SIGNAL PROCESSING FUNDAMENTALS Through NCERT

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Contents

Introduction

This book introduces some concepts in signal processing through maths and physics problems in NCERT textbooks.

Chapter 1

Analog

1.1. Harmonics

1.1.1 Suppose that the electric field amplitude of an electromagnetic wave is $E_0 = 120\text{N/C}$ and that its frequency is $f = 50.0$ MHz.

(a) Determine, B_0, ω, k and λ

(b) Find expressions for $\mathbf{E}$ and $\mathbf{B}$

Solution:

Table 1.1: Input Parameters

Symbol	Description	value
f	frequency of source	50.0 MHz
E_0	Electric field amplitude	120 N/C
c	speed of light	3 x 10^8 m/s
$\mathbf{e_2}, \mathbf{e_3}$	Standard Basis vectors	N/A

Table 1.2: Formulae and Output

Symbol	Description	Formula	Value
$\mathbf{E}$	Electric field vector	$E_0 \sin(kx - 2\pi ft)\mathbf{e_2}$	$120 \sin[1.05x - 3.14\text{x}10^8 t]\mathbf{e_2}$
$\mathbf{B}$	Magnetic field vector	$B_0 \sin(kx - 2\pi ft)\mathbf{e_3}$	$(4x10^{-7}) \sin[1.05x - 3.14\text{x}10^8 t]\mathbf{e_3}$
B_0	Magnetic field strength	$\frac{E_0}{c}$	400nT
ω	Angular frequency	$2\pi f$	3.14 x 10^8m/s
k	Propagation constant	$\frac{2\pi f}{c}$	1.05rad/s
λ	Wavelength	$\frac{c}{f}$	6.0m

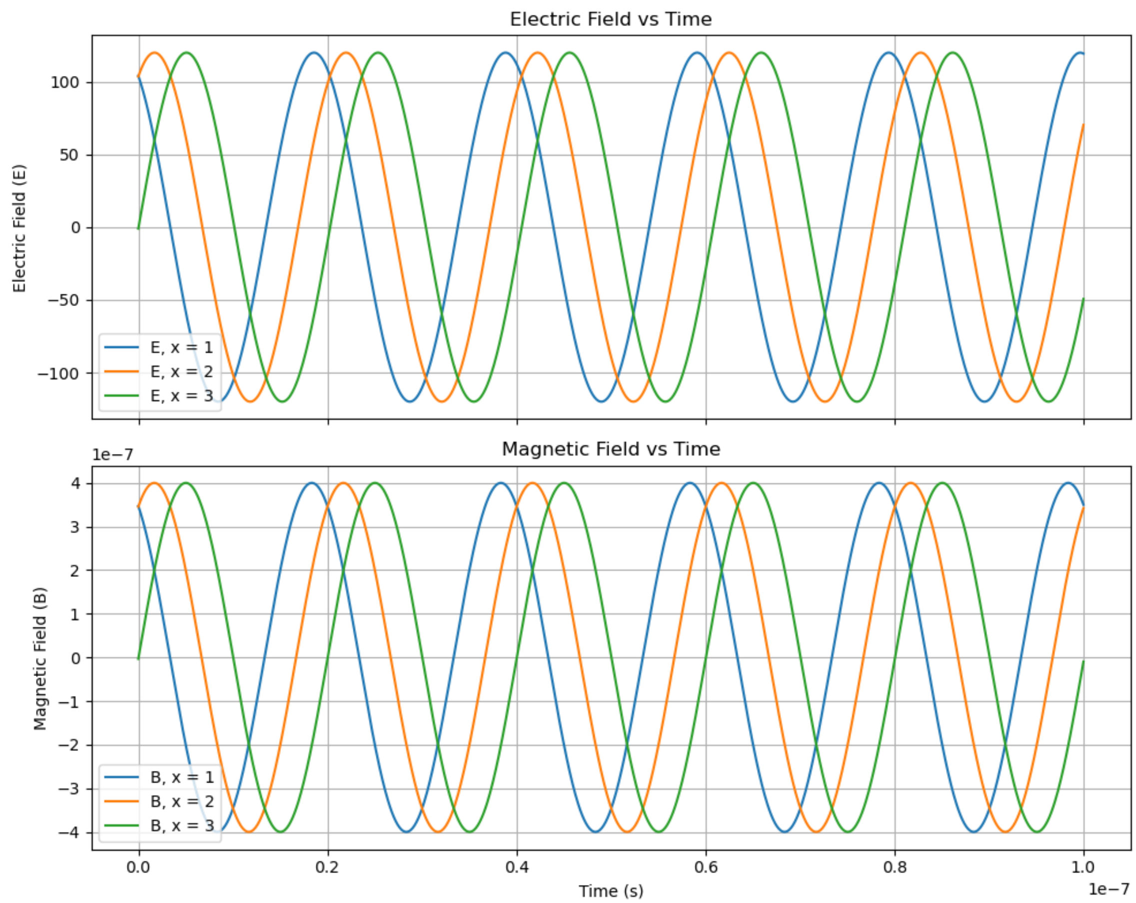


Figure 1.1.1: Graphs of **E** and **B**

1.1.2 A charged particle oscillates about its mean equilibrium position with a frequency of $10^9 Hz$. What is the frequency of the electromagnetic waves produced by the oscillator?

Solution:

Symbol	Value	Description
$y(t)$	$\cos(2\pi f_c t)$	Wave equation of electro-magnetic wave
f_c	10^9	Frequency of electromagnetic wave
t	seconds	Time

Table 1.1.2: Variable description

1.1.3 Given below are some functions of x and t to represent the displacement (transverse or longitudinal) of an elastic wave. State which of these represents (i) travelling wave, (ii) a stationary wave or (iii) none at all:

(a) $y = 2\cos(3x)\sin(10t)$

(b) $y = 2\sqrt{x - vt}$

(c) $y = 3\sin(5x - 0.5t) + 4\cos(5x - 0.5t)$

(d) $y = \cos x \sin t + \cos 2x \sin 2t$

Solution:

TRAVELLING WAVE	STATIONARY WAVE
$y(x,t) = A\sin(kx \pm \omega t)$	$y(x,t) = A\sin kx \cos \omega t$

PARAMETERS	DEFINITION
A	Amplitude
ω	Angular Velocity
x	Position
k	Wavenumber

Table 1.1.3: Travelling wave *vs* Stationary wave

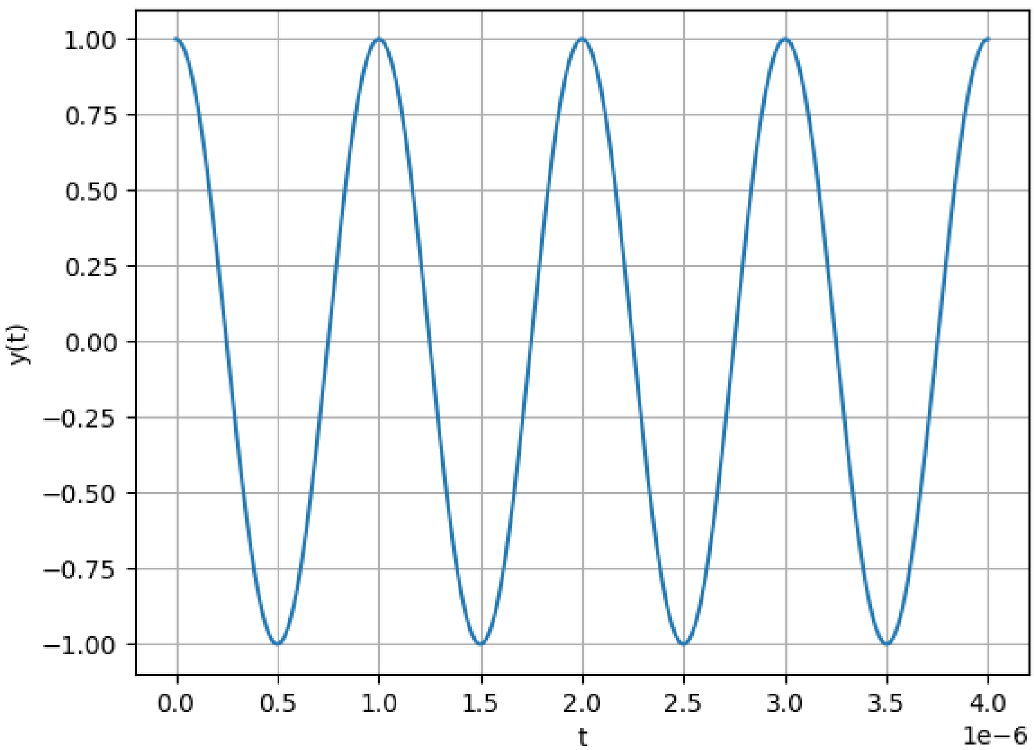


Figure 1.1.2: $y(t) = \cos\left(2\pi \times 10^9 t\right)$

Let us assume an equation:

$$y = A(x)\cos\left(\omega t + \phi\left(x\right)\right) \tag{1.1}$$

Fig. 1.1.3 and Fig. 1.1.3 are self explanatory for stationary and travelling waves.Fig. 1.1.3 and Fig. 1.1.3 are neither stationary nor travelling waves.

