FREE EDITION · NOTES + 3 SAMPLE MCQS

CUET · PHYSICS · CLASS XI · CODE 322

Waves

CUET unit: Waves

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📌 Snapshot

- Establishes that a wave is a propagating disturbance that transports energy and information without bulk transfer of matter through the medium.
- Classifies mechanical waves into transverse and longitudinal, and develops the sinusoidal travelling-wave description $y(x, t) = a \sin(kx - \omega t + \phi)$.
- Derives the speeds of mechanical waves — on a stretched string $v = \sqrt{T/\mu}$, in solids $v = \sqrt{Y/\rho}$, in fluids $v = \sqrt{B/\rho}$, and Newton-Laplace $v = \sqrt{\gamma P/\rho}$ for a gas.
- Builds the principle of superposition, reflection at rigid and free boundaries, and the resulting standing waves on strings and in pipes (with normal modes/ harmonics).
- Closes with beats — slow waxing and waning of intensity at frequency $\nu_{beat} = |\nu_1 - \nu_2|$ when two close-frequency sounds interfere. CUET tests all four: travelling-wave parameters, wave-speed calculation, harmonics of strings/ pipes, and beats.

📖 Detailed Notes

2.1 Core concepts

- A wave is a pattern of disturbance that moves through a medium without actual physical transfer of matter as a whole; the medium oscillates while energy and information propagate (NCERT §14.1, p. 278).
- Mechanical waves (string, water, sound, seismic) need an elastic medium and arise from coupling between oscillating constituents; electromagnetic waves do not need a medium and travel at $c = 299{,}792{,}458 \text{ m s}^{-1}$ in vacuum; matter waves are associated with electrons, protons, atoms, etc. (NCERT §14.1, p. 279).
- In a transverse wave the constituents oscillate perpendicular to the direction of propagation (e.g. a wave on a stretched string); in a longitudinal wave they oscillate along the direction of propagation (e.g. sound in a long air-filled pipe with a piston) (NCERT §14.2, pp. 280–281).
- Transverse waves require shear elasticity, so they can propagate only in solids and on the surface of liquids; longitudinal waves need only bulk/compressional elasticity and so propagate in solids, liquids and gases. In steel both can propagate; in air only longitudinal (NCERT §14.2, p. 281; Points to ponder 4, p. 297).

- A sinusoidal travelling wave on a string is described by $y(x, t) = a \sin(kx - \omega t + \phi)$; for a longitudinal wave the same form is used with displacement $s(x, t)$ (NCERT §14.3, p. 281; Eqs. 14.2 and 14.9, p. 283).
- Amplitude a is the maximum displacement of a particle from equilibrium; phase $(kx - \omega t + \phi)$ determines the displacement at any (x, t); ϕ is the initial phase angle at x = 0, t = 0 (NCERT §14.3.1, p. 282).
- Wavelength λ is the minimum distance between two points of equal phase; angular wave number $k = 2\pi/\lambda$ with SI unit rad m^{-1} (NCERT §14.3.2, p. 283, Eq. 14.6).
- Period T is the time for one complete oscillation of a particle, angular frequency $\omega = 2\pi/T$, and frequency $\nu = 1/T = \omega/(2\pi)$, measured in hertz (NCERT §14.3.3, p. 283, Eqs. 14.7–14.8).
- Speed of a travelling wave is $v = \omega/k = \lambda/T = \nu\lambda$; in one period the wave pattern advances exactly one wavelength (NCERT §14.4, p. 284, Eqs. 14.11–14.12).
- For a transverse wave on a stretched string with tension T and linear mass density $\mu = m/L$, the speed is $v = \sqrt{T/\mu}$; it depends only on the medium, not on wavelength or frequency (NCERT §14.4.1, p. 285, Eq. 14.14).
- For a longitudinal wave in a fluid of bulk modulus B and density ρ, $v = \sqrt{B/\rho}$; in a linear solid bar (Young's modulus Y), $v = \sqrt{Y/\rho}$ (NCERT §14.4.2, p. 286, Eqs. 14.19–14.20).
- Newton's formula for sound in an ideal gas, treating compressions/rarefactions as isothermal, gives $v = \sqrt{P/\rho} \approx 280$ m s^{-1} at STP, about 15% below the measured 331 m s^{-1} (NCERT §14.4.2, pp. 286–287, Eqs. 14.22–14.23).
- Laplace correction notes the variations are adiabatic (PV^{γ} = constant), so the adiabatic bulk modulus is $B_{ad} = \gamma P$ and $v = \sqrt{\gamma P/\rho}$. For air $\gamma = 7/5$, giving 331.3 m s^{-1}, matching experiment (NCERT §14.4.2, p. 287, Eq. 14.24).
- Principle of superposition: when waves overlap, the net displacement is the algebraic sum $y(x, t) = y_1(x, t) + y_2(x, t) + \cdots = \Sigma f_i(x - vt)$; this principle underlies interference (NCERT §14.5, pp. 287–288, Eqs. 14.25–14.26).
- Two waves of equal a, k, ω differing in phase by ϕ add to $y = 2a \cos(\phi/2) \sin(kx - \omega t + \phi/2)$; $\phi = 0$ gives constructive interference (amplitude 2a), $\phi = \pi$ gives destructive interference (zero displacement everywhere) (NCERT §14.5, p. 288, Eqs. 14.31–14.34).
- A wave reflected at a rigid boundary undergoes a phase change of π (the boundary point must remain at zero displacement); at an open/free boundary there is no phase change (NCERT §14.6, pp. 288–289, Eqs. 14.35–14.36).
- When two identical waves travel in opposite directions, superposition gives a standing wave $y(x, t) = 2a \sin kx \cos \omega t$ — same ω at every point but amplitude $2a \sin kx$ varies with x. Points of zero amplitude are nodes; of maximum amplitude are antinodes; consecutive nodes (or antinodes) are $\lambda/2$ apart (NCERT §14.6.1, pp. 289–291, Eqs. 14.37–14.39).

