following is the CORRECT expression for the transfer function $G_{d2}(s)$?



Figure 8.6:

- A. $\frac{1}{(11s+21)(0.1s+1)}$
- B. $\frac{1}{(s+1)(0.1s+1)}$
- C. $\frac{(s+1)}{(s+2)(0.1s+1)}$
- D. $\frac{(s+1)}{(s+1)(0.1s+1)}$

(GATE CH 2023) **Solution:**

| Variable | Description |
|--------------|---|
| $d_1(s)$ | Primary disturbance |
| $d_2(s)$ | Secondary disturbance |
| $G_{d2}(s)$ | Transfer function between $y(s)$ and $d_2(s)$ |
| $y_{set}(s)$ | Set point for desired output |
| $y(s)$ | Output |

Table 8.5: Input Parameters

| Variable | Description | value |
|------------|-----------------------------------|---------------------------|
| P_1 | Forward path gain e-c-d | $\frac{1}{(0.1s+1)(s+1)}$ |
| Δ_1 | Determinant of forward path e-c-d | 1 |
| Δ | Determinant of system | $1 + \frac{10}{s+1} + 10$ |
| n | Number of forward path | 1 |

Table 8.6: Defined Parameters

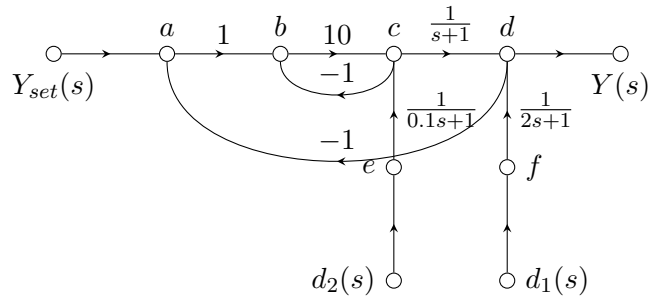


Figure 8.7: signal flow graph

Using Mason's Gain formula for the above Signal flow graph,

$$G_{d2}(s) = \frac{y(s)}{d_2(s)} = \frac{\sum_{i=1}^n P_i \Delta_i}{\Delta} \quad (8.17)$$

$$= \frac{P_1 \Delta_1}{\Delta} \quad (8.18)$$

$$= \frac{1}{\frac{(0.1s+1)(s+1)}{1 + \frac{10}{s+1} + 10}} \quad (8.19)$$

$$= \frac{1}{\frac{(0.1s+1)(s+1)}{\frac{11s+21}{s+1}}} \quad (8.20)$$

$$\Rightarrow G_{d2}(s) = \frac{1}{(11s + 21)(0.1s + 1)} \quad (8.21)$$

Now taking the inverse laplace transform we have,

$$G_{d2}(t) = \mathcal{L}^{-1} \left(\frac{10}{(s + 10)(11s + 21)} \right) \quad (8.22)$$

$$= \mathcal{L}^{-1} \left(\frac{-10}{89(x + 10)} + \frac{110}{89(11x + 21)} \right) \quad (8.23)$$

$$= \frac{-10e^{-10t}}{89}u(t) + \frac{10e^{\frac{-21t}{11}}}{89}u(t) \quad (8.24)$$

$$= \left(\frac{10 \left(e^{\frac{-21t}{11}} - e^{-10t} \right)}{89} \right) u(t) \quad (8.25)$$

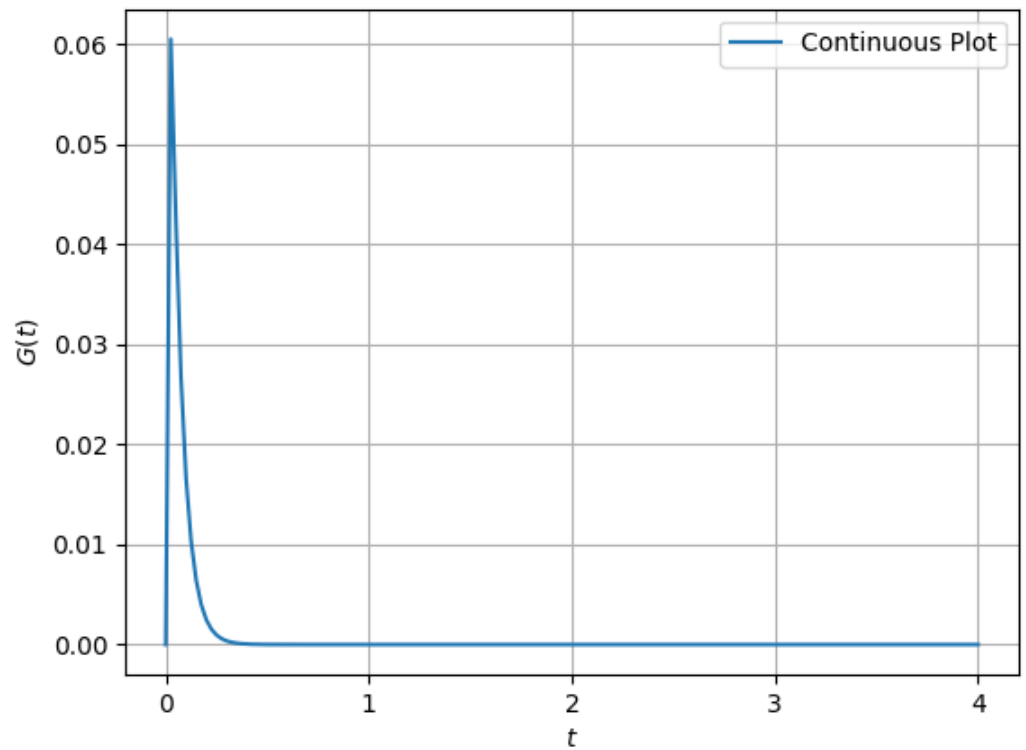
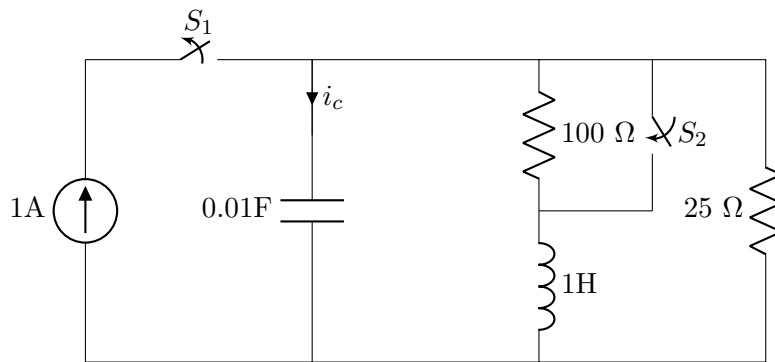


Figure 8.8:

8.5 In the differential equation $\frac{dy}{dx} + \alpha xy = 0$, α is a positive constant. If $y = 1.0$ at $x = 0.0$, and $y = 0.8$ at $x = 1.0$, the value of α is (rounded off to three decimal places). (GATE CE 2023) **Solution:**

8.6 The switch S_1 was closed and S_2 was open for a long time. At $t=0$, switch S_1 is opened and S_2 is closed, simultaneously. The value of $i_c(0^+)$, in amperes, is (GATE EC 44)



Solution:

1) Switch S_1 was closed and S_2 was open

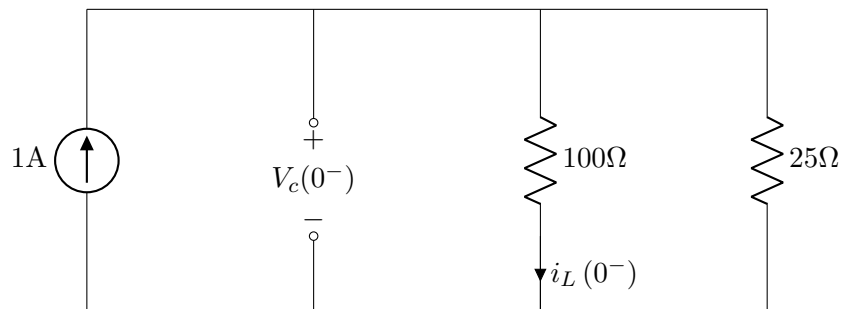


Figure 8.9: S_1 is closed and S_2 is open

$$R_{eff} = \frac{25(100)}{(25 + 100)} \Omega \quad (8.26)$$

$$R_{eff} = 20 \Omega \quad (8.27)$$

$$V_c(0^-) = 1(R_{eff}) \quad (8.28)$$

$$V_c(0^-) = 20V \quad (8.29)$$

2) Switch S_1 is open and S_2 was closed

At $t = 0^+$ The capacitor is charged. Thus, it acts as a voltage source. The inductor acts as the current source.

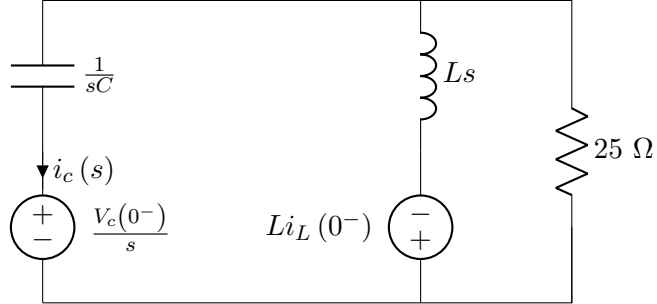


Figure 8.10: S_1 is open and S_2 is closed

By Superposition Theorem

Case (i):

$$\left(\frac{25(Ls)}{25 + Ls} + \frac{1}{sC} \right) i_c^1(s) + \frac{V_c(0^-)}{s} = 0 \quad (8.30)$$

$$i_c^1(s) = -\frac{V_c(0^-)}{s} \left(\frac{25sC + LCs^2}{25LCs^2 + Ls + 25} \right) \quad (8.31)$$

$$i_c^1(s) = -\left(\frac{5 + 0.2s}{0.25s^2 + s + 25} \right) \quad (8.32)$$

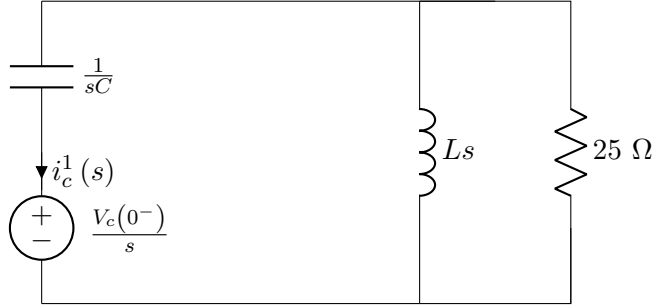


Figure 8.11: Circuit 4

Case (ii):

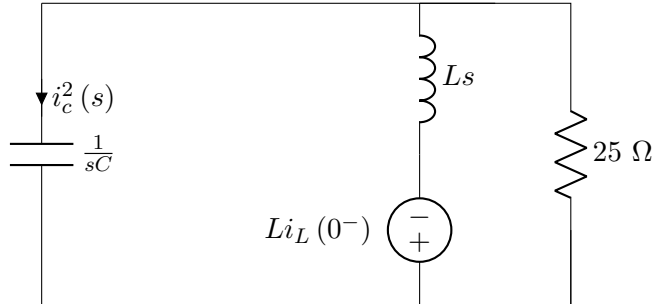


Figure 8.12: Circuit 5

$$Li_L(0^-) + \left(\frac{25}{25sC + 1} + Ls \right) i_c^2(s) = 0 \quad (8.33)$$

$$0.2 = - \left(\frac{25LCs^2 + Ls + 25}{25sC + 1} \right) i_c^2(s) \quad (8.34)$$

$$i_c^2(s) = - \left(\frac{0.05s + 0.2}{0.25s^2 + s + 25} \right) \quad (8.35)$$

From eq (8.32) and eq (8.35)

$$i_c(s) = i_c^1(s) + i_c^2(s) \quad (8.36)$$

$$i_c(s) = - \left(\frac{0.25s + 5.2}{0.25s^2 + s + 25} \right) \quad (8.37)$$

Using Inverse Laplace Transform

From eq (8.37)

$$i_c(t) = -e^{-2t} \left(\cos(4\sqrt{6}t) + \frac{18.8}{4\sqrt{6}} \sin(4\sqrt{6}t) \right) \quad (8.38)$$

$$i_c(0^+) = -1A \quad (8.39)$$

| Parameter | Description | Remarks |
|------------|---------------------------------------|---------|
| $V_c(0^-)$ | Voltage across capacitor when $t < 0$ | 20V |
| $i_L(0^-)$ | current across inductor when $t < 0$ | 0.2 |
| $i_L(0^+)$ | current across inductor when $t > 0$ | 0.2 |
| C | Capacitance | 0.01F |
| L | Inductance | 1H |

Table 8.7: Parameters

8.7 The continuous time signal $x(t)$ is described by:

$$x(t) = \begin{cases} 1, & \text{if } 0 \leq t \leq 1 \\ 0, & \text{elsewhere} \end{cases} \quad (8.40)$$

If $y(t)$ represents $x(t)$ convolved with itself, which of the following options is/are TRUE?

A $y(t) = 0$ for all $t < 0$

B $y(t) = 0$ for all $t > 1$

C $y(t) = 0$ for all $t > 3$

D $\int_{0.1}^{0.75} \frac{dy(t)}{dt} dt \neq 0$

Solution:

8.8 The Z-transform of a discrete signal $x(n)$ is

$$X(z) = \frac{4z}{\left(z - \frac{1}{5}\right)\left(z - \frac{2}{3}\right)(z - 3)} \text{ with ROC} = R \quad (8.41)$$

Which one of the following statements is TRUE?