STATIONARY WAVE CONDITION	TRAVELLING WAVE CONDITION
(1) $A(x)$ should be a function of position x, and it can be expressed as $A(x) = A_0 cos(\omega t + \alpha)$ where A_0 is a constant, k is the wavenumber, x is the position and α is a phase constant.	(1) $A(x)$ should be a constant, and it can be expressed as $A(x) = A_0$ where A_0 is a constant number.
(2) $\phi(x)$ can be expressed as $\phi(x) = c$ where c is a constant.	(2) $\phi(x)$ represents a linear expression in x, and it can be expressed as $\phi(x) = kx + \theta$ where k is the wavenumber and θ is the phaseconstant.

Table 1.1.3: Travelling wave *vs* Stationary wave

1.1.4 For the travelling harmonic wave $y(x,t) = 2.0 \cos 2\pi (10t - 0.0080x + 0.35)$ where x and y are in cm and t in s. Calculate the phase difference between oscillatory motion of two points separated by a distance of

(a) $4m$

(b) $0.5m$

(c) $\lambda/2$

(d) $3\lambda/4$

Solution:

$$(\Delta\theta) = (2\pi f t - kx_1 + \phi) - (2\pi f t - kx_2 + \phi) \tag{1.2}$$

$$= k(x_2 - x_1) \tag{1.3}$$

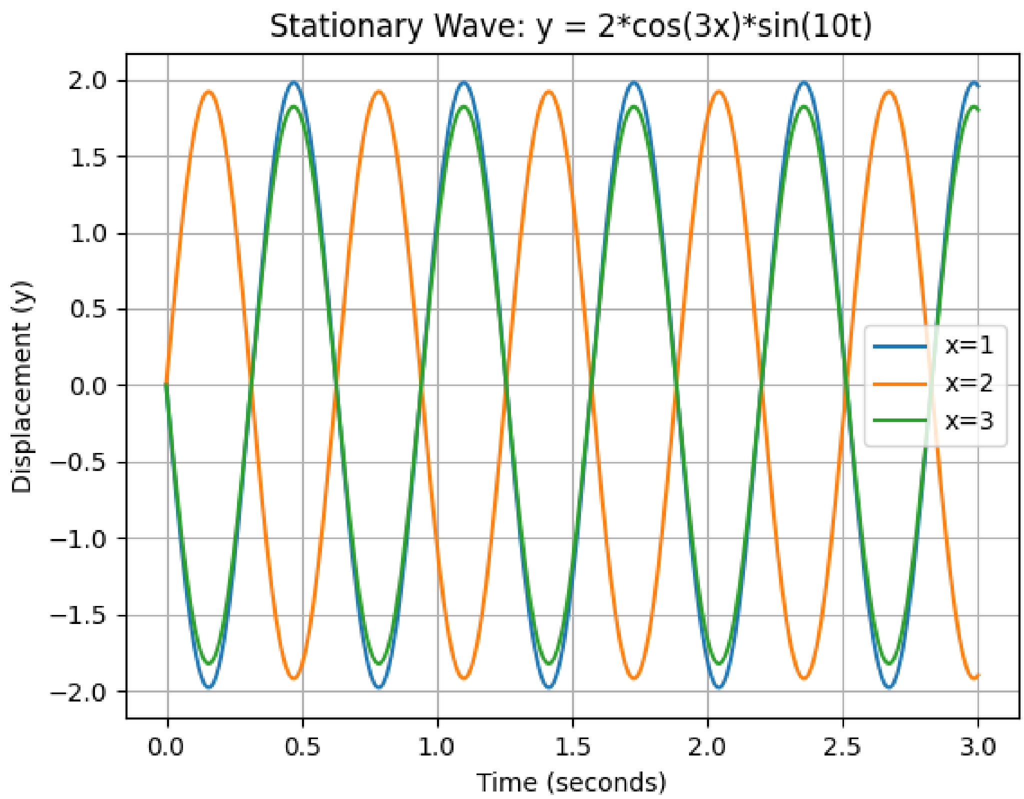


Figure 1.1.3: DIPLACEMENT vs TIME-graph1

1.1.5 (a) The peak voltage of an AC supply is 300 V. What is the rms voltage?

(b) The rms value of current in an AC circuit is 10 A. What is the peak current?

Solution:

Parameter	Description	Value
$y\left(x_i, t\right)$	equation of harmonic wave	$A\cos\left(2\pi ft - kx_i + \phi\right)$
k	angular wave number	$2\pi\left(0.008\right)$
$\lambda = \dfrac{2\pi}{k}$	wavelength	$125\,cm$
f	frequency	10
A	amplitude	2.0
ϕ	phase constant	$2\pi\left(0.35\right)$
θ_i	phase of i^{th} harmonic wave	$\left(2\pi ft - kx + \phi\right)$
x_i	position of i^{th} harmonic wave	
t	time	
$x_2 - x_1$	path difference	$400\,cm$
		$50\,cm$
		$\dfrac{\lambda}{2}$
		$\dfrac{3\lambda}{4}$

Table 1.1.4: Given parameters list

Parameter	Description	subquestion	Value
$\Delta\theta$	$\theta_1 - \theta_2$	(a)	6.4π radians
		(b)	0.8π radians
		(c)	π radians
		(d)	$\dfrac{3\pi}{2}$ radians

Table 1.1.4: Phase differences

parameter	value	description
$V(t)$	$V_0 \cdot \sin(2\pi ft + \phi)$	voltage in terms of time
$I(t)$	$I_0 \cdot \sin(2\pi ft + \phi)$	current in terms of time
V_0	$300\,\mathrm{V}$	peak voltage
V_{rms}	$\sqrt{\frac{1}{T}\int_0^T [V(t)]^2\,dt}$	rms value of Voltage
I_{rms}	$10\,\mathrm{A}$	rms value of current
I_0	$\sqrt{2} \times I_{\mathrm{rms}}$	peak current
f	$50\,\mathrm{Hz}$	frequency of the sinusoidal wave
T	$0.02\,\mathrm{s}$	time period of sinusoidal wave