- For a stretched string of length L fixed at both ends (nodes at both ends), $L = n\lambda/2$, so allowed wavelengths $\lambda = 2L/n$ and frequencies $\nu_{\boxed{?}} = nv/(2L)$, n = 1, 2, 3 ⋯ — all harmonics are present; n = 1 gives fundamental $\nu_1 = v/(2L)$ (NCERT §14.6.1, p. 291, Eqs. 14.40–14.42).
- For a pipe closed at one end (node at closed end, antinode at open end), $L = (n + ½)\lambda/2$, so $\nu_{\boxed{?}} = (n + ½)\, v/(2L)$ for n = 0, 1, 2, ⋯ — only odd harmonics $\nu_1 = v/4L$, 3v/4L, 5v/4L, ⋯ are present (NCERT §14.6.1, pp. 291–292, Eqs. 14.43–14.44).
- A pipe open at both ends has antinodes at both ends; like the string fixed at both ends, all harmonics are present with $\nu_1 = v/(2L)$, and $\nu_{\boxed{?}} = nv/(2L)$ (NCERT §14.6.1, p. 292; Example 14.5, p. 292).
- Beats occur when two harmonic sound waves of close (but unequal) frequencies superpose. The resultant has average angular frequency $\omega_a = (\omega_1 + \omega_2)/2$ modulated by amplitude that oscillates at $2\omega_\beta = \omega_1 - \omega_2$, so the audible beat frequency is $\nu\_beat = |\nu_1 - \nu_2|$ (NCERT §14.7, pp. 293–294, Eqs. 14.45–14.48).
- The wave function y(x, t) must be a solution of the linear wave equation $\partial^2y/\partial t^2 = v^2\, \partial^2y/\partial x^2$, so any function of the form f(x − vt) describes a wave travelling in the +x direction at speed v, and g(x + vt) describes one travelling in the −x direction (NCERT §14.3, p. 281).
- For sound in an ideal gas, v depends only on temperature (not on pressure) because P/ρ is set by T via the ideal-gas law; in air $v \approx 331\ m\ s^{-1}$ at 0 °C and increases by roughly $0.61\ m\ s^{-1}$ per °C rise — a standard NCERT remark (NCERT §14.4.2, p. 287).
- A travelling wave on a string transports both kinetic energy (oscillating string elements) and elastic potential energy (string segments alternately stretched); the average power transmitted is proportional to $a^2\omega^2$ so doubling either amplitude or frequency quadruples the power carried — relevant to NCERT examples on string waves (NCERT §14.4, p. 285).

2.2 Definitions to memorise

Term	Definition	Page
Transverse wave	Wave in which constituents oscillate perpendicular to the direction of propagation.	280
Longitudinal wave	Wave in which constituents oscillate along the direction of propagation.	280
Amplitude (a)	Maximum displacement of a particle of the medium from its equilibrium position.	282
Wavelength (λ)	Minimum distance between two points having the same phase at a given instant.	283
Angular wave number (k)	$k = 2\pi/\lambda$; SI unit rad m^{-1}.	283
Period (T)	Time for one complete oscillation of a particle; $T = 2\pi/\omega$.	283