- (a) Discrete time Fourier transform of $x[n]$ converges if R is $|z| > 3$
- (b) Discrete time Fourier transform of $x[n]$ converges if R is $\frac{2}{3} < |z| < 3$
- (c) Discrete time Fourier transform of $x[n]$ converges if R is such that $x[n]$ is a left-sided sequence.
- (d) Discrete time Fourier transform of $x[n]$ converges if R is such that $x[n]$ is a right-sided sequence.

GATE EE 2023

Solution: Poles of $X(z)$ are located at $z = \frac{1}{5}$, $z = \frac{2}{3}$, and $z = 3$.

For DTFT to converge, the ROC of Z-transform of $x[n]$ should contain unit circle.

- (a) If ROC is $|z| > 3$, it does not include unit circle

Option (a) is wrong.

- (b) If ROC is $\frac{2}{3} < |z| < 3$, the ROC includes unit circle.

So, option (b) is correct.

(c) If $x(n)$ is a left-sided sequence, then ROC will be $|z| < \frac{1}{5}$, which does not include the unit circle.

Option (c) is wrong.

(d) If $x(n)$ is a right-sided sequence, then the ROC is $|z| > 3$, which does not include the unit circle.

Option (d) is wrong.

Hence, the correct option is (b).

- 8.9 The phase margin of the transfer function $G(s) = \frac{2(1-s)}{(1+s)^2}$ is _____ degrees. (rounded off to the nearest integer). (GATE IN 2023)

Solution:

| Parameters | Description |
|---------------------|--|
| ω_c | crossover frequency |
| $\angle G(j\omega)$ | phase angle of the transfer function |
| PM | $\angle G(j\omega_c) + 180^\circ$; Phase Margin |

Table 8.8: Parameters

Considering $s = j\omega$,

$$G(j\omega) = \frac{2(1 - j\omega)}{(1 + j\omega)^2} \quad (8.42)$$

$$= \frac{2(1 - j\omega)^3}{|1 + j\omega|^4} \quad (8.43)$$

$$= \frac{2}{(1 + \omega^2)^2} (1 - j\omega)^3 \quad (8.44)$$

$$= \frac{2}{\sqrt{1 + \omega^2}} (e^{-j\omega})^3 \quad (8.45)$$

$$\Rightarrow |G(j\omega)| = \frac{2}{\sqrt{1 + \omega^2}} \quad (8.46)$$

$$\Rightarrow \angle G(j\omega) = 3 \tan^{-1}(-\omega) \quad (8.47)$$

At $\omega = \omega_c$, $Gain = 0$

$$\Rightarrow |G(j\omega_c)| = 1 \quad (8.48)$$

$$\frac{2}{\sqrt{1 + \omega_c^2}} = 1 \quad (8.49)$$

$$\Rightarrow \omega_c = \sqrt{3} \quad (8.50)$$

$$\angle G(j\omega_c) = 3 \tan^{-1}(-\sqrt{3}) \quad (8.51)$$

$$= -180^\circ \quad (8.52)$$

From Table 8.8,

$$PM = 0^\circ \tag{8.53}$$

8.10 Consider the second-order linear differential equation

$$x^2 \frac{d^2 y}{dx^2} + x \frac{dy}{dx} - y = 0, \quad x \geq 1$$

with the initial conditions

$$y(x=1) = 6, \quad \left. \frac{dy}{dx} \right|_{x=1} = 2.$$

Then the value of y at $x = 2$ is _____.

GATE ME 2023

Solution:

| Symbol | Value | Description |
|---------|-------|-------------------|
| $y(x)$ | ? | Function |
| $y(1)$ | 6 | Initial Condition |
| $y'(1)$ | 2 | Initial Condition |

Table 8.9: Given Information

By Euler-Cauchy substitution for the given question,

$$x = e^t, \quad t \geq 0 \tag{8.54}$$

$$\implies \frac{dt}{dx} = e^{-t} \tag{8.55}$$

$$\implies \frac{dy}{dx} = \frac{dy}{dt} \frac{dt}{dx} = e^{-t} \frac{dy}{dt} \tag{8.56}$$

$$\implies \frac{d^2 y}{dx^2} = \frac{d^2 y}{dt^2} \left(\frac{dt}{dx} \right)^2 + \frac{d^2 t}{dx^2} \left(\frac{dy}{dt} \right) \tag{8.57}$$

$$= e^{-2t} \frac{d^2 y}{dt^2} + e^{-2t} \frac{dy}{dt} \tag{8.58}$$

So the given equation becomes

$$e^{2t} \left(e^{-2t} \frac{d^2 y}{dt^2} - e^{-2t} \frac{dy}{dt} \right) + e^{-t} \left(e^{-t} \frac{dy}{dt} \right) - y = 0 \quad (8.59)$$

$$\frac{d^2 y}{dt^2} - \frac{dy}{dt} + \frac{dy}{dt} - y = 0 \quad (8.60)$$

$$\frac{d^2 y}{dt^2} - y = 0, \quad t \geq 0 \quad (8.61)$$

Taking Laplace Transform,

$$s^2 Y(s) - sy(0) - y'(0) - Y(s) = 0 \quad (8.62)$$

$$Y(s) = \frac{sy(0) + y'(0)}{s^2 - 1} \quad (8.63)$$

$$= \frac{6s + 2}{s^2 - 1} \quad (8.64)$$

By partial fractions,

$$Y(s) = \frac{4}{s-1} + \frac{2}{s+1} \quad (8.65)$$

Taking Inverse Laplace using

$$\frac{1}{s+a} \xleftrightarrow{\mathcal{L}^{-1}} e^{-at} \quad (8.66)$$

We get,

$$y(t) = 4e^t + 2e^{-t} \quad (8.67)$$

From (8.54)

$$y(t) = 4x + \frac{2}{x} \quad (8.68)$$

$$\implies y(2) = 9 \quad (8.69)$$

8.11 The transfer function of a measuring instrument is

$$G_m(s) = \frac{1.05}{2s + 1} \exp(-s)$$

At time $t = 0$, a step change of +1 unit is introduced in the input of this instrument. The time taken by the instrument to show an increase of 1 unit in its output is (rounded off to two decimal places).

(GATE CH 2023) **Solution:**

8.12 The laplace transform of $x_1(t) = e^{-t}u(t)$ is $X_1(s)$, where $u(t)$ is the unit step function. The laplace transform of $x_2(t) = e^t u(-t)$ is $X_2(s)$. Which one of the following statements is TRUE?

- (a) The region of convergence of $X_1(s)$ is $\text{Re}(s) \geq 0$
- (b) The region of convergence of $X_2(s)$ is confined to the left half-plane of s .
- (c) The region of convergence of $X_1(s)$ is confined to the right half-plane of s .
- (d) the imaginary axis in the s -plane is included in both the region of convergence of $X_1(s)$ and the region of convergence of $X_2(s)$.

(GATE BM 2023)

Solution:

| Symbols | Description |
|----------|-------------------------------|
| $X_1(s)$ | Laplace transform of $x_1(t)$ |
| $X_2(s)$ | Laplace transform of $x_2(t)$ |
| $u(t)$ | Unit step function |

Table 8.10: Parameters, Descriptions

(a) Laplace transform of $x_1(t)$ is given by :

$$X_1(s) = \int_{-\infty}^{\infty} e^{-t} e^{-st} u(t) dt \quad (8.70)$$

Let $s = \sigma + j\omega$:

$$X_1(s) = \int_0^{\infty} e^{-t(\sigma+1)} e^{-tj\beta} dt \quad (8.71)$$

$$= \left[\frac{-e^{-t(\sigma+1)} e^{-tj\beta}}{(\sigma+1) + j\beta} \right]_0^{\infty} \quad (8.72)$$

For $X_1(s)$ to be convergent, $|-e^{-t(\sigma+1)} e^{-tj\beta}|$ must converge $\forall t \in (0, \infty)$, so:

$$|e^{-tj\beta}| = |1|, \forall \beta \in \mathbb{R} \implies \text{Im}(s) \in \mathbb{R} \quad (8.73)$$

$$\sigma + 1 > 0 \implies \Re(s) > -1 \quad (8.74)$$

Putting the limits :

$$X_1(s) = \frac{1}{s+1}, \Re(s) > -1 \quad (8.75)$$

(b) Laplace transform of $x_2(t)$ is given by :

$$X_2(s) = \int_{-\infty}^{\infty} e^t e^{-st} u(-t) dt \quad (8.76)$$

Let $s = \sigma + j\omega$:

$$= \int_{-\infty}^0 e^{t(1-\sigma)} e^{-tj\beta} dt \quad (8.77)$$

$$= \left[\frac{e^{t(1-\sigma)} e^{-tj\beta}}{(1-\sigma) - j\beta} \right]_{-\infty}^0 \quad (8.78)$$

For $X_2(s)$ to be convergent, $|e^{t(1-\sigma)} e^{-tj\beta}|$ must converge $\forall t \in (-\infty, 0)$, so:

$$|e^{-tj\beta}| = |1|, \forall \beta \in \mathbb{R} \implies \text{Im}(s) \in \mathbb{R} \quad (8.79)$$

$$1 - \sigma > 0 \implies \Re(s) < 1 \quad (8.80)$$

Putting the limits

$$X_2(s) = \frac{1}{1-s}, \Re(s) < 1 \quad (8.81)$$

Based on the overlap of regions of convergence of $X_1(s)$ and $X_2(s)$ from 8.18 , we can conclude that option 4) is correct .

8.13 Given that $\frac{dy}{dx} = 2x + y$ and $y = 1$, when $x = 0$ Using Runge-Kutta fourth order method, the value of y at $x = 0.2$ is (GATE 2023 AG 50)

Solution:

8.14 The magnitude and phase plots shown in the figure match with the transfer- function

(a) $\frac{10000}{s^2 + 2s + 10000}$

(b) $\frac{10000}{s^2 + 2s + 10000} e^{-0.05s}$

(c) $\frac{10000}{s^2 + 2s + 10000} e^{-0.5 \times 10^{-12}s}$

(d) $\frac{100}{s^2 + 2s + 100}$

(GATE IN 2023) **Solution:**

8.15 The Laplace transform of the continuous-time signal $x(t) = e^{-3t}u(t-5)$ is _____, where $u(t)$ denotes the continuous-time unit step signal.

A) $\frac{e^{-5s}}{s+3}$, $\text{Real}\{s\} > -3$

B) $\frac{e^{-5(s-3)}}{s-3}$, $\text{Real}\{s\} > 3$

C) $\frac{e^{-5(s+3)}}{s+3}$, $\text{Real}\{s\} > -3$

D) $\frac{e^{-5(s-3)}}{s+3}$, $\text{Real}\{s\} > -3$

Solution:

| Parameter | Description | Value |
|-----------|-----------------------------|---------------------------|
| $x(t)$ | Given Function | $x(t) = e^{-3t}u(t)$ |
| $X(s)$ | Laplace Transform of $x(t)$ | $\frac{e^{-5(s+3)}}{s+3}$ |

Table 1: Table of parameters

$$e^{-3t}u(t) \xleftrightarrow{\mathcal{L}} \frac{1}{s+3} \quad \Re(s) > -3 \quad (8.82)$$

Using time shifting,

$$e^{-3(t-5)}u(t-5) \xleftrightarrow{\mathcal{L}} \frac{e^{-5s}}{s+3} \quad (8.83)$$

$$e^{-15}e^{-3(t-5)}u(t-5) \xleftrightarrow{\mathcal{L}} e^{-15}\frac{e^{-5s}}{s+3} \quad (8.84)$$

$$e^{-3t}u(t-5) \xleftrightarrow{\mathcal{L}} \frac{e^{-5(s+3)}}{s+3} \quad (8.85)$$

$$\therefore x(t) \xleftrightarrow{\mathcal{L}} \frac{e^{-5(s+3)}}{s+3} \quad \Re(s) > -3 \quad (8.86)$$

8.16 The solution $x(t), t \geq 0$, to the differential equation $\ddot{x} = -k\dot{x}, k > 0$ with initial conditions $x(0) = 1$ and $\dot{x}(0) = 0$ is

Solution:

8.17 Consider the differential equation

$$x^2 \frac{d^2 y}{dx^2} + 4x \frac{dy}{dx} + 2y = 0 \quad \text{for } x \geq 1$$

with initial conditions $y = 0$ and $\frac{dy}{dx} = 1$ at $x = 1$. The value of y at $x = 2$ is ?