Table 1.1.5: Input Parameter Table

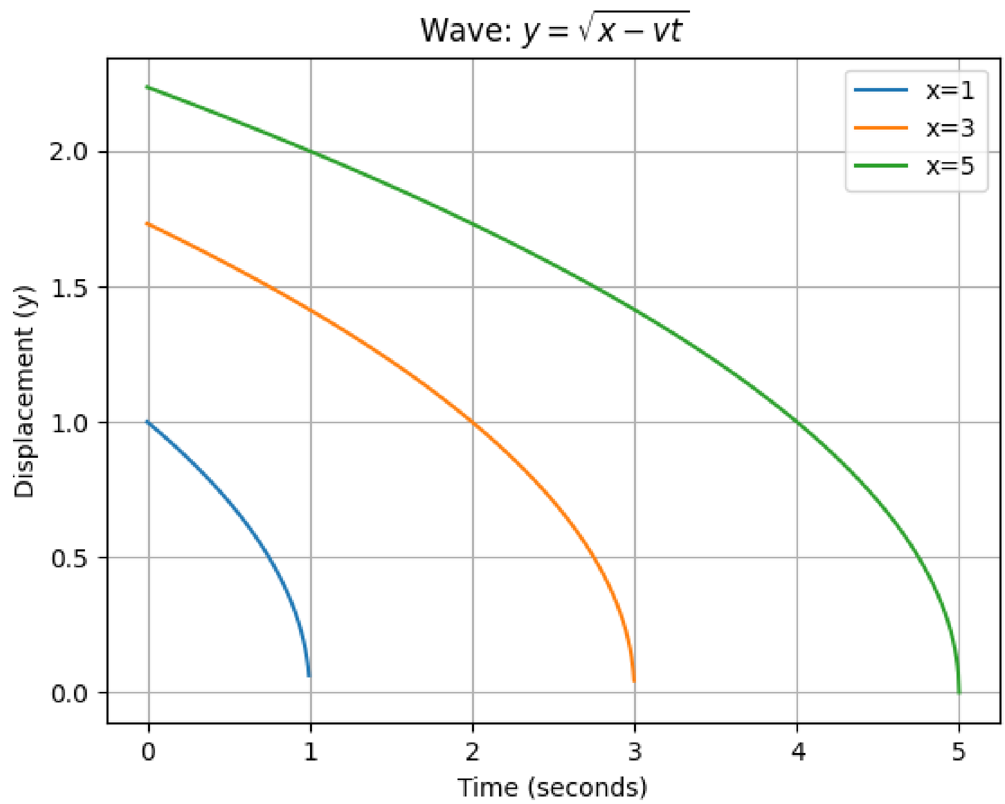


Figure 1.1.3: DIPLACEMENT vs TIME-graph2

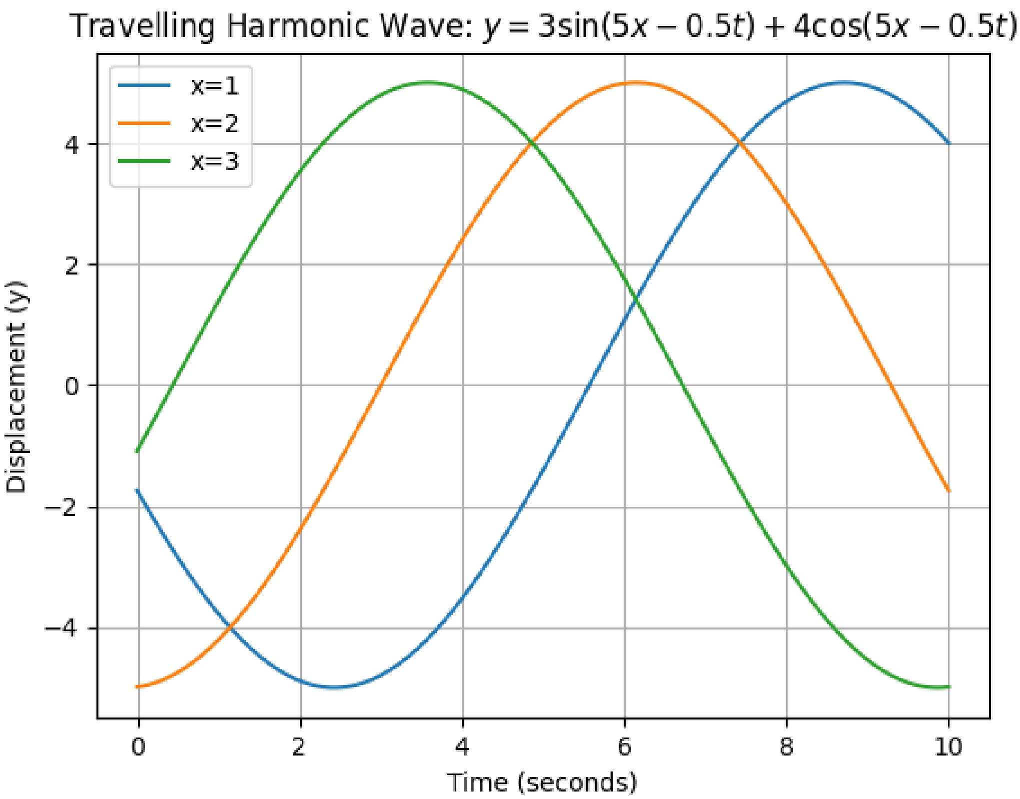


Figure 1.1.3: DIPLACEMENT vs TIME-graph3

(a)

$$
\begin{aligned}
V_{\mathrm{rms}}^2 &= \frac{1}{T}\int_0^T [V(t)]^2\,dt && (1.4)\\
&= f\int_0^{\frac{1}{f}} V_0^2 \cdot \sin^2(2\pi f t + \phi)\,dt && (1.5)\\
&= \frac{1}{2}V_0^2\left(1 - \frac{1}{f}\int_0^{\frac{1}{f}} \cos(4\pi f t + 2\phi)\,dt\right) && (1.6)\\
&= \frac{1}{2}V_0^2\left(1 - \frac{1}{f}\left[\frac{\sin(4\pi f t + 2\phi)}{4\pi f}\right]_0^{\frac{1}{f}}\right) && (1.7)\\
&= \frac{1}{2}V_0^2\left(1 - \frac{1}{f}\cdot\frac{\sin\left(4\pi + 2\phi\right) - \sin(0 + 2\phi)}{4\pi f}\right) && (1.8)\\
V_{\mathrm{rms}} &= \frac{V_0}{\sqrt{2}} && (1.9)
\end{aligned}
$$

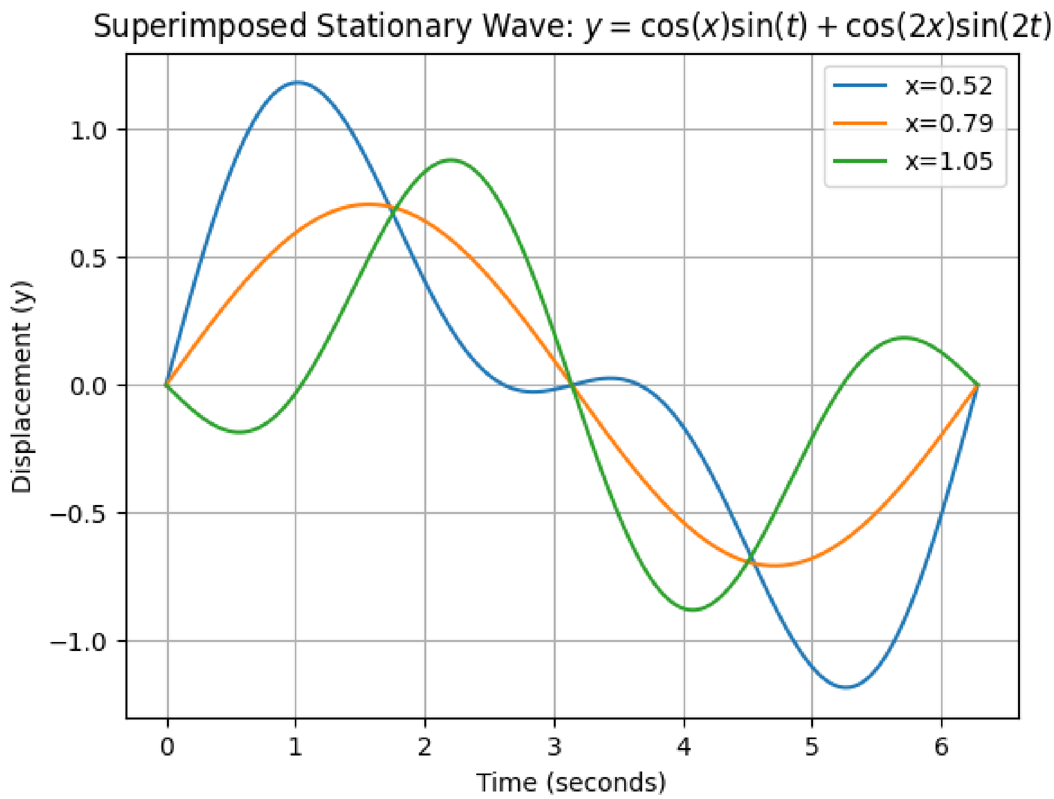


Figure 1.1.3: DIPLACEMENT *vs* TIME-graph4

To find the RMS voltage (V_{rms}) when the peak voltage (V_0) is 300V, you can use equation (1.9)

$$V_{\text{rms}} = \frac{300V}{\sqrt{2}} \approx 212.13V \tag{1.10}$$

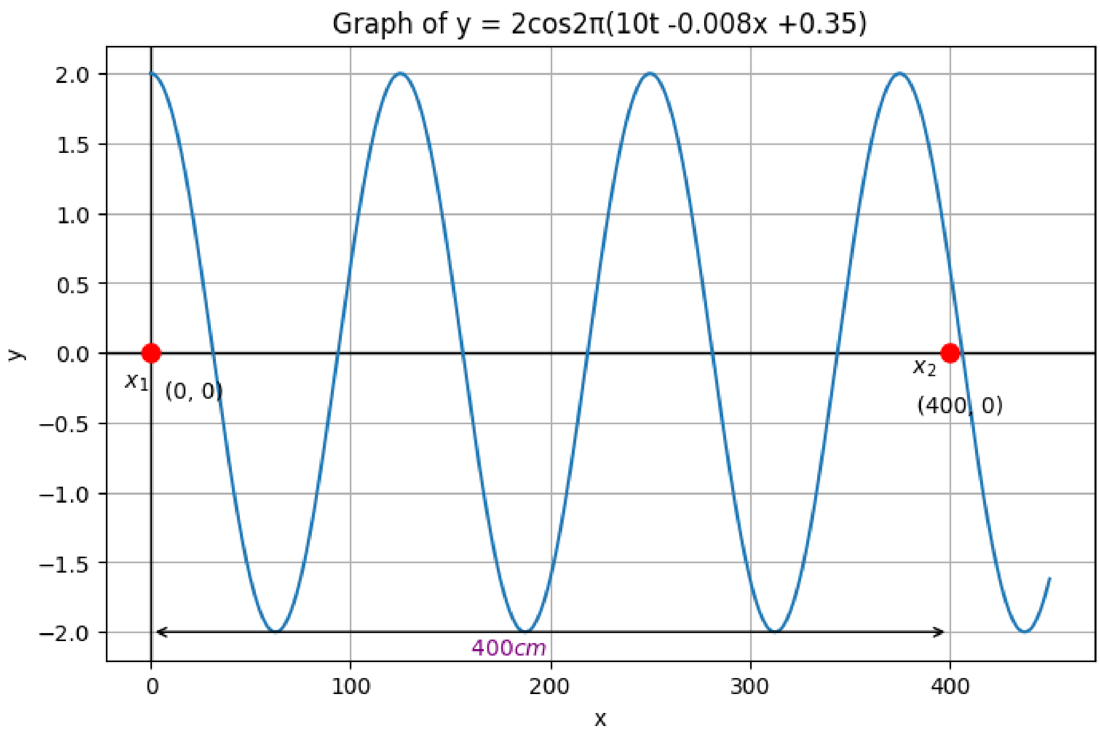


Figure 1.1.4:

(b)

$$I_{\text{rms}}^2 = \frac{1}{T}\int_0^T [I(t)]^2\, dt \tag{1.11}$$

$$= f\int_0^{\frac{1}{f}} I_0^2 \cdot \sin^2(2\pi f t + \phi)\, dt \tag{1.12}$$

$$= \frac{1}{2}I_0^2\left(1 - \frac{1}{f}\left[\frac{\sin(4\pi f t + 2\phi)}{4\pi f}\right]_0^{\frac{1}{f}}\right) \tag{1.13}$$

$$= \frac{1}{2}I_0^2\left(1 - \frac{1}{f}\cdot\frac{\sin(4\pi + 2\phi) - \sin(0 + 2\phi)}{4\pi f}\right) \tag{1.14}$$

$$I_{\text{rms}} = \frac{I_0}{\sqrt{2}} \tag{1.15}$$

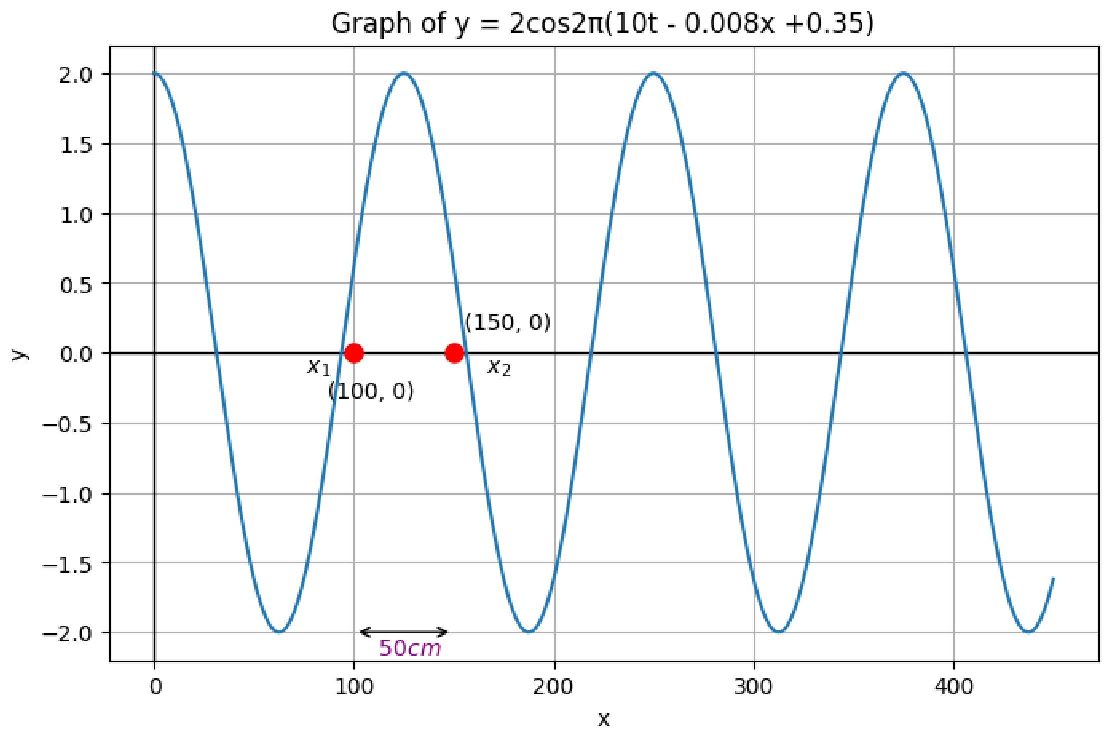


Figure 1.1.4:

To find the peak current (I_0) when the RMS current (I_{rms}) is given, you can use equation (1.15)