(GATE AE 54 2023)

Solution: Given :

$$x^2 \frac{d^2 y}{dx^2} + 4x \frac{dy}{dx} + 2y = 0 \quad \text{for } x \geq 1 \quad (8.87)$$

Using Euler Substitution :

$$x = e^t \quad (8.88)$$

$$\frac{dy}{dx} = e^{-t} \frac{dy}{dt} \quad (8.89)$$

$$\frac{d^2 y}{dx^2} = e^{-2t} \frac{d^2 y}{dt^2} - e^{-2t} \frac{dy}{dt} \quad (8.90)$$

Substituting equations (8.88),(8.89),(8.90) in equation (8.87):

$$\frac{d^2 y}{dt^2} + 3 \frac{dy}{dt} + 2y = 0 \quad (8.91)$$

Taking Laplace on Both Sides:

$$s^2 Y(s) - sy(1) - y'(1) + 3sY(s) - y(1) + 2Y(s) = 0 \quad (8.92)$$

We know that:

$$y(1) = 0 \quad (8.93)$$

$$y'(1) = 1 \quad (8.94)$$

Substituting equations (8.93),(8.94) in (8.92)

$$s^2Y(s) + 3sY(s) + 2Y(s) = 1 \quad (8.95)$$

$$\Rightarrow Y(s) = \frac{1}{s^2 + 3s + 2} \quad (8.96)$$

$$\Rightarrow Y(s) = \frac{1}{s+1} - \frac{1}{s+2} \quad (8.97)$$

Taking Inverse Laplace:

$$y(t) = (e^{-t} - e^{-2t})u(t) \quad (8.98)$$

Substituting $x = e^t$:

$$y(x) = e^{-\ln x} - e^{-2\ln x}, \quad x \geq 1 \quad (8.99)$$

$$y(x) = \frac{1}{x} - \frac{1}{x^2}, \quad x \geq 1 \quad (8.100)$$

$$\therefore y(2) = 0.25 \quad (8.101)$$

8.18 Consider a lead compensator of the form

$$K(s) = \frac{1 + \frac{s}{a}}{1 + \frac{s}{\beta a}}, \quad \beta > 1, \quad a > 0$$

The frequency at which this compensator produces maximum phase lead is 4 rad/s.

At this frequency, the gain amplification provided by the controller, assuming an asymptotic Bode-magnitude plot of $K(s)$, is 6 dB. The values of a and β , respectively, are

(a) 1, 16

(b) 2, 4

(c) 3, 5

(d) 2.66, 2.25

(GATE EC 2023) **Solution:**

8.19 Second order ordinary differential equation $\frac{d^2y}{dx^2} - \frac{dy}{dx} - 2y = 0$ has values $y = 2$ and $\frac{dy}{dx} = 1$ at $x = 0$. The value of y at $x = 1$ is? (round off to three decimal places)
[GATE-ES 2023]

Solution: We convert given second order differential equation to s domain using Laplace transform and solve for $Y(s)$ and take inversion to get $y(x)$.

| Symbol | Values | Description |
|---------|---|--------------------|
| $Y(s)$ | $\frac{2s-1}{s^2-s-2}$ | y in s domain |
| $y(x)$ | $e^{2x} + e^{-x}$ | y in x domain |
| $y(0)$ | 2 | y at $x = 0$ |
| $y'(0)$ | 1 | $y'(x)$ at $x = 0$ |
| $u(x)$ | $= \begin{cases} 1 & \text{if } x \geq 0 \\ 0 & \text{o.w} \end{cases}$ | unit step function |

Table 8.12: Parameters

$$\frac{d^2y}{dx^2} - \frac{dy}{dx} - 2y \xleftrightarrow{\mathcal{L}} s^2Y(s) - sy(0) - y'(0) - sY(s) + y(0) - 2Y(s) \quad (8.102)$$

$$Y(s) (s^2 - s - 2) = 2s - 1 \quad (8.103)$$

$$\Rightarrow Y(s) = \frac{2s - 1}{s^2 - s - 2} \quad (8.104)$$

$$\Rightarrow Y(s) = \frac{1}{s - 2} + \frac{1}{s + 1} \quad (8.105)$$

For inversion of $Y(s)$ in partial fractions-

$$\frac{b}{s + a} \xleftrightarrow{\mathcal{L}^{-1}} be^{-ax}u(x) \quad (8.106)$$

Where b, a are real numbers, we invert $Y(s)$ to get $y(x)$:-

From (8.106)

$$Y(s) \xleftrightarrow{\mathcal{L}^{-1}} y(x)u(x) \quad (8.107)$$

$$y(x) = (e^{2x} + e^{-x}) u(x) \quad (8.108)$$

$$\Rightarrow y(1) = 7.757 \quad (8.109)$$

8.20 A continuous-time system that is initially at rest is described by,

$$\frac{dy(t)}{dt} + 3y(t) = 2x(t)$$

where $x(t)$ is the input voltage and $y(t)$ is the output voltage.

The impulse response of the system is?

(GATE 2023 EE) **Solution:**

8.21 Consider the equation $\frac{dy}{dx} + ay = \sin \omega x$, where a and ω are constants. Given $y = 1$ at $x = 0$, correct all the correct statement(s) from the following as $x \rightarrow \infty$.

(A) $y \rightarrow 0$ if $a \neq 0$

(B) $y \rightarrow 1$ if $a = 0$

(C) $y \rightarrow A \exp(|a|x)$ if $a < 0$; A is constant

(D) $y \rightarrow B \sin(\omega x + C)$ if $a > 0$; B and C are constants

(GATE AE 2023) **Solution:**

8.22 **Question :** The position $x(t)$ of a particle, at constant ω , is described by the equation

$$\frac{d^2x}{dt^2} = -\omega^2 x. \quad (8.110)$$

The initial conditions are $x(t = 0) = 1$ and $\left. \frac{dx}{dt} \right|_{t=0} = 0$. The position of the particle at $t = \frac{3\pi}{\omega}$ is _____ (in integer). (GATE CH 2023) **Solution:**

8.23 **Question:** The initial value problem $\frac{dy}{dt} + 2y = 0, y(0) = 1$ is solved numerically using the forward Euler's method with a constant and positive time step of δ .

Let y_n represent the numerical solution obtained after n steps. The condition $|y_{n+1}| \leq |y_n|$ is satisfied if and only if δ does not exceed

(GATE ME 2023) **Solution:**

8.24 In the context of signals and systems, determine the phase cross-over frequency of the open-loop transfer function

$$G(s) = \frac{k \cdot s \cdot (1 + sT_1) \cdot (1 + sT_2)}{s}$$

with positive constants k, T_1, T_2 are positive constants. The phase crossover frequency, in rad/s, is

(a) $\frac{1}{\sqrt{T_1 T_2}}$

(b) $\frac{1}{T_1 T_2}$

(c) $\frac{1}{T_1 \sqrt{T_2}}$

(d) $\frac{1}{\sqrt{T_2} T_1}$

(GATE EC 2023) **Solution:**

8.25 Which one of the options given is the inverse Laplace transform of $\frac{1}{s^3-s}$?

$u(t)$ denotes the unit-step function.

(A) $\left(-1 + \frac{1}{2}e^{-t} + \frac{1}{2}e^t\right) u(t)$

(B) $\left(\frac{1}{3}e^{-t} - e^t\right) u(t)$

(C) $\left(-1 + \frac{1}{2}e^{-(t-1)} + \frac{1}{2}e^{(t-1)}\right) u(t-1)$

(D) $\left(-1 - \frac{1}{2}e^{-(t-1)} - \frac{1}{2}e^{(t-1)}\right) u(t-1)$

(GATE ME 2023)

Solution:

Using partial fraction,

$$\frac{1}{s^3-s} = \frac{A}{s} + \frac{B}{s+1} + \frac{C}{s-1} \quad (8.111)$$

On Solving,

$$\implies A = -1 \quad B = \frac{1}{2} \quad C = \frac{1}{2} \quad (8.112)$$

$$X(s) = \frac{-1}{s} + \frac{1}{2(s+1)} + \frac{1}{2(s-1)} \quad (8.113)$$

$$\text{As } e^{-at}u(t) \xrightarrow{\mathcal{L}} \frac{1}{s+a} \quad \Re(s) > -a \quad (8.114)$$

$$\text{And } -e^{-at}u(-t) \xrightarrow{\mathcal{L}} \frac{1}{s+a} \quad \Re(s) < -a \quad (8.115)$$

Now,

$$\mathcal{L}^{-1}(X(s)) = x(t) \quad (8.116)$$

There are 4 cases possible,

$$x(t) = \begin{cases} \left(1 - \frac{1}{2}e^{-t} - \frac{1}{2}e^t\right) u(-t) & \Re(s) < -1 \\ -1u(-t) + \frac{1}{2}e^{-t}u(t) - \frac{1}{2}e^t u(-t) & \Re(s) \in (-1, 0) \\ -u(t) + \frac{1}{2}e^{-t}u(t) - \frac{1}{2}e^t u(-t) & \Re(s) \in (0, 1) \\ \left(-1 + \frac{1}{2}e^{-t} + \frac{1}{2}e^t\right) u(t) & \Re(s) > 1 \end{cases} \quad (8.117)$$

Thus the correct option is (A) $\left(-1 + \frac{1}{2}e^{-t} + \frac{1}{2}e^t\right) u(t)$ for $\Re(s) > 1$

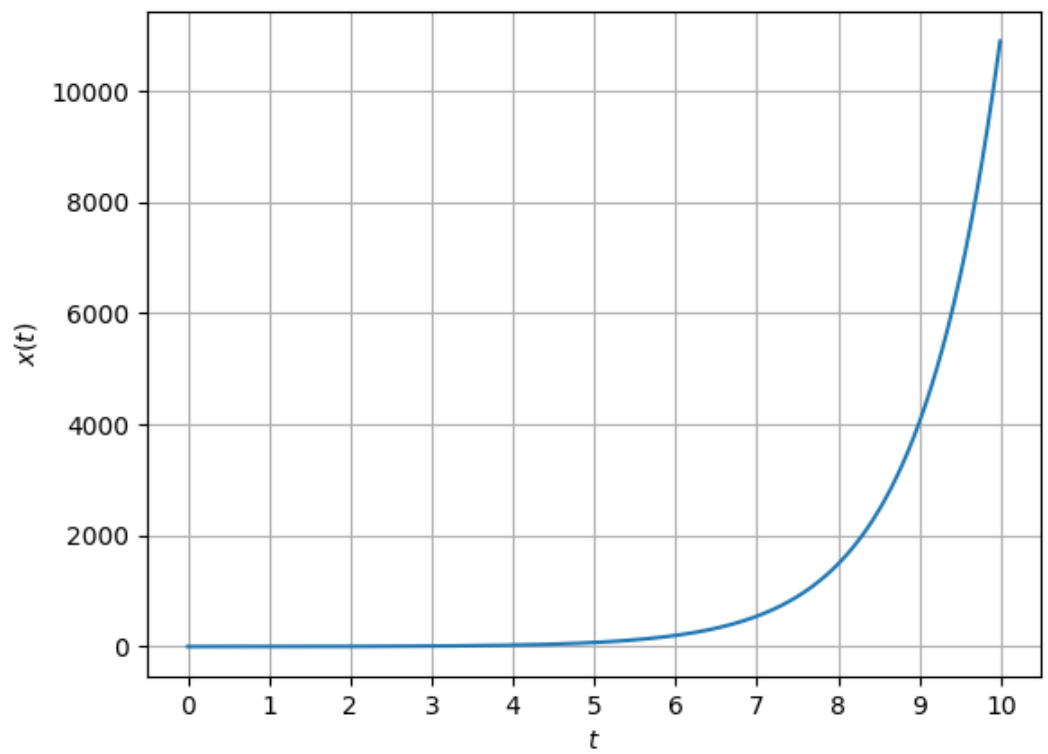


Figure 8.22: Plot for $x(t) = (-1 + \frac{1}{2}e^{-t} + \frac{1}{2}e^t)u(t)$

8.26 The state equation of a second order system is

$$\dot{x}(t) = Ax(t), \quad x(0) \text{ is the initial condition.}$$

Suppose λ_1 and λ_2 are two distinct eigenvalues of A , and ν_1 and ν_2 are the corresponding eigenvectors. For constants α_1 and α_2 , the solution, $x(t)$, of the state equation is

(A) $\sum_{i=1}^2 \alpha_i e^{\lambda_i t} \nu_i$

(B) $\sum_{i=1}^2 \alpha_i e^{2\lambda_i t} \nu_i$

(C) $\sum_{i=1}^2 \alpha_i e^{3\lambda_i t} \nu_i$

(D) $\sum_{i=1}^2 \alpha_i e^{4\lambda_i t} \nu_i$

GATE EC 2023

Solution:

| Variable | Description | Value |
|----------------------------|-----------------------------------|--------------------|
| $x(t)$ | state variable | - |
| $\dot{x}(t)$ | derivative of $x(t)$ w.r.t t | $\frac{dx(t)}{dt}$ |
| A | 2x2 matrix | - |
| λ_i for $i = 1, 2$ | eigen values of A | - |
| ν_i for $i = 1, 2$ | eigen vectors of A | - |
| α_i for $i = 1, 2$ | component of $x(t)$ along ν_i | - |

Table 8.13: input parameters

Theories and Proofs:

$$A\mathbf{y} = \lambda\mathbf{y} \quad (8.118)$$

Eigen values of inverse of a matrix is reciprocal of eigen value of the given matrix

$$A^{-1}A\mathbf{y} = A^{-1}\lambda\mathbf{y} \quad (8.119)$$

$$\implies \mathbf{y} = \lambda A^{-1}\mathbf{y} \quad (8.120)$$

$$\implies A^{-1}\mathbf{y} = \frac{1}{\lambda}\mathbf{y} \quad (8.121)$$

Eigen value of a matrix shifts by the same amount as that of the matrix.

$$(A - \sigma I)\mathbf{y} = A\mathbf{y} - \sigma I\mathbf{y} \quad (8.122)$$

$$= \lambda\mathbf{y} - \sigma\mathbf{y} \quad (8.123)$$

$$= (\lambda - \sigma)\mathbf{y} \quad (8.124)$$

Sol:

Using Laplace transform:

Given Equation:

$$\dot{x}(t) = Ax(t) \quad (8.125)$$

$$\frac{dx(t)}{dt} = Ax(t) \quad (8.126)$$

Taking Laplace Transform:

$$\mathcal{L}\left(\frac{dx(t)}{dt}\right) = \mathcal{L}(Ax(t)) \quad (8.127)$$

$$sX(s) - x(0) = AX(s) \quad (8.128)$$

$$(sI - A)X(s) = x(0) \quad (8.129)$$

$$X(s) = (sI - A)^{-1}x(0) \quad (8.130)$$

From Table 8.13, we can write $x(0)$ in terms of two linearly independent variables as

$$x(0) = \alpha_1 v_1 + \alpha_2 v_2 \quad (8.131)$$

$$= \sum_{i=1}^2 \alpha_i v_i \quad (8.132)$$

From (8.130), (8.132)

$$X(s) = (sI - A)^{-1} \left(\sum_{i=1}^2 \alpha_i v_i \right) \quad (8.133)$$

$$= \sum_{i=1}^2 (sI - A)^{-1} \alpha_i v_i \quad (8.134)$$

From (8.121), (8.124)

$$X(s) = \sum_{i=1}^2 \frac{1}{s - \lambda_i} (\alpha_i v_i) \quad (8.135)$$

Now take inverse Laplace Transform

$$\mathcal{L}^{-1}(X(s)) = \mathcal{L}^{-1}\left(\sum_{i=1}^2 \frac{1}{s - \lambda_i} (\alpha_i v_i)\right) \quad (8.136)$$

$$x(t) = \sum_{i=1}^2 e^{\lambda_i t} (\alpha_i v_i) \quad (8.137)$$

Hence the answer is option (A).

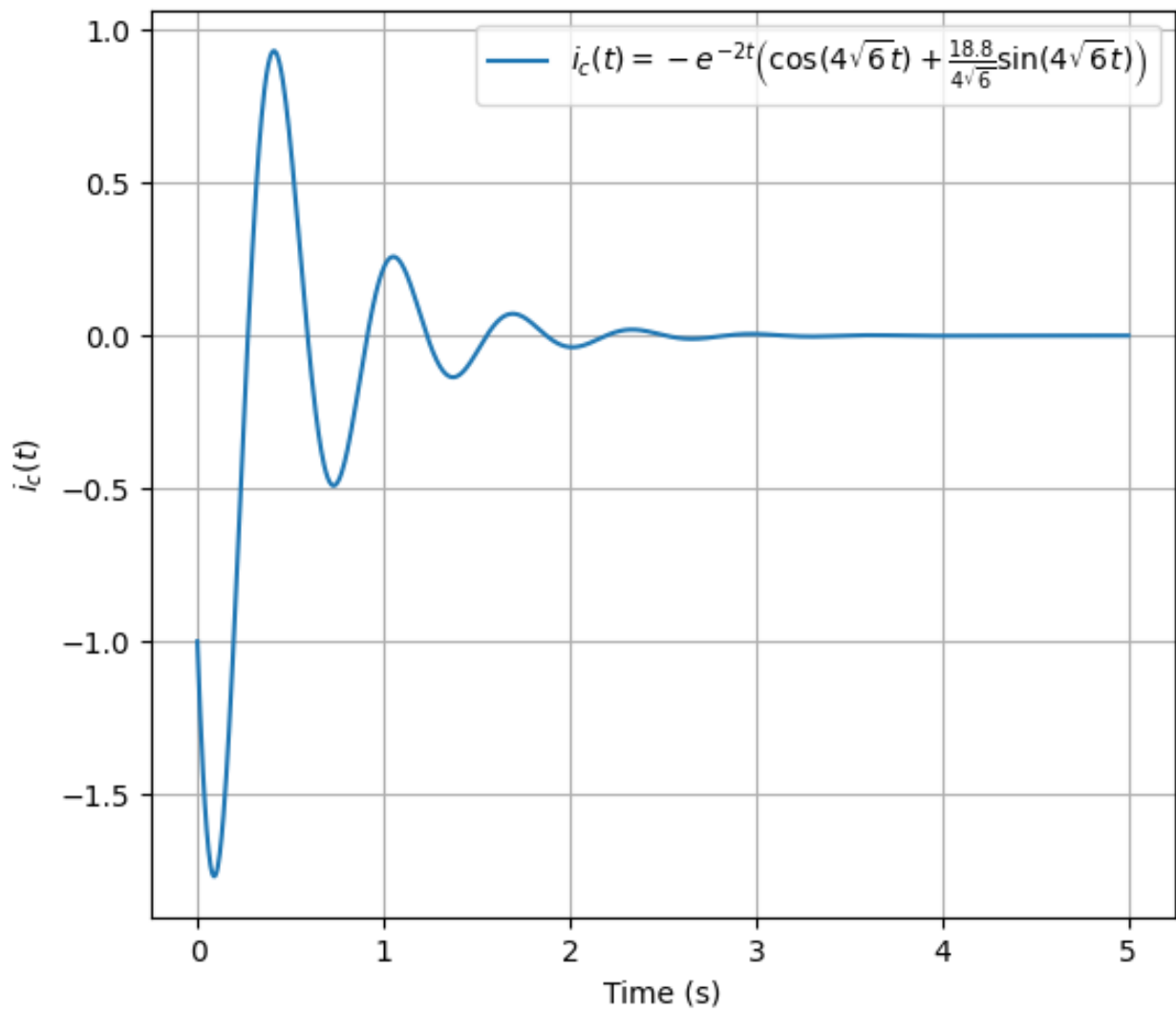


Figure 8.13: Plot of $i_c(t)$ vs time

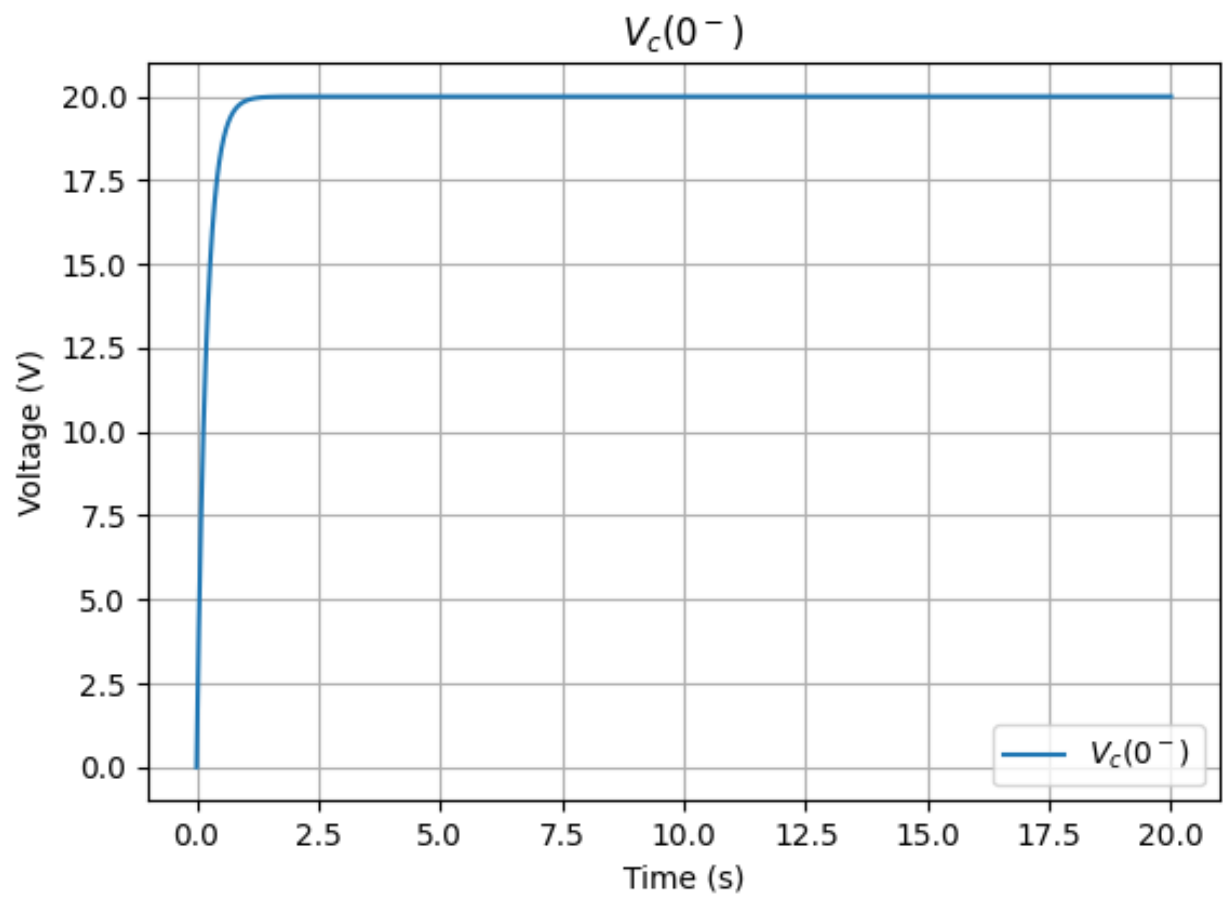


Figure 8.14: Plot of $V_c(0^-)$ vs time

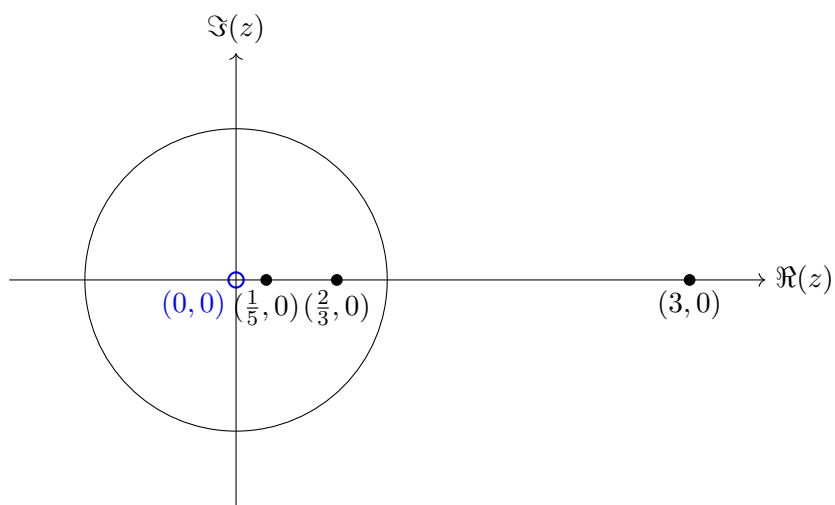


Figure 8.15: Representation of Poles

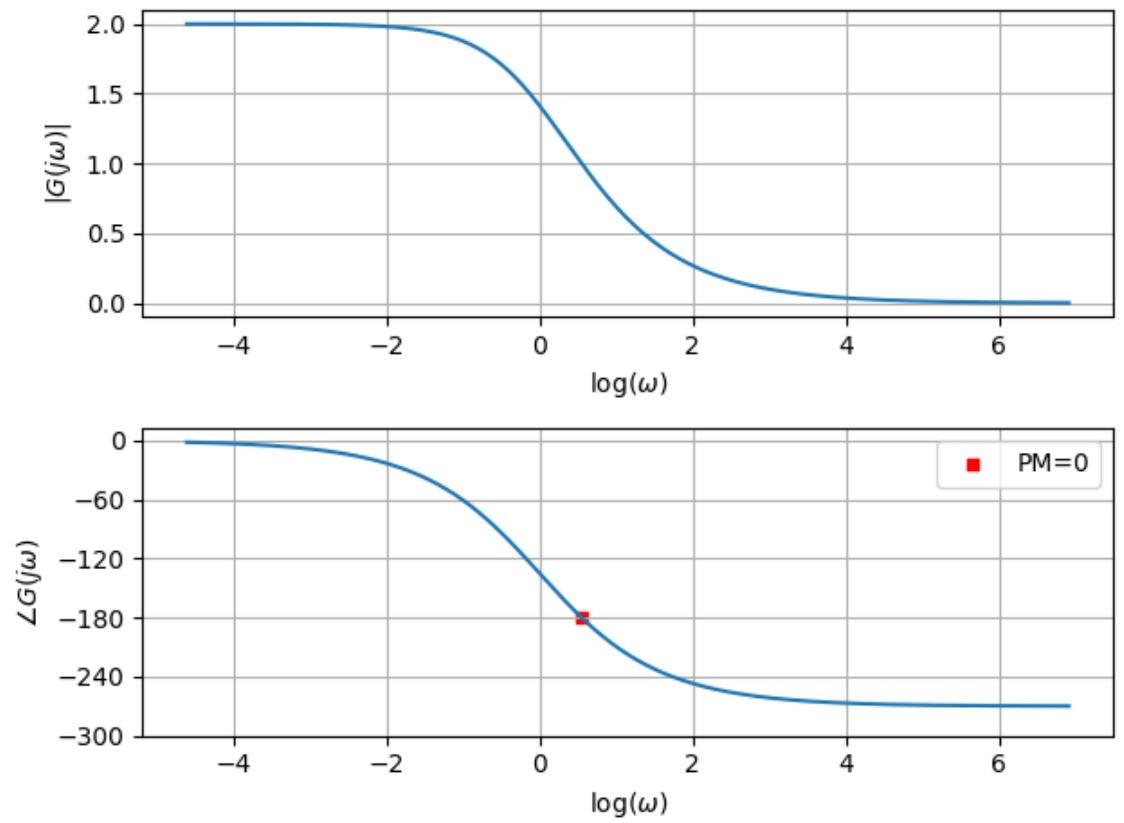


Figure 8.16: Bode Plot of Transfer Function $G(s)$

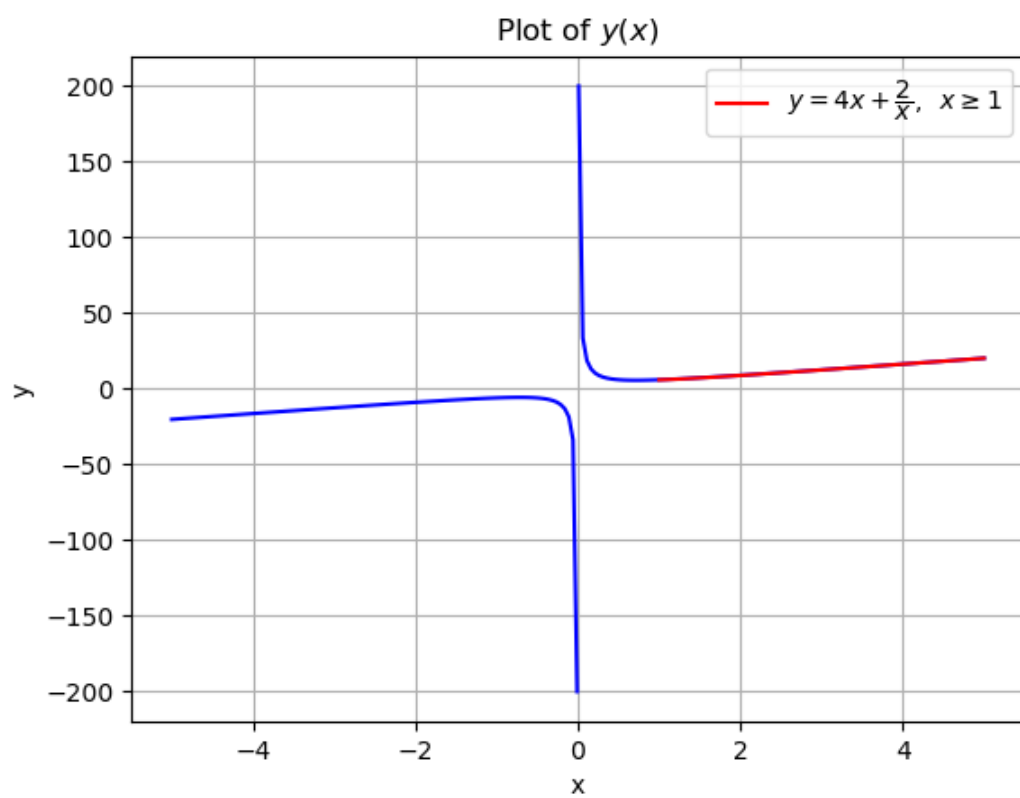


Figure 8.17: Plot of $y(x)$ v/s x

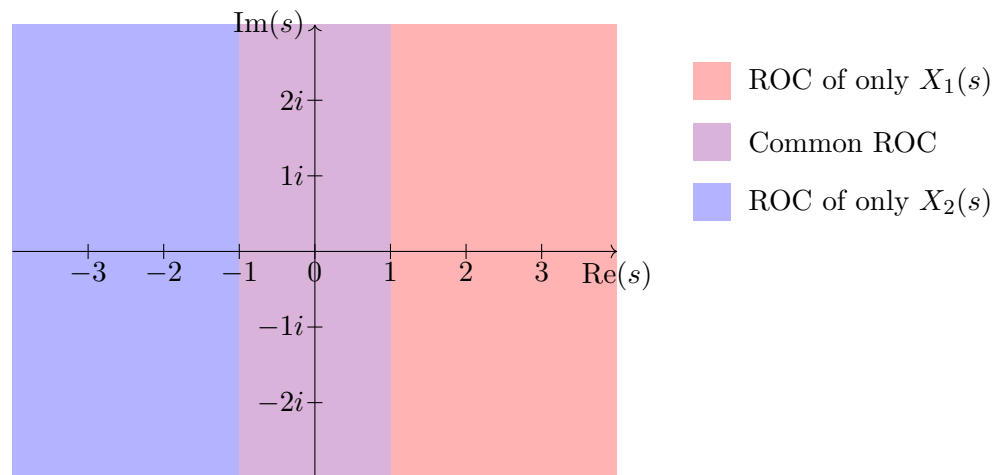
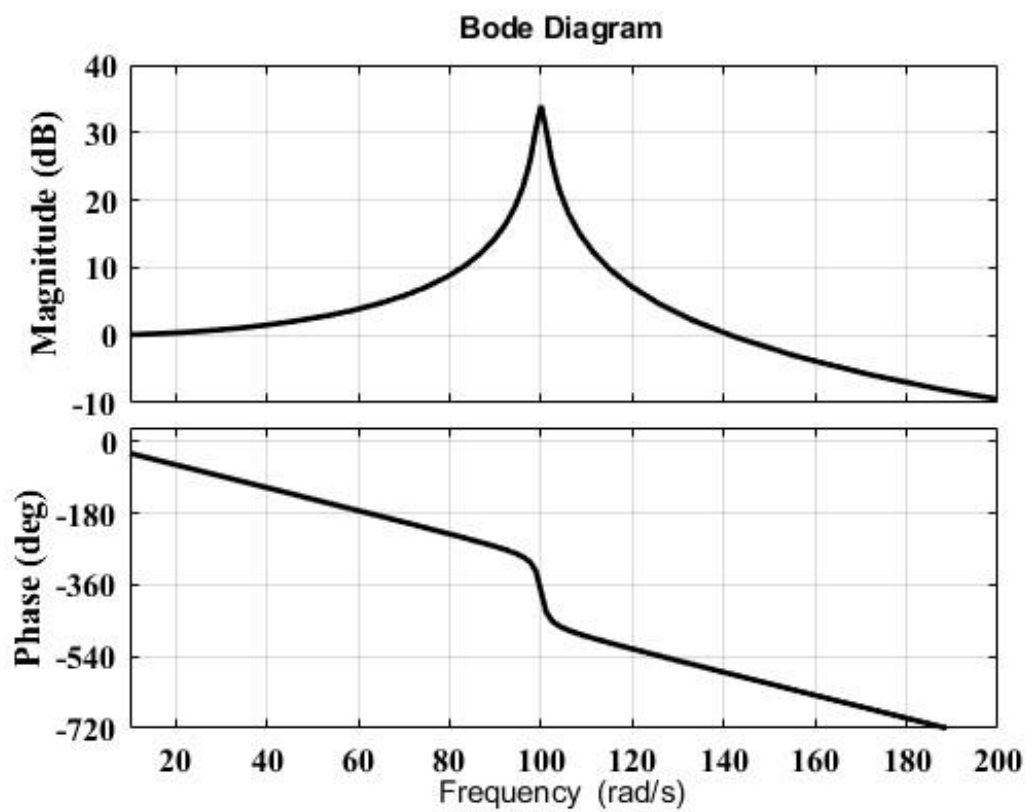


Figure 8.18: Representation of ROCs of $X_1(s)$ and $X_2(s)$



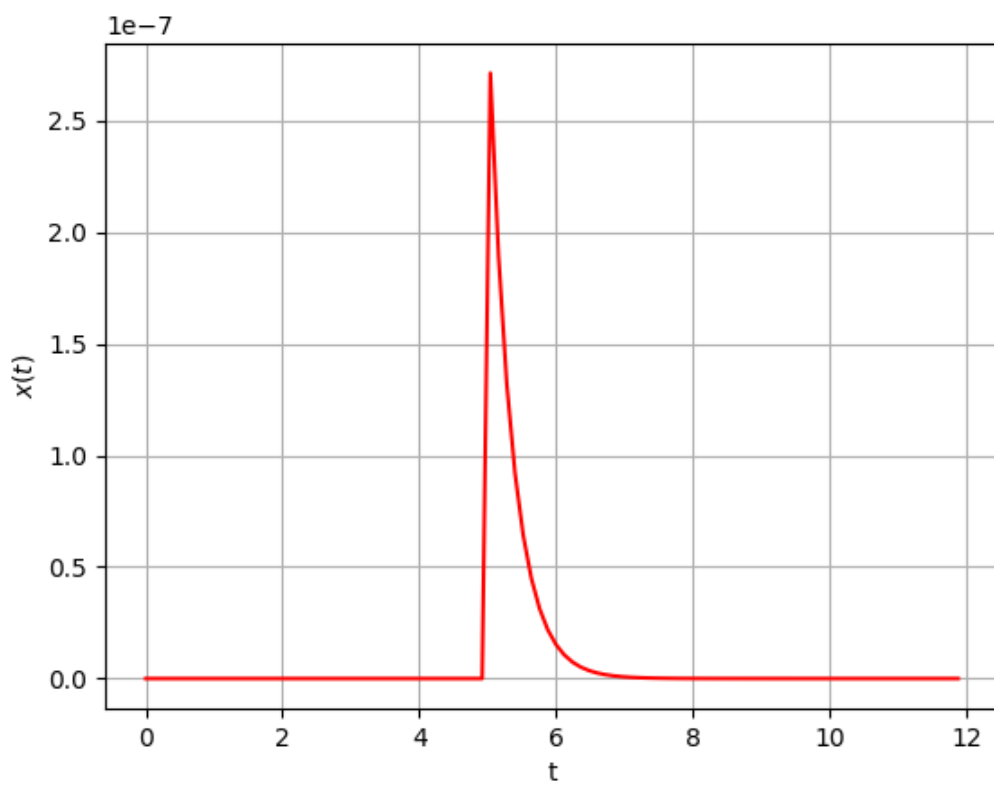