$$I_0 \approx 10\,\text{A} \times 1.414 \approx 14.14\,\text{A} \tag{1.16}$$

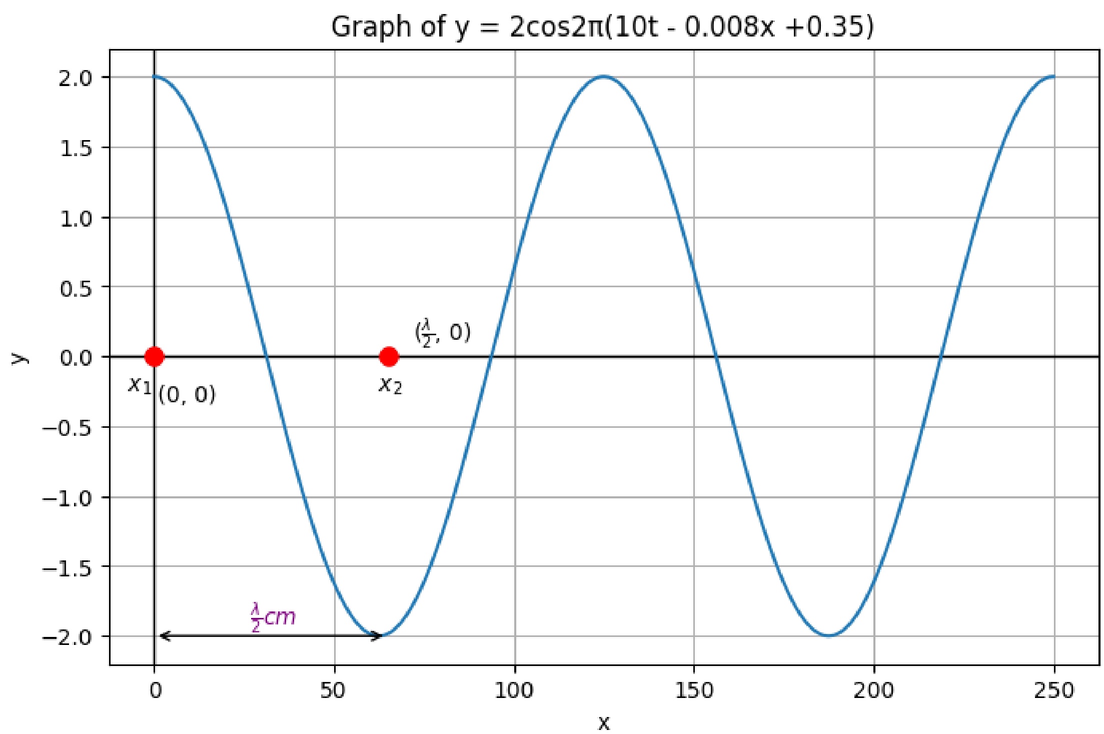
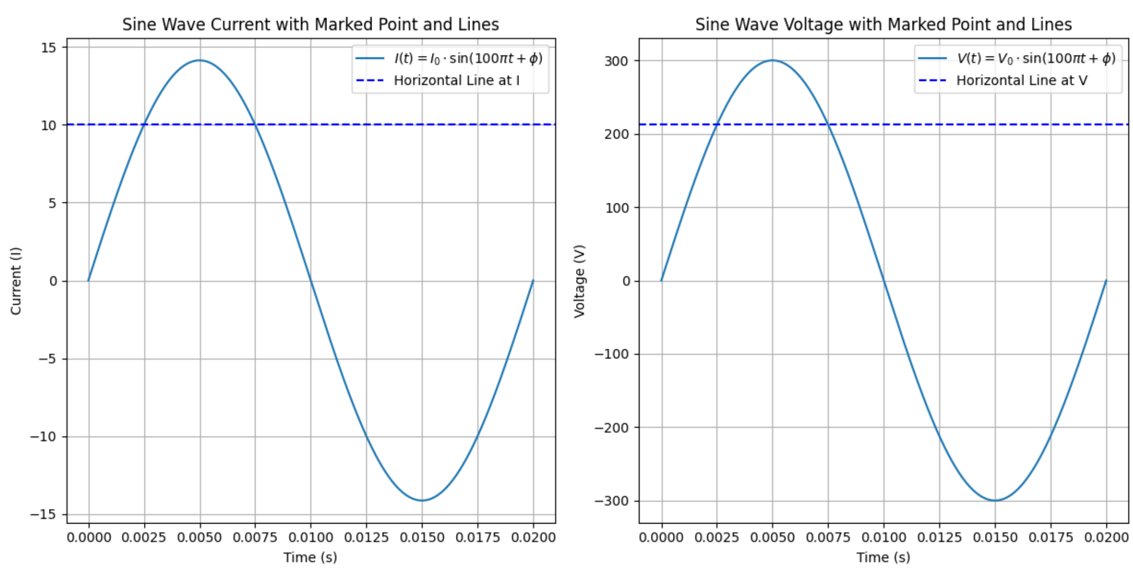

Graph of y = 2cos2π(10t - 0.008x +0.35)
$(\frac{\lambda}{2}, 0)$
x_1 (0, 0)
x_2
$\frac{\lambda}{2}cm$
y
x

Figure 1.1.4:


Sine Wave Current with Marked Point and Lines
$I(t) = I_0 \cdot \sin(100\pi t + \phi)$
Horizontal Line at I
Current (I)
Time (s)
Sine Wave Voltage with Marked Point and Lines
$V(t) = V_0 \cdot \sin(100\pi t + \phi)$
Horizontal Line at V
Voltage (V)
Time (s)

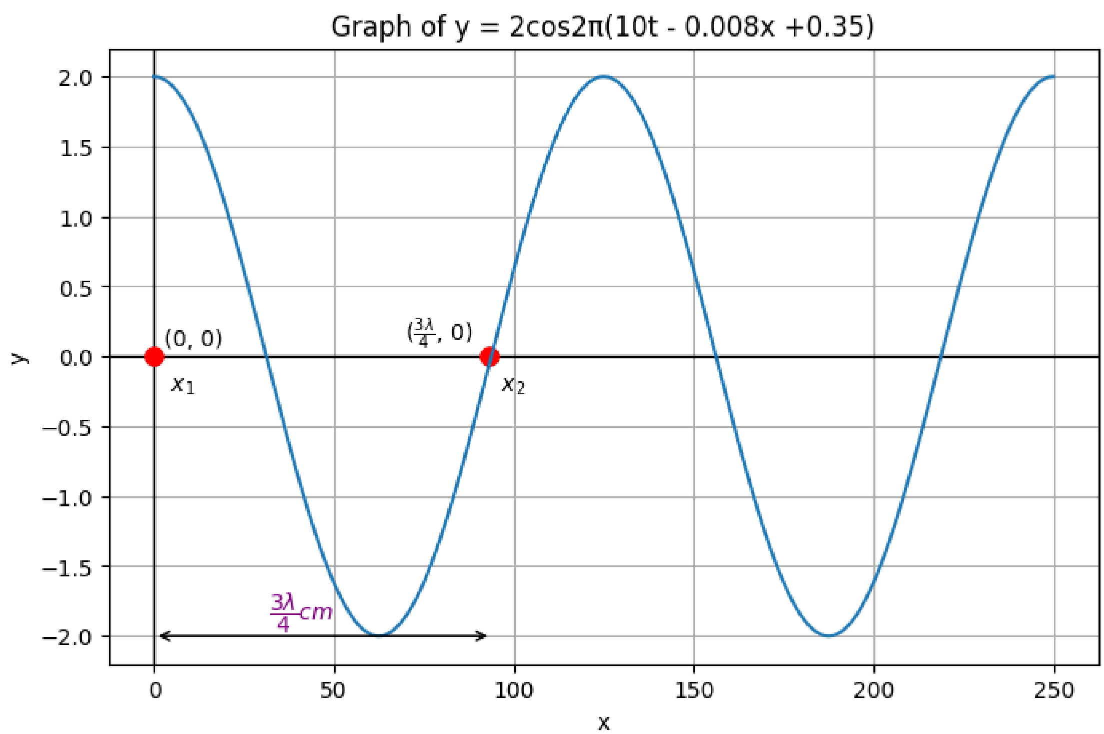


Figure 1.1.4:

1.1.6 In Young's double-slit experiment using monochromatic light of wavelength λ, the intensity of light at a point on the screen where path difference is λ, is K units. What is the intensity of light at a point where path difference is $\lambda/3$?

Solution:

From Table 1.1.6:

$$y(t) = A\sin(2\pi ft - kx_1) + A\sin(2\pi ft - kx_2) \tag{1.17}$$

$$y(t) = 2A\cos\left(\frac{k\Delta x}{2}\right)\sin\left(2\pi ft - \frac{k(x_1 + x_2)}{2}\right) \tag{1.18}$$

Parameter	**Description**	**Value**
$y_i\,(t)$	Equation of light from $S_{i^{\text{th}}}$	$A\sin(\omega t - kx_i)$
k	Wave number	$\frac{2\pi}{\lambda}$
I	Intensity of wave	$\propto A^2$
$\Delta x = x_1 - x_2$	Path difference	λ
		$\frac{\lambda}{3}$
K	Intensity of light at $\Delta x = \lambda$	
A	Amplitude of wave from source	
r	constant	$r \geq 0$

Table 1.1.6: Parameters

From Table 1.1.6 and equation (1.18):

$$\therefore I \propto 4A^2\cos^2\left(\frac{k\Delta x}{2}\right) \tag{1.19}$$

From Table 1.1.6 and equation (1.19):

$$\frac{K}{I_r} = \frac{4A^2\cos^2\left(\frac{2\pi}{2}\right)}{4A^2\cos^2\left(\frac{\pi}{3}\right)} \implies I_r = \frac{K}{4} \tag{1.20}$$

Hence, the Intensity of light at a point where path difference is $\frac{\lambda}{3}$ is $\frac{K}{4}$ units.

Parameter	**Description**	**Value**
I_r	Net Intensity of light at $\Delta x = \frac{\lambda}{3}$	$\frac{K}{4}$

Table 1.1.6:

Assuming $\Delta x = r\lambda$,

From equation (1.19):

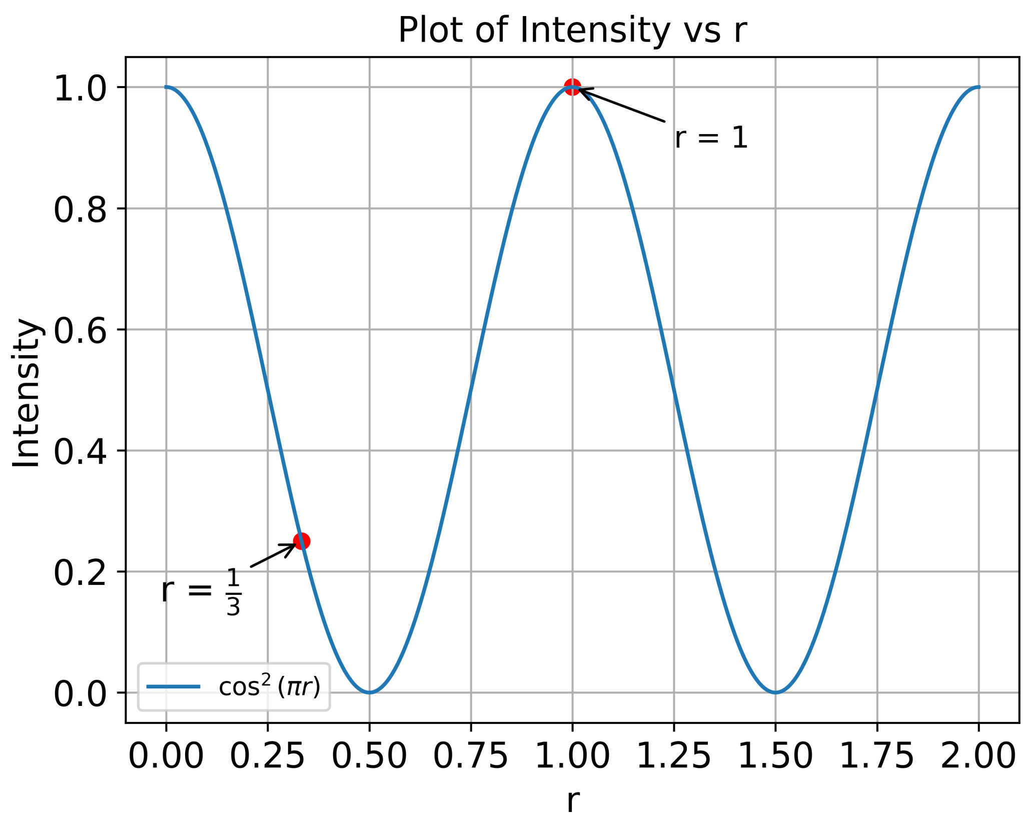


Figure 1.1.6:

1.2. Filters

1.2.1 Obtain the resonant frequency and Q-factor of a series LCR circuit with $L = 3.0\,H$, $C = 27\,\mu F$, and $R = 7.4\,\Omega$. It is desired to improve the sharpness of the resonance of the circuit by reducing its 'full width at half maximum' by a factor of 2. Suggest a suitable way.

Solution: Given parameters are:

Symbol	**Value**	**Description**
L	$3.0\,\mathrm{H}$	Inductance
C	$27\,\mu\mathrm{F}$	Capacitance
R	$7.4\,\Omega$	Resistance
Q		Quality Factor: ratio of voltage across inductor or capacitor to that across the resistor at resonance
ω_0	$\frac{1}{\sqrt{LC}}$	Angular Resonant Frequency

Table 1.11: Given Parameters

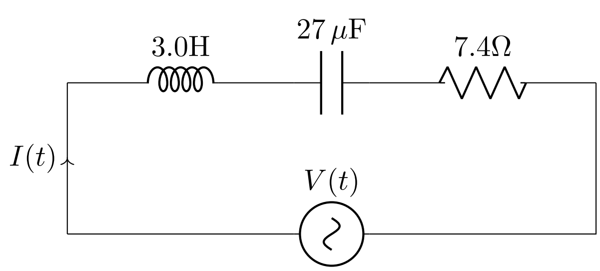


Figure 1.12: LCR Circuit

(a) Frequency Response of the Circuit

From Kirchhoff's Voltage Law (KVL):

$$V(t) = V_R + V_L + V_C \tag{1.21}$$

Using reactances from Fig. 1.13,

$$V(s) = RI(s) + sLI(s) + \frac{1}{sC}I(s) \tag{1.22}$$

$$= I(s)\left(R + Ls + \frac{1}{sC}\right) \tag{1.23}$$

$$\implies I(s) = \frac{V(s)}{\left(R + Ls + \frac{1}{sC}\right)} \tag{1.24}$$

At resonance, the circuit becomes purely resistive. The reactances of capacitor

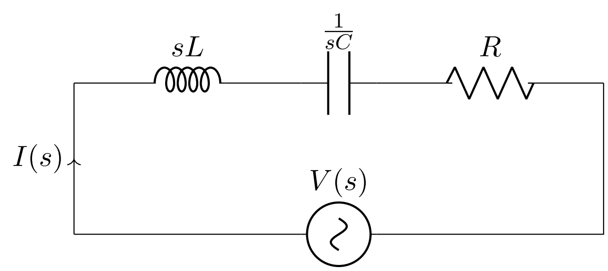


Figure 1.13: LCR Circuit

and inductor cancel out as follows:

$$Ls + \frac{1}{sC} = 0 \tag{1.25}$$

$$\implies s = j\frac{1}{\sqrt{LC}} \tag{1.26}$$

s can be expressed in terms of angular resonance frequency as

$$s = j\omega_0 \tag{1.27}$$

Comparing (1.26) and (1.27), we get

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{1.28}$$

(b) Quality Factor

i. Using voltage across inductor,

$$Q = \left(\frac{V_L}{V_R}\right)_{\omega_0} = \frac{|sLI(s)|}{|RI(s)|} \tag{1.29}$$

$$= \frac{1}{\sqrt{LC}}\frac{L}{R} \tag{1.30}$$

$$= \frac{1}{R}\sqrt{\frac{L}{C}} \tag{1.31}$$

ii. Using voltage across capacitor,

$$Q = \left(\frac{V_C}{V_R}\right)_{\omega_0} = \frac{\left|\frac{I(s)}{sC}\right|}{|RI(s)|} \tag{1.32}$$

$$= \frac{\sqrt{LC}}{RC} \tag{1.33}$$

$$= \frac{1}{R}\sqrt{\frac{L}{C}} \tag{1.34}$$

(c) Plot of Impedance vs Angular Frequency

Impedance is defined as

$$H(s) = \frac{V(s)}{I(s)} \tag{1.35}$$

Using (1.24),

$$H(s) = R + sL + \frac{1}{sC} \tag{1.36}$$

$$\implies H(j\omega) = R + j\omega L + \frac{1}{j\omega C} \tag{1.37}$$

$$\implies |H(j\omega)| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \tag{1.38}$$