Figure 3: Plot of $x(t)$ vs t . See Table 1

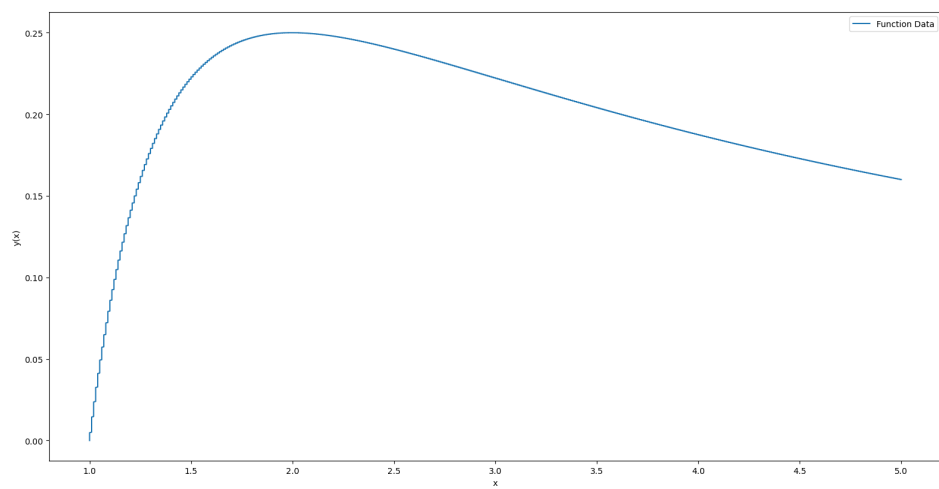


Figure 8.20: Plot of $y(x)$ vs x

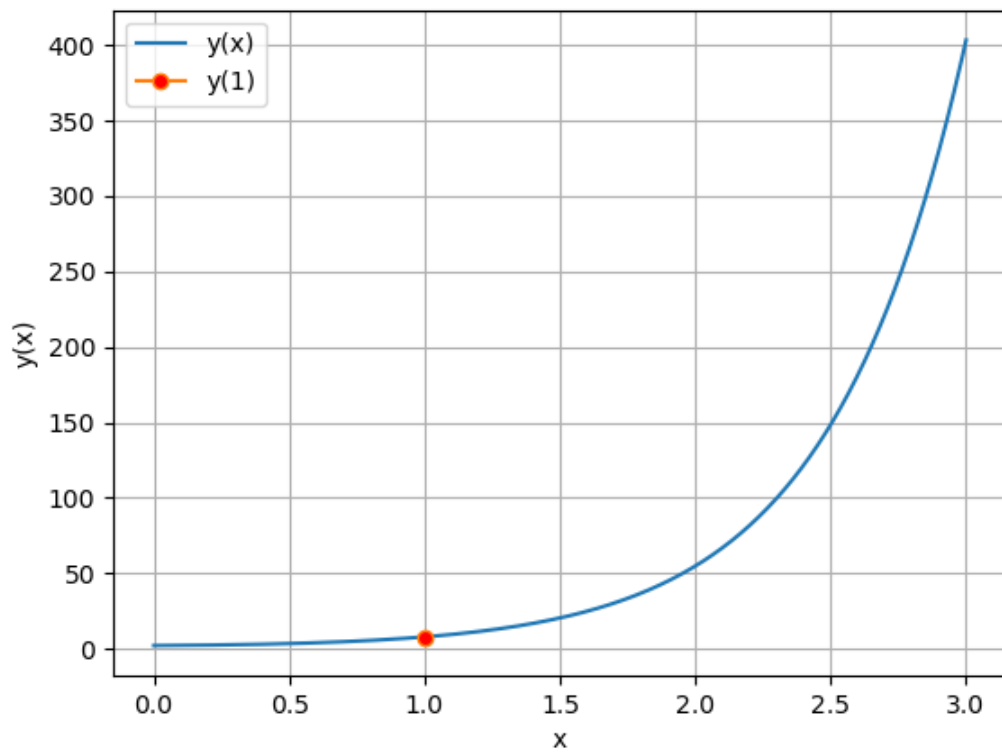


Figure 8.21: Plot of $y(x)$

Chapter 9

Fourier transform

9.1 Let a frequency modulated (FM) signal : $x(t) = A \cos(\omega_c t + k_f \int_{-\infty}^t m(\lambda) d\lambda)$, where $m(t)$ is a message signal of bandwidth W . It is passed through a non-linear system with output $y(t) = 2x(t) + 5(x(t))^2$. Let B_T denote the FM bandwidth. The minimum value of ω_c required to recover $x(t)$ from $y(t)$ is:

(A) $B_T + W$

(B) $\frac{3}{2}B_T$

(C) $2B_T + W$

(D) $\frac{5}{2}B_T$

Solution:

9.2 Let an input $x[n]$ having discrete-time Fourier transform $X(e^{j\Omega}) = 1 - e^{-j\Omega} + 2e^{-3j\Omega}$ be passed through an LTI system. The frequency response of the LTI system is $H(e^{j\Omega}) = 1 - \frac{1}{2}e^{-2j\Omega}$. The output $y[n]$ of the system is
(GATE EC 2023) **Solution:**

9.3 The Fourier transform $X(\omega)$ of $x(t) = e^{-t^2}$ is

Note: $\int_{-\infty}^{\infty} e^{-y^2} dy = \sqrt{\pi}$

A) $\sqrt{\pi} e^{\frac{\omega^2}{2}}$

B) $\frac{e^{-\frac{\omega^2}{4}}}{2\sqrt{\pi}}$

C) $\sqrt{\pi} e^{-\frac{\omega^2}{4}}$

D) $\sqrt{\pi} e^{-\frac{\omega^2}{2}}$

Gate 2023 EC Question 28

9.4 Let $x(t) = 10 \cos(10.5\omega t)$ be passed through an LTI system with impulse response

$h(t) = \pi \left(\frac{\sin(\omega t)}{\pi t} \right)^2 \cos(10\omega t)$. The output of the system is:

(GATE EC 2023) **Solution:**

9.5 Q27) Let $m(t)$ be a strictly band-limited signal with bandwidth B and energy E . Assuming $\omega_0 = 10B$, the energy in the signal $m(t) \cos(\omega_0 t)$

(A) $\frac{E}{4}$

(B) $\frac{E}{2}$

(C) E

(D) $2E$

(GATE EC 2023)

Solution:

9.6 The following function is defined over the interval $[-L, L]$:

$$f(x) = px^4 + qx^5$$

It is expressed as a Fourier series,

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left\{ a_n \sin\left(\frac{\pi x}{L}\right) + b_n \cos\left(\frac{\pi x}{L}\right) \right\}$$

which options amongst the following are true?

- (a) $a_n, n = 1, 2, \dots, \infty$ depend on p
- (b) $a_n, n = 1, 2, \dots, \infty$ depend on q
- (c) $b_n, n = 1, 2, \dots, \infty$ depend on p
- (d) $b_n, n = 1, 2, \dots, \infty$ depend on q

(GATE 2023 CE Question 25)

Solution:

9.7 A continuous real-valued signal $x(t)$ has finite positive energy and $x(t) = 0, \forall t < 0$. From the list given below, select ALL the signals whose continuous-time Fourier transform is purely imaginary.

- (a) $x(t) + x(-t)$
- (b) $x(t) - x(-t)$
- (c) $j(x(t) + x(-t))$
- (d) $j(x(t) - x(-t))$

(GATE IN 2023)

Solution:

| Parameter | Description |
|-----------|-------------------------------|
| $x(t)$ | Continuous real valued signal |
| t | time |
| f | frequency of the signal |
| $Y(f)$ | Fourier Transform of $y(t)$ |

Table 9.1: Variables and their descriptions

Fourier transform of a signal $y(t)$

$$\mathcal{F}\{y(t)\} = Y(f) \quad (9.1)$$

$$Y(f) = \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.2)$$

$$Y^*(f) = \int_{-\infty}^{\infty} y^*(t) e^{j2\pi ft} dt \quad (9.3)$$

Fourier transform is purely imaginary if $Y(f) + Y^*(f) = 0$

(a) $x(t) + x(-t)$

$$y(t) = x(t) + x(-t) \quad (9.4)$$

$$y^*(t) = y(t) \quad (9.5)$$

$$y(t) = y(-t) \quad (9.6)$$

$$Y(f) + Y^*(f) = \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt + \int_{-\infty}^{\infty} y^*(t) e^{j2\pi ft} dt \quad (9.7)$$

$$= 2 \int_{-\infty}^{\infty} y(t) \cos(2\pi ft) dt \quad (9.8)$$

\therefore Fourier Transform is Purely real.

(b) $x(t) - x(-t)$

$$y(t) = x(t) - x(-t) \quad (9.9)$$

$$y^*(t) = y(t) = -y(-t) \quad (9.10)$$

$$Y(f) = \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.11)$$

$$Y^*(f) = - \int_{-\infty}^{\infty} y(-t) e^{j2\pi ft} dt \quad (9.12)$$

$$= - \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.13)$$

$$Y(f) + Y^*(f) = 0 \quad (9.14)$$

\therefore Fourier Transform is purely imaginary.

$$(c) \quad j(x(t) + x(-t))$$

$$y(t) = j(x(t) + x(-t)) \quad (9.15)$$

$$y(-t) = y(t) \quad (9.16)$$

$$y^*(t) = -y(t) \quad (9.17)$$

$$Y(f) = \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.18)$$

$$Y^*(f) = - \int_{-\infty}^{\infty} y(t) e^{j2\pi ft} dt \quad (9.19)$$

$$= - \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.20)$$

$$Y(f) + Y^*(f) = 0 \quad (9.21)$$

\therefore Fourier Transform is Purely imaginary.

(d) $j(x(t) - x(-t))$

$$y(t) = j(x(t) - x(-t)) \quad (9.22)$$

$$y(-t) = -y(t) \quad (9.23)$$

$$y^*(t) = -y(t) \quad (9.24)$$

$$Y(f) = \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.25)$$

$$Y^*(f) = - \int_{-\infty}^{\infty} y(t) e^{j2\pi ft} dt \quad (9.26)$$

$$= \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.27)$$

$$Y(f) + Y^*(f) = 2 \int_{-\infty}^{\infty} y(t) e^{-j2\pi ft} dt \quad (9.28)$$

\therefore Fourier Transform is not Purely imaginary.

9.8 Let $x_1(t) = u(t + 1.5) - u(t - 1.5)$ and $x_2(t)$ is shown in the figure below. For

$y(t) = x_1(t) * x_2(t)$, the $\int_{-\infty}^{\infty} y(t) dt$ is _____.

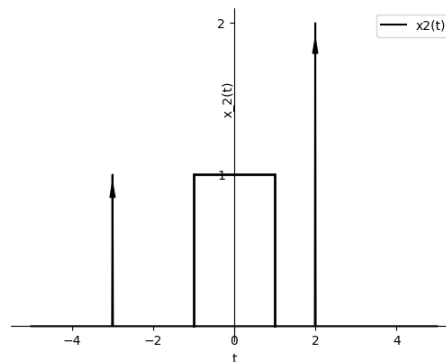


Figure 9.1: Figure

(GATE IN 2023)

Solution:

| Input Parameters | | |
|------------------|--|--|
| Function | Expression | Description |
| $x_1(t)$ | $u(t + 1.5) - u(t - 1.5)$ | Step function with delay and width parameters. |
| $X_1(f)$ | | Fourier Transform of $x_1(t)$. |
| $x_2(t)$ | $\delta(t + 3) + \text{rect}\left(\frac{t}{2}\right) + 2\delta(t - 2)$ | Impulse function followed by a rectangle and two impulses. |
| $X_2(f)$ | | Fourier Transform of $x_2(t)$. |

Table 9.2: Input Parameters

$$x_1(t) = u(t + 1.5) - u(t - 1.5) \quad (9.29)$$

$$x_1(t) = \text{rect}\left(\frac{t}{3}\right) \quad (9.30)$$

$$(9.31)$$

The Fourier Transform of $\text{rect}\left(\frac{t}{a}\right)$:

$$\text{rect}\left(\frac{t}{a}\right) \xleftrightarrow{\mathcal{F}} a \times \sin(2\pi f \frac{a}{2}) \quad (9.32)$$

$$\text{where } \text{rect}\left(\frac{t}{a}\right) = \begin{cases} 1 & \text{if } |t| < \frac{a}{2} \\ 0 & \text{otherwise} \end{cases} \quad (9.33)$$

$$X_1(f) = 3\text{sinc}(1.5 \cdot 2\pi f) \quad (9.34)$$

$$x_2(t) = \delta(t+3) + \text{rect}\left(\frac{t}{2}\right) + 2\delta(t-2) \quad (9.35)$$

$$X_2(f) = e^{3j \cdot 2\pi f} + 2\text{sinc}(2\pi f) + 2e^{-2j \cdot 2\pi f} \quad (9.36)$$

$$Y(f) = X_1(f) \cdot X_2(f) \quad (9.37)$$

$$Y(f) = 3\text{sinc}(1.5 \cdot 2\pi f) \cdot (e^{3j \cdot 2\pi f} + 2\text{sinc}(2\pi f) + 2e^{-2j \cdot 2\pi f}) \quad (9.38)$$

$$y(t) = x_1(t) * x_2(t) \quad (9.39)$$

$$Y(f) \xleftrightarrow{\mathcal{F}} y(t) \quad (9.40)$$

$$y(t) = \text{rect}\left(\frac{t+3}{3}\right) + 2\text{rect}\left(\frac{t-2}{3}\right) + (t+2.5)u(t+2.5) + (t-2.5)u(t-2.5) \quad (9.41)$$

$$- (t+0.5)u(t+0.5) - (t-0.5)u(t-0.5) \quad (9.42)$$

$$Y(f) = \int_{-\infty}^{\infty} y(t)e^{-j2\pi ft} dt \quad (9.43)$$

$$\int_{-\infty}^{\infty} y(t) dt = Y(0) \quad (9.44)$$

$$Y(0) = 3\text{sinc}(0) \cdot (e^0 + 2\text{sinc}(0) + 2e^0) \quad (9.45)$$

$$= 3 \cdot (1 + 2 + 2) \quad (9.46)$$

$$= 15 \quad (9.47)$$

Therefore, the value of $\int_{-\infty}^{\infty} y(t) dt$ is 15

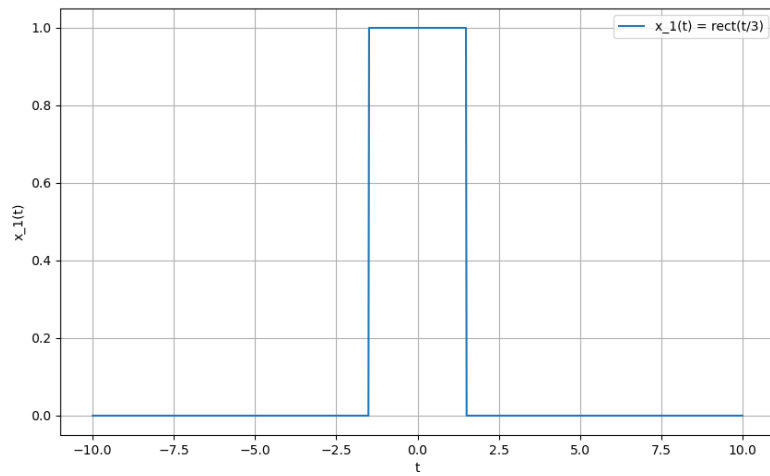


Figure 9.2: Graph of $x_1(t) = \text{rect}\left(\frac{t}{3}\right)$

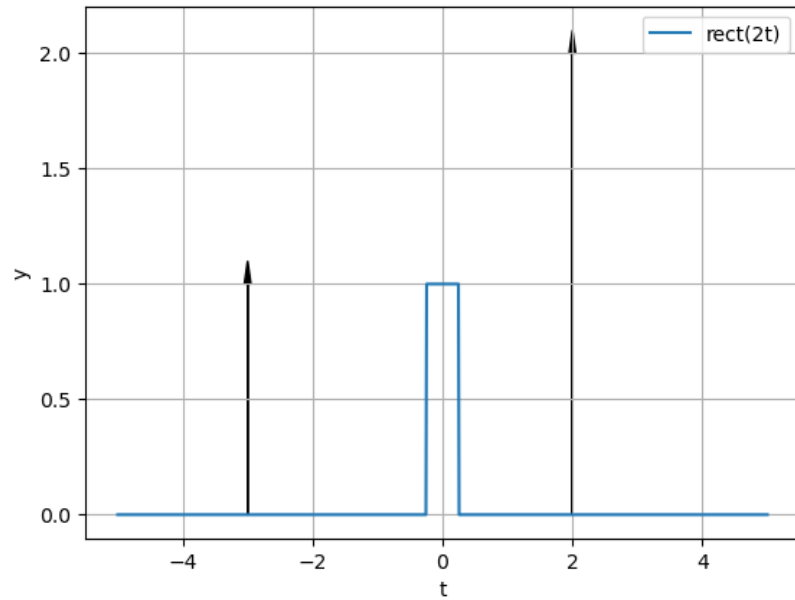


Figure 9.3: Graph of $x_2(t) = \delta(t+3) + \text{rect}(2t) + 2\delta(t-2)$

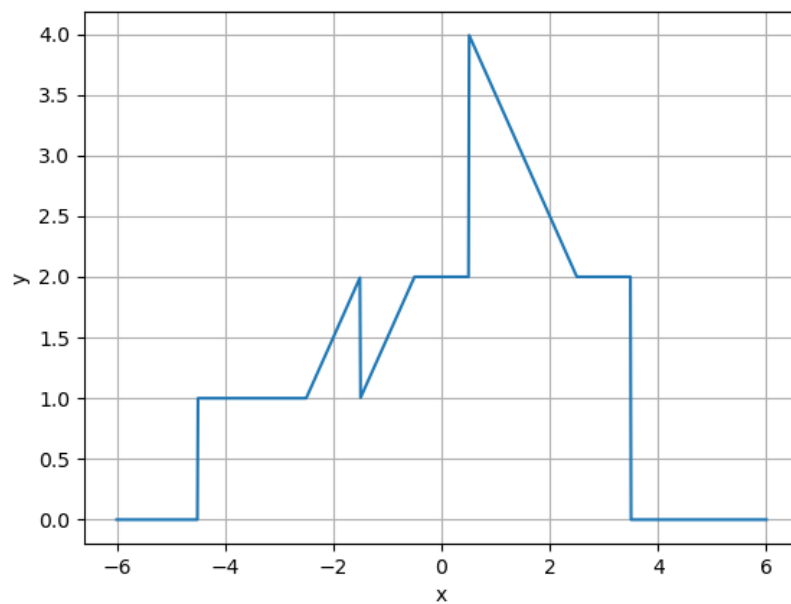


Figure 9.4: Graph of $y(t)$

- 9.9 Consider a discrete-time signal with period $N = 5$. Let the discrete-time Fourier series (DTFS) representation be $x[n] = \sum_{k=0}^4 a_k e^{\frac{jk2\pi n}{5}}$ where $a_0 = 1$, $a_1 = 3j$, $a_2 = 2j$, $a_3 = -2j$, $a_4 = -3j$. The value of the sum $\sum_{n=0}^4 x[n] \sin\left(\frac{4\pi n}{5}\right)$ is
- (A) -10
 - (B) 10
 - (C) -2
 - (D) 2