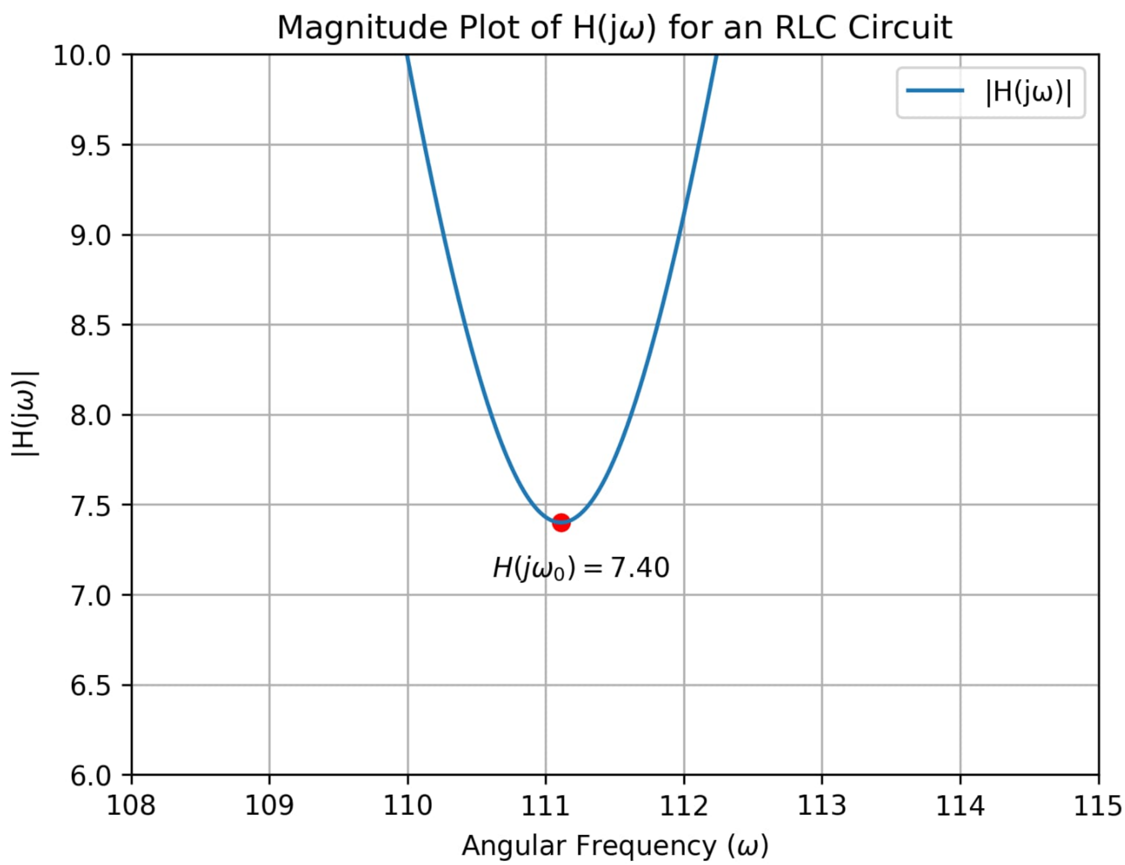


Figure 1.14: Impedance vs ω (using values in Table 1.11)

Chapter 2

Discrete

2.1. Z-transform

2.1.1 Write the five terms at n = 1, 2, 3, 4, 5 of the sequence and obtain the Z-transform of the series

$$x(n) = -1, \qquad n = 0 \tag{2.1}$$

$$= \frac{x(n-1)}{n}, \qquad n > 0 \tag{2.2}$$

$$= 0, \qquad n < 0 \tag{2.3}$$

Solution:

$$x(1) = \frac{x(0)}{1} = -1 \tag{2.4}$$
$$x(2) = \frac{x(1)}{2} = -\frac{1}{2} \tag{2.5}$$
$$x(3) = \frac{x(2)}{3} = -\frac{1}{(2)(3)} = -\frac{1}{6} \tag{2.6}$$
$$x(4) = \frac{x(3)}{4} = -\frac{1}{(2)(3)(4)} = -\frac{1}{24} \tag{2.7}$$
$$x(5) = \frac{x(4)}{5} = -\frac{1}{(2)(3)(4)(5)} = -\frac{1}{120} \tag{2.8}$$
$$x(n) = \frac{-1}{n!}(u(n)) \tag{2.9}$$

$$x(n) \overset{\mathcal{Z}}{\longleftrightarrow} X(z) \tag{2.10}$$

$$X(z) = \sum_{n=-\infty}^{\infty} x(n) z^{-n} \tag{2.11}$$

using (2.9),

$$= \sum_{n=-\infty}^{\infty} \frac{-1}{n!} u(n) z^{-n} \tag{2.12}$$
$$= \sum_{n=0}^{\infty} \frac{-1}{n!} z^{-n} \tag{2.13}$$
$$= -e^{z^{-1}} \qquad \{z \in \mathbb{C} : z \neq 0\} \tag{2.14}$$

Symbol	**Value**	**Description**
$x(n)$	$\frac{-1}{n!}$	general term of the series
$X(z)$	$-e^{z^{-1}}$	Z-transform of x(n)
$u(n)$		unit step function

Table 2.1: Parameters

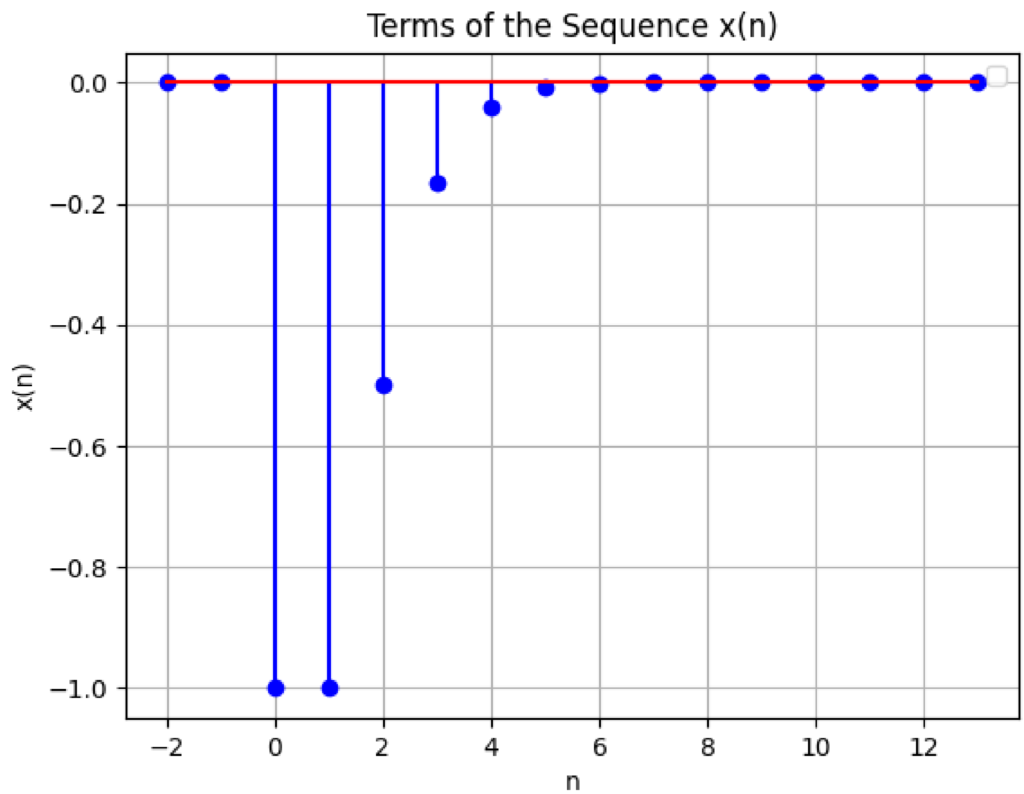


Figure 2.1: Plot of x(n) vs n

2.1.2 Subba Rao started work in 1995 at an annual salary of Rs. 5000 and received an increment of Rs. 200 each year. In which year did his income reach Rs. 7000?

Solution:

Parameter	Value	Description
$x(0)$	5000	Initial Income
d	200	Annual Increment (Common Difference)
$x(n)$	$(x(0) + nd)u(n)$	n^{th} term of the AP

Table 2.2: Input Parameters

From the values given in Table 2.2:

$$7000 = 5000 + 200n \tag{2.15}$$

$$\implies 2000 = 200n \tag{2.16}$$

$$\therefore n = 10 \tag{2.17}$$

Let Z-transform of $x(n)$ be $X(z)$.