Gate 2023 EC 47 **Solution:**

9.10 A continuous time, band-limited signal $x(t)$ has its Fourier transform described by:

$$X(f) = \begin{cases} 1 - \frac{|f|}{200} & \text{if } |f| \leq 200 \\ 0 & \text{if } |f| > 200 \end{cases}$$

The signal is uniformly sampled at a sampling rate of 600 Hz. The Fourier transform of the signal is $X_s(f)$. What is the value of $\frac{X_s(600)}{X_s(500)}$?

(GATE 2023 BM) **Solution:**

9.11 The magnitude and phase plots of an LTI systems are shown in figure. Find the transfer function.

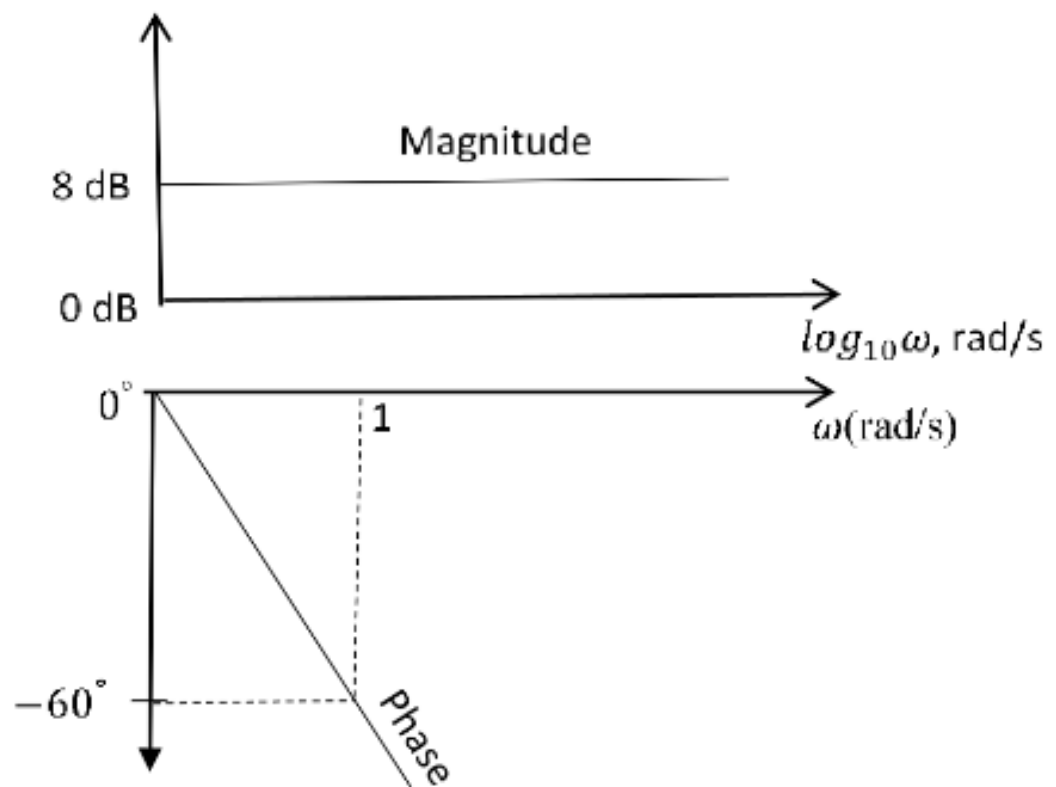


Figure 9.5:

(a) $2.511e^{-0.0032s}$

(b) $\frac{e^{-2.514s}}{s+1}$

(c) $1.04e^{-2.514s}$

(d) $2.511e^{-1.047s}$

(GATE EE 23)

Solution: From Fig. 9.5

$$|H(j\omega)| = 8 \quad (9.48)$$

$$\angle H(j\omega) = \frac{-\pi}{3}\omega \quad (9.49)$$

Substituting the values from Fig. 9.5, magnitude of transfer function is:

$$8 = 20 \log_{10}(|H(j\omega)|) \quad (9.50)$$

$$|H(j\omega)| = 10^{0.4} = 2.511 \quad (9.51)$$

Substituting the values from Fig. 9.5, The direction of the transfer function is:

$$\frac{H(j\omega)}{|H(j\omega)|} = e^{-j\frac{\pi}{3}\omega} \quad (9.52)$$

$$H(j\omega) = 2.511e^{-j\frac{\pi}{3}\omega} \quad (9.53)$$

$$= 2.511e^{-1.047s} \quad (9.54)$$

9.12 The value of the convolution of $f(x) = 3\cos(2x)$ and $g(x) = \frac{1}{3}\sin(2x)$ where $x \in [0, 2\pi)$, at $x = \frac{\pi}{3}$, is (Rounded off to 2 decimal places)
(GATE 2023 GE)

Solution:

9.13 A system is described by the following differential equation

$$0.01 \frac{d^2 y(t)}{dt^2} + 0.2 \frac{dy(t)}{dt} + y(t) = 6x(t)$$

where time t is in seconds. If $x(t)$ is the unit step input applied at $t = 0$ s to this system, the magnitude of the output at $t = 1$ s is _____. (Round off the answer to two decimal places.) (GATE-2023.BM)

Solution:

9.14 In the differential equation $\frac{dy}{dx} + \alpha xy = 0$, α is a positive constant. If $y = 1.0$ at $x = 0.0$, and $y = 0.8$ at $x = 1.0$, the value of α is (rounded off to three decimal places). (GATE CE 30 2023)

Solution:

| Parameter | Value |
|-----------|-------|
| x | 0.0 |
| | 1.0 |
| y | 1.0 |
| | 0.8 |

Table 9.3: Given parameters

Let, $t = x$

$$\frac{dy}{dt} + \alpha ty = 0 \quad (9.55)$$

$$\int \frac{dy}{y} = - \int \alpha t dt \quad (9.56)$$

$$\ln(|y|) = -\frac{\alpha t^2}{2} + c \quad (9.57)$$

$$y(t) = e^c \cdot e^{-\frac{\alpha t^2}{2}} \quad (9.58)$$

Taking Fourier Transform:

where,

$$\frac{dy}{dt} \xleftrightarrow{\mathcal{F}} j2\pi f Y(f) \quad (9.59)$$

$$\alpha ty(t) \xleftrightarrow{\mathcal{F}} \alpha \frac{j}{2\pi} \frac{d}{df} Y(f) \quad (9.60)$$

From equation (9.59) and (9.60):

$$\frac{4\pi^2 f}{\alpha} Y(f) + \frac{d}{df} Y(f) = 0 \quad (9.61)$$

$$Y(f) = K e^{-\frac{4\pi^2 f^2}{2\alpha}} \quad (9.62)$$

Substituting x and y values:

$$c = \ln(1) = 0 \quad (9.63)$$

$$\alpha = -2 \ln(0.8) = 0.446 \quad (9.64)$$

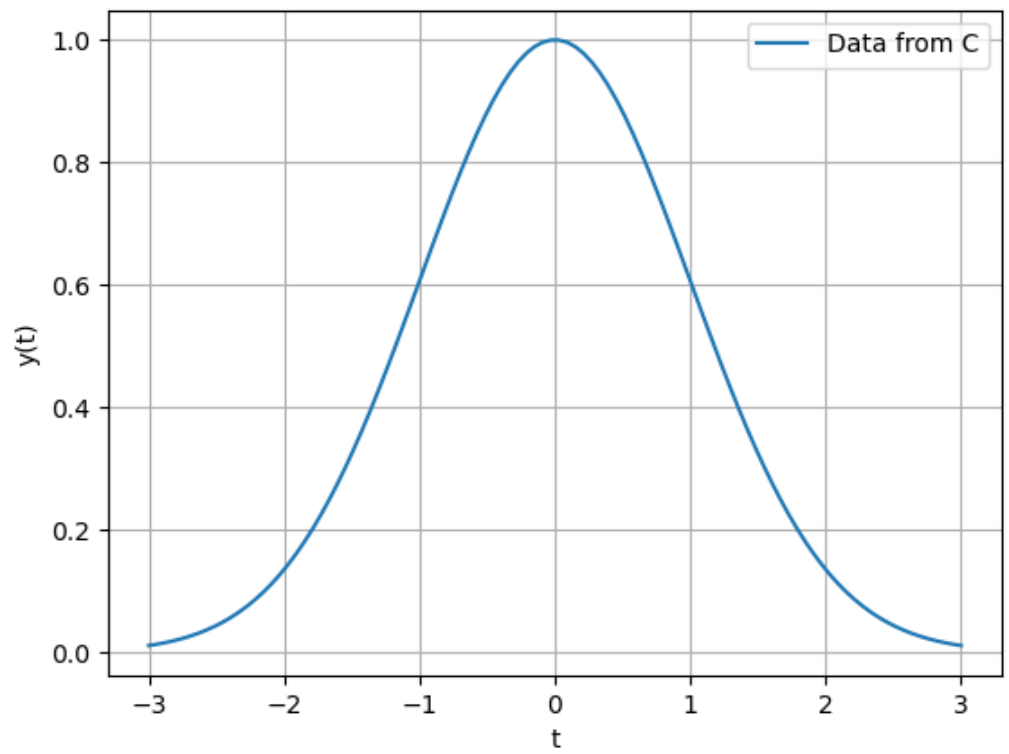


Figure 9.2: Graph of $y(t)$

Chapter 10

FFT

10.1 The discrete-time Fourier transform of a signal $x[n]$ is $X(\Omega) = (1 + \cos \Omega) e^{-j\Omega}$.

Consider that $x_p[n]$ is a periodic signal of period $N = 5$ such that

$$x_p[n] = x[n], \text{ for } n = 0, 1, 2 \quad (10.1)$$

$$= 0, \text{ for } n = 3, 4 \quad (10.2)$$

Note that $x_p[n] = \sum_{k=0}^{N-1} a_k e^{j\frac{2\pi}{N}kn}$. The magnitude of the Fourier series coefficient a_3 is _____ (Round off to 3 decimal places). (GATE EE 2023) **Solution:**

Using Euler's form of representation of complex numbers,

$$e^{j\Omega} = \cos \Omega + j \sin \Omega \quad (10.3)$$

$X(\Omega)$ can be expressed as,

$$X(\Omega) = \frac{1}{2} + e^{-j\Omega} + \frac{e^{-j2\Omega}}{2} \quad (10.4)$$

| Symbol | Value | Description |
|-------------|---|----------------------|
| $X(\Omega)$ | $(1 + \cos \Omega) e^{-j\Omega}$ | Frequency function |
| Ω | ωF_s | angular frequency |
| ω | $\omega \in (-\pi, \pi)$ | radian frequency |
| F_s | $1Hz$ | Sampling frequency |
| $X(\omega)$ | $\sum_{n=-\infty}^{\infty} x(n) e^{-j\omega n}$ | D.T.F.T |
| $x(n)$ | $x(n)$ | Signal |
| $X(k)$ | $\frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-\frac{j2\pi}{N} kn}$ | Fourier coefficient |
| N | 5 | Period of the signal |

Table 10.1: variable description

As sampling frequency is $1Hz$ ($\omega = \Omega$) from DTFT(discrete time fourier transform) we get,

$$X(\Omega) = \sum_{n=0}^{n=2} x(n) e^{-j\Omega n}, \Omega \in (-\pi, \pi) \quad (10.5)$$

$$\Rightarrow \sum_{n=0}^{n=2} x(n) e^{-j\Omega n} = \frac{1}{2} + e^{-j\Omega} + \frac{e^{-j2\Omega}}{2} \quad (10.6)$$