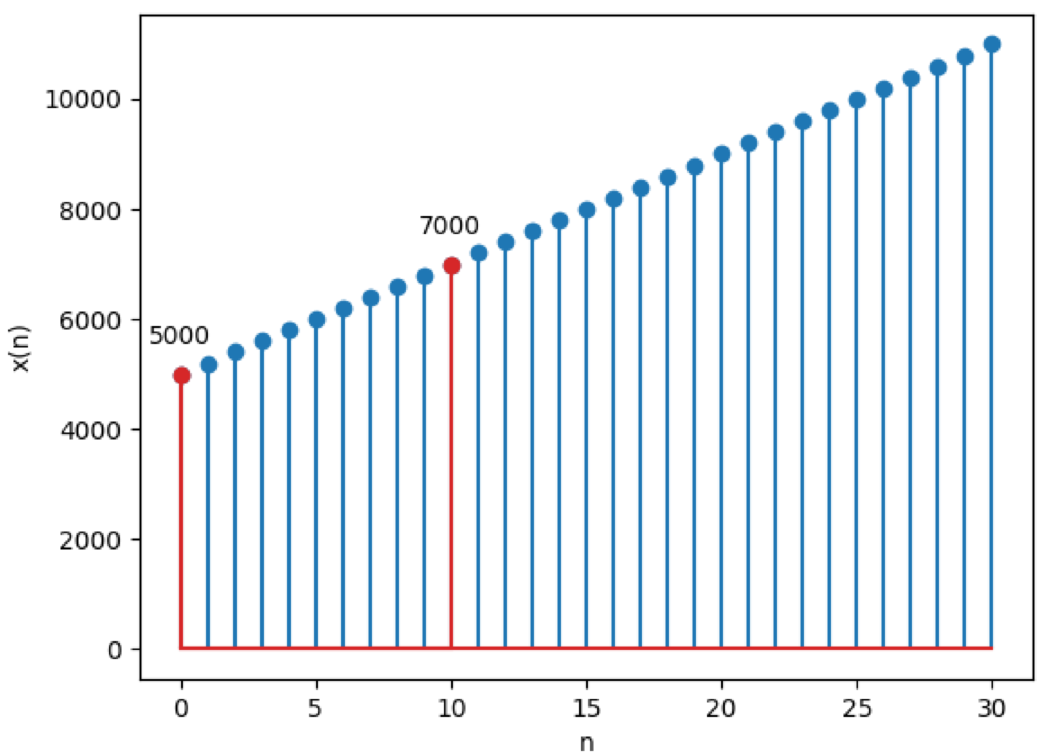


Figure 2.2: Plot of $x(n)$ vs n. See Table 2.2 for details.

$$X(z) = \frac{x(0)}{1 - z^{-1}} + \frac{dz^{-1}}{(1 - z^{-1})^2} \quad |z| > 1 \tag{2.18}$$

Using the values from Table 2.2:

$$X(z) = \frac{5000}{1 - z^{-1}} + \frac{200z^{-1}}{(1 - z^{-1})^2} \quad |z| > 1 \tag{2.19}$$

2.2. Sequences

2.2.1 Two APs have the same common difference.The difference between their 100th terms is 100,what is the difference between their 1000th terms?

Solution:

$$x(n) = \{x(0) + nd\}u(n) \tag{2.20}$$

$$x(99) - y(99) = 100 \tag{2.21}$$

$$\implies (x(0) + 99d) - (y(0) + 99d) = 100 \tag{2.22}$$

$$\implies x(0) - y(0) = 100 \tag{2.23}$$

$$x(n) - y(n) = (x(0) + nd) - (y(0) + nd) \tag{2.24}$$

$$= x(0) - y(0) \tag{2.25}$$

$$= 100 \tag{2.26}$$

$$\implies x(999) - y(999) = 100 \tag{2.27}$$

Variable	**Description**	**Value**
$x(n)$	n^{th} term of X	none
$y(n)$	n^{th} term of Y	none
d	common difference between the terms of AP	none
$x(99) - y(99)$	difference of 99^{th} terms of X and Y	100

Table 2.3: input parameters

Let

$$x(n) = \{101, 106, 111, ...\} \tag{2.28}$$

$$y(n) = \{1, 6, 11, ...\} \tag{2.29}$$

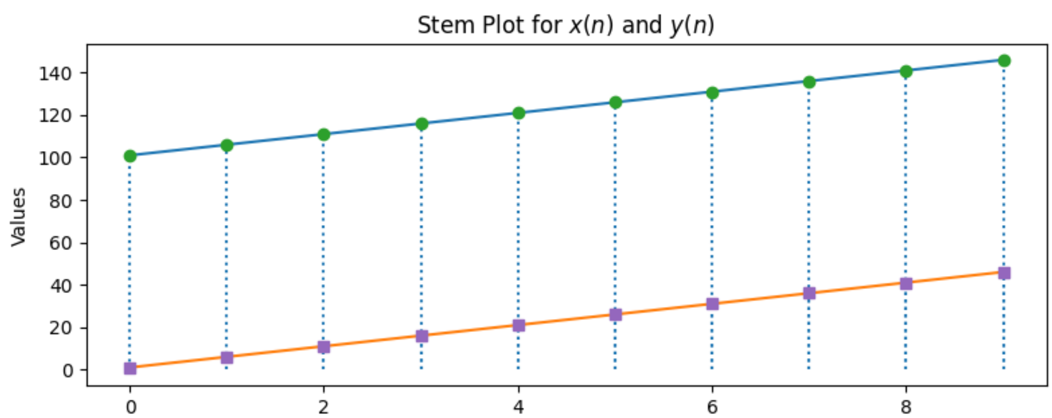


Figure 2.3:

Appendix A

Convolution

A.1 The convolution sum is defined as

$$y(n) = x(n) * h(n) = \sum_{k=-\infty}^{\infty} x(k) h(n-k) \tag{A.1.1}$$

A.2 The unit step function is defined as

$$u(n) = \begin{cases} 1 & n \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{A.2.1}$$

A.3 If

$$x(n) = 0, \quad n < 0, \tag{A.3.1}$$

from (A.1.1),

$$x(n) * u(n) = \sum_{k=0}^{n} x(k) \tag{A.3.2}$$

Appendix B

Z-transform

B.1 The Z-transform of $p(n)$ is defined as

$$P(z) = \sum_{n=-\infty}^{\infty} p(n) z^{-n} \tag{B.1.1}$$

B.2 If

$$p(n) = p_1(n) * p_2(n), \tag{B.2.1}$$

$$P(z) = P_1(z) P_2(z) \tag{B.2.2}$$

B.3 For a Geometric progression

$$x\left(n\right) = x\left(0\right) r^n u\left(n\right), \tag{B.3.1}$$

$$\implies X\left(z\right) = \sum_{n=-\infty}^{\infty} x\left(n\right) z^{-n} = \sum_{n=0}^{\infty} x\left(0\right) r^n z^{-n} \tag{B.3.2}$$

$$= \sum_{n=0}^{\infty} x\left(0\right) \left(rz^{-1}\right)^n \tag{B.3.3}$$

$$= \frac{x\left(0\right)}{1 - rz^{-1}}, \quad |z| > |r| \tag{B.3.4}$$

B.4 Substituting $r = 1$ in (B.3.4),

$$u(n) \overset{\mathcal{Z}}{\longleftrightarrow} U(z) = \frac{1}{1 - z^{-1}}, \quad |z| > 1 \tag{B.4.1}$$

B.5 From (B.1.1) and (B.4.1),

$$U(z) = \sum_{n=-\infty}^{\infty} u(n) z^{-n} \tag{B.5.1}$$

$$\implies \frac{dU(z)}{dz} = -z^{-1} \sum_{n=-\infty}^{\infty} n u(n) z^{-n} \tag{B.5.2}$$

$$\therefore n u(n) \overset{\mathcal{Z}}{\longleftrightarrow} \frac{z^{-1}}{(1 - z^{-1})^2}, \quad |z| > 1 \tag{B.5.3}$$

B.6 For an AP,

$$x(n) = \left[x(0) + nd\right] u(n) = x(0)u(n) + dnu(n) \tag{B.6.1}$$

$$\implies X(z) = \frac{x(0)}{1 - z^{-1}} + \frac{dz^{-1}}{(1 - z^{-1})^2}, \quad |z| > 1 \tag{B.6.2}$$

upon substituting from (B.4.1) and (B.5.3).

B.7 From (A.3.2), the sum to n terms of a GP can be expressed as

$$y(n) = x(n) * u(n) \tag{B.7.1}$$

where $x(n)$ is defined in (B.3.1). From (B.2.2), (B.3.4) and (B.4.1),

$$Y(z) = X(z)\,U(z) \tag{B.7.2}$$

$$= \left(\frac{x(0)}{1 - rz^{-1}}\right)\left(\frac{1}{1 - z^{-1}}\right) \quad |z| > |r| \cap |z| > |1| \tag{B.7.3}$$

$$= \frac{x(0)}{(1 - rz^{-1})(1 - z^{-1})} \quad |z| > |r| \tag{B.7.4}$$

which can be expressed as

$$Y(z) = \frac{x(0)}{r - 1}\left(\frac{r}{1 - rz^{-1}} - \frac{1}{1 - z^{-1}}\right) \tag{B.7.5}$$

using partial fractions. Again, from (B.3.4) and (B.4.1), the inverse of the above can be expressed as

$$y(n) = x(0)\left(\frac{r^{n+1} - 1}{r - 1}\right)u(n) \tag{B.7.6}$$