On comparing coefficients we get,

$$x(n) = \left\{ \frac{1}{2}, 1, \frac{1}{2} \right\}$$

$$x_p(n) = \left\{ \frac{1}{2}, 1, \frac{1}{2}, 0, 0 \right\} \text{ with period, } N=5 \quad (10.7)$$

$$X(3) = \frac{1}{5} \sum_{n=0}^4 x(n) e^{-j\frac{6\pi}{5}n} \quad (10.8)$$

$$|X(3)| = 0.038 \quad (10.9)$$

| Fourier series coef- ficient | Real part | Imaginary part |
|------------------------------------|-----------|----------------|
| X(0) | 0.4000 | 0 |
| X(1) | 0.081 | -0.249 |
| X(2) | -0.031 | -0.225 |
| X(3) | -0.031 | 0.225 |
| X(4) | 0.081 | 0.249 |

Table 10.2: variable description

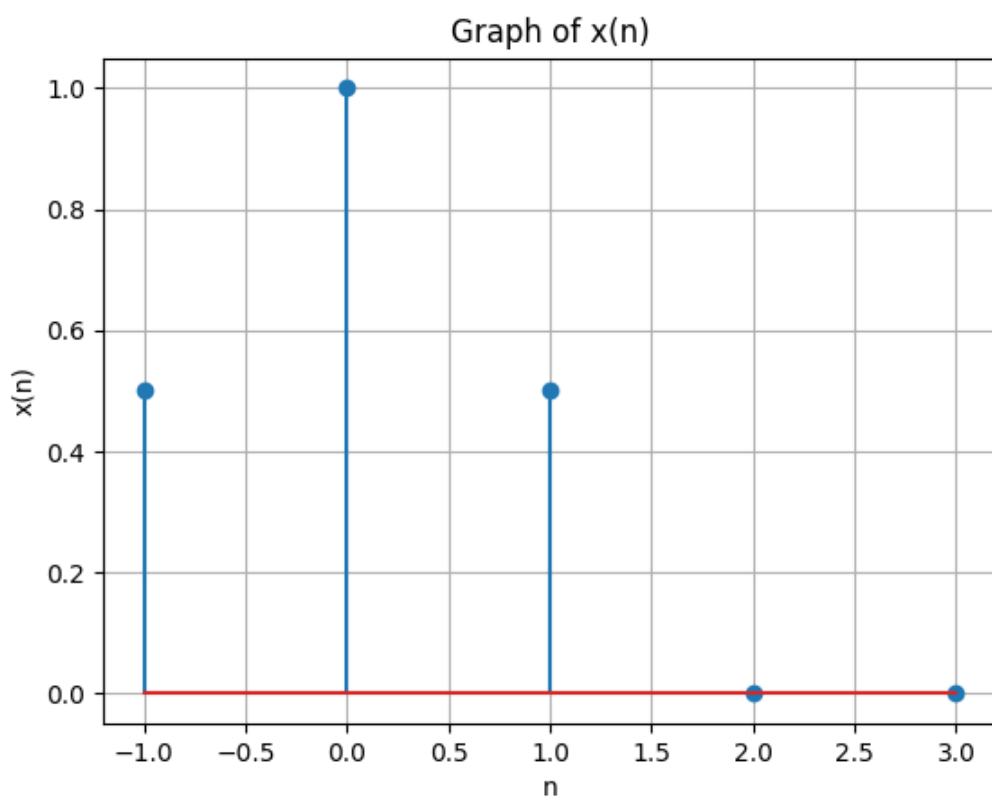


Figure 10.1: Plot of $x(n)$ *vs* n

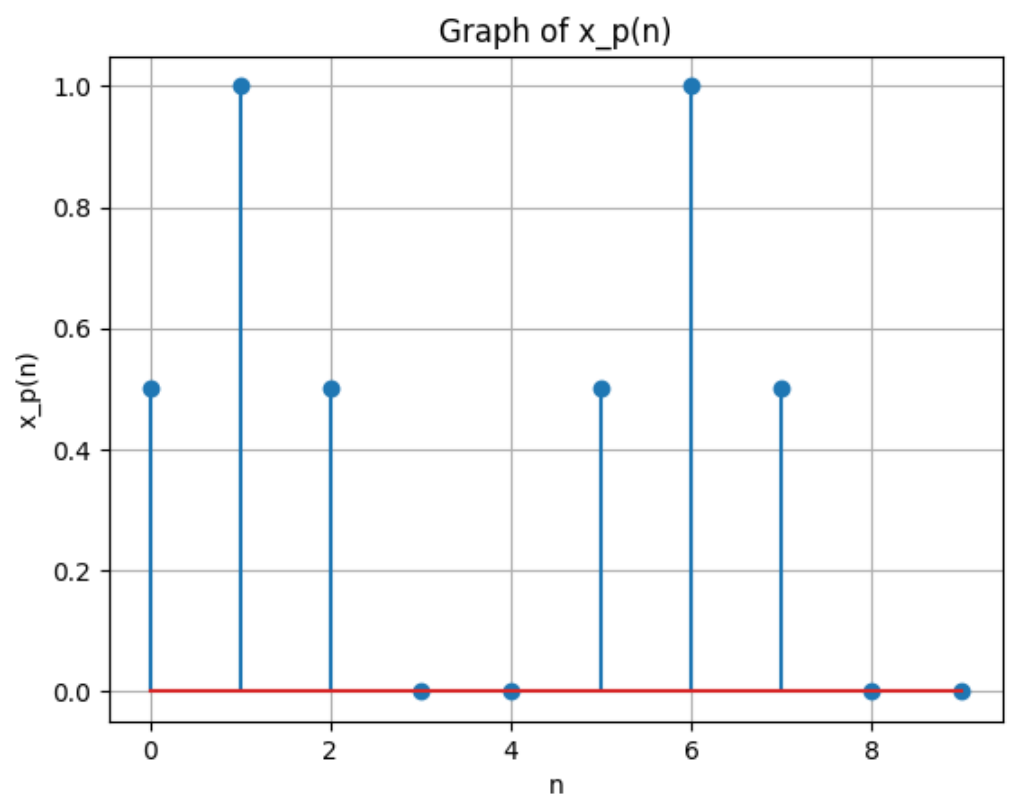


Figure 10.2: Plot of $x_p(n)$ vs n

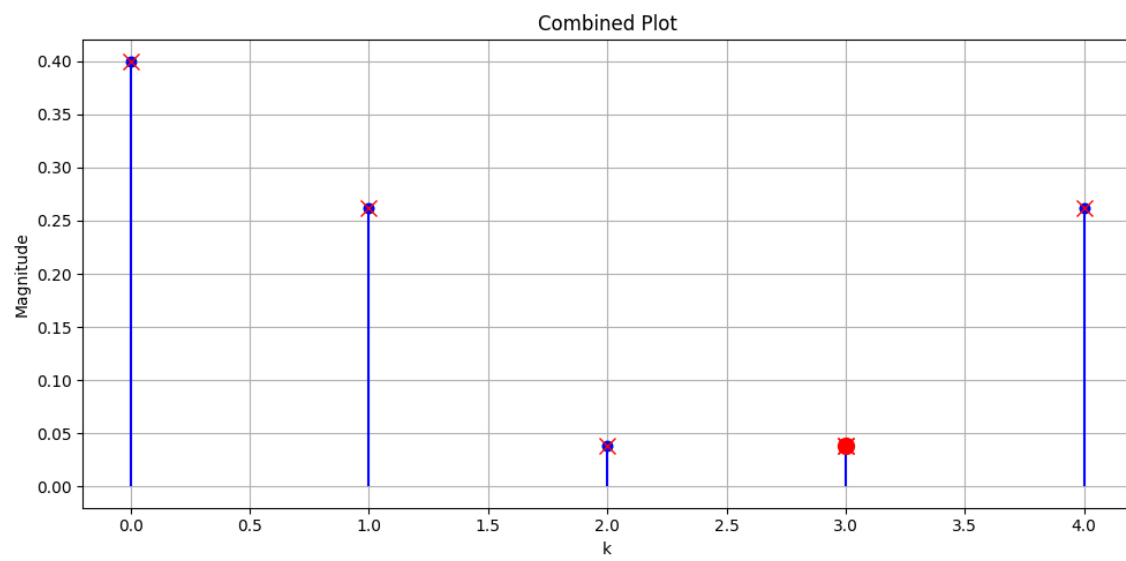


Figure 10.3: Plot of $x_p(n)$ vs n

Chapter 11

Filter Design

11.1 The time-dependent growth of a bacterial population is governed by the equation

$$\frac{dx}{dt} = x \left(1 - \frac{x}{200} \right) \tag{11.1}$$

where x is the population size at time t . The initial population size is $x_0 = 100$ at $x = 0$. As $t \rightarrow \infty$, the population size of bacteria asymptotically approaches ...

(GATE BM 2023) **Solution:** The growth equation is given by,

| Parameters | Values | Description |
|------------|--------|---------------------------------------|
| t | | Time, Independent variable |
| $x(t)$ | | Population size at any time |
| $x(0)$ | 100 | Initial population |
| h | | Step size |
| $x(n)$ | | Discrete-Time approximation of $x(t)$ |

Table 11.1: Parameters

$$\frac{dx}{dt} = x \left(1 - \frac{x}{200} \right) \quad (11.2)$$

$$dx(t)dt = \frac{1}{200} x (200 - x) \quad (11.3)$$

$$\frac{1}{200} \left(\int_0^{x(t)} \frac{dx}{200 - x} + \int_0^{x(t)} \frac{dx}{x} \right) = \int_0^t \frac{dt}{200} \quad (11.4)$$

$$-\ln(200 - x)|_{100}^{x(t)} + \ln(x)|_{100}^{x(t)} = t \quad (11.5)$$

$$\frac{x(t)}{200 - x(t)} = e^t \quad (11.6)$$

$$\Rightarrow x(t) = \frac{200}{1 + e^{-t}} \quad (11.7)$$

We can also express the growth equation as,

$$\int_0^{x(t)} dx = \int_0^t x dt - \frac{1}{200} \int_0^t x^2 dt \quad (11.8)$$

Now approximating by trapezoidal rule of integration between t_{n-1} to t_n with the step size being h we have,

$$\begin{aligned} x(t_n) - x(t_{n-1}) &= \frac{h}{2} [x(t_n) + x(t_{n-1})] - \\ &\quad \frac{h}{400} [x^2(t_n) + x^2(t_{n-1})] \end{aligned} \quad (11.9)$$

Next, replacing $t_n = hn$ we get the difference equation,

$$x(hn) = \frac{-(1 - \frac{h}{2}) + \sqrt{(1 - \frac{h}{2})^2 + \frac{h}{100}p_1}}{h/200} \quad (11.10)$$

Where,

$$p_1 = \left[\left(1 - \frac{h}{2} \right) x(h(n-1)) - \frac{h}{400} x^2(h(n-1)) \right] \quad (11.11)$$

And relabeling $hn \longleftrightarrow n$ we will be having the discrete time equation as,

$$x(n) = \frac{-(1 - \frac{h}{2}) + \sqrt{(1 - \frac{h}{2})^2 + \frac{h}{100}p_2}}{h/200} \quad (11.12)$$

Where,

$$p_2 = \left[\left(1 - \frac{h}{2}\right) x(n-1) - \frac{h}{400} x^2(n-1) \right] \quad (11.13)$$

Now, plotting both the differential and the difference equations,

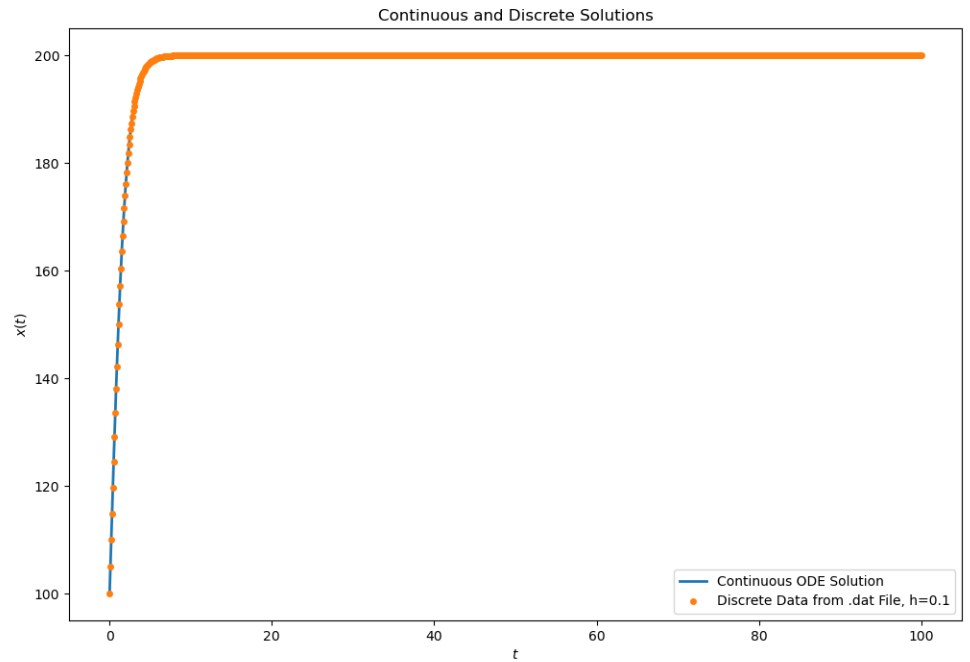


Figure 11.1: Plot in Continuous and Discrete Time

As we can see the discrete time plot is following the actual curve, which means (11.12) is indeed a good approximation of the original continuous-time equation.

And the population size approaches to 200 as $t \rightarrow \infty$.