Term	Definition	Page
Frequency (ν)	Number of oscillations per second; $\nu = 1/T = \omega/2\pi$, measured in hertz.	283
Wave speed (v)	Speed of propagation of a fixed phase point; $v = \omega/k = \lambda/T = \nu\lambda$.	284
Speed on a stretched string	$v = \sqrt{(T/\mu)}$, with T the tension and μ the linear mass density.	285
Speed in a fluid	$v = \sqrt{(B/\rho)}$, with B the bulk modulus and ρ the density.	286
Speed in a solid bar	$v = \sqrt{(Y/\rho)}$, with Y Young's modulus and ρ density.	286
Newton-Laplace formula	Speed of sound in a gas $v = \sqrt{(\gamma P/\rho)}$, with $\gamma = Cp/Cv$.	287
Principle of superposition	Net displacement when waves overlap is the algebraic sum of the individual displacements.	287
Node	Point on a stationary wave where the amplitude is zero.	290
Antinode	Point on a stationary wave where the amplitude is maximum.	290
Fundamental frequency / first harmonic	Lowest natural frequency of a vibrating system.	291
Beat frequency	ν_beat = $\nu_1 - \nu_2$; rate of waxing/waning of intensity when two close-frequency waves superpose.	294
Phase	The argument $(kx - \omega t + \phi)$ of a sinusoidal wave; determines displacement at any (x, t).	282
Initial phase angle (ϕ)	Value of the phase at x = 0, t = 0; SI unit radian.	282
Mechanical wave	Wave that requires an elastic material medium for propagation.	279
Electromagnetic wave	Wave that does not require a medium and travels at $c = 3 \times 10^8$ m s^{-1} in vacuum.	279
Standing (stationary) wave	Wave pattern produced by superposition of two oppositely travelling identical waves; nodes and antinodes are fixed.	290
Normal mode	A natural pattern of oscillation of a bounded system with a definite frequency (ν?).	291
Overtone	Any allowed frequency higher than the fundamental; the first overtone is the second harmonic for an open pipe/string.	292

2.3 Diagrams / processes to remember

- Fig. 14.1 (p. 279): chain of coupled springs showing how a disturbance at one end travels along, while each spring only oscillates about its equilibrium — the model for mechanical wave propagation.

- Fig. 14.2 / 14.3 (p. 280): pulse and sinusoidal transverse wave on a stretched string; string elements oscillate in y while the wave moves in x.
- Fig. 14.4 (p. 280): longitudinal wave generated in a piston-driven air column — compressions and rarefactions parallel to the propagation direction.
- Fig. 14.5 / 14.6 (p. 282): meaning of a, ω, k, ϕ in $y = a \sin(kx - \omega t + \phi)$, and snapshots of a harmonic wave at successive times showing the crest advancing.
- Fig. 14.7 (p. 283): displacement of one element as a function of time — period T, amplitude a.
- Fig. 14.8 (p. 284): two snapshots of a wave at t and $t + \Delta t$ to read off the phase speed $v = \Delta x/\Delta t$.
- Fig. 14.9 (p. 287): two equal-and-opposite pulses crossing — instantaneous cancellation illustrating superposition.
- Fig. 14.10 (p. 288): resultant of two harmonic waves of equal amplitude — constructive ($\phi = 0$, amplitude 2a) versus destructive ($\phi = \pi$, zero).
- Fig. 14.11 (p. 289): reflection of a pulse from a rigid boundary with phase change π.
- Fig. 14.12 (p. 290): two oppositely-travelling waves combining into a stationary wave with fixed nodes.
- Fig. 14.13 (p. 291): first six harmonics of a string fixed at both ends — $\nu_1 : \nu_2 : \nu_3 \cdots = 1 : 2 : 3 \cdots$
- Fig. 14.14 (p. 292): first six odd harmonics of an air column closed at one end — ν_1, $3\nu_1$, $5\nu_1 \cdots$ only.
- Fig. 14.15 (p. 293): first four harmonics of a pipe open at both ends — all harmonics present.
- Fig. 14.16 (p. 294): superposition of 11 Hz and 9 Hz waves giving a 2 Hz beat envelope.

2.4 Common confusions / NTA trap points

- Confusing wind with sound: wind carries air bodily; a sound wave only carries the compression/rarefaction pattern — no net flow of air (NCERT §14.2, p. 281; Points to ponder 1, p. 297).
- Forgetting that transverse waves cannot propagate inside fluids — fluids cannot sustain shearing stress, so in air only longitudinal sound waves exist (NCERT §14.2, p. 281).
- Misusing Newton's bare $v = \sqrt{(P/\rho)}$: it gives ~280 m s^{-1} for air at STP, off by 15%. The Laplace-corrected $v = \sqrt{(\gamma P/\rho)}$ with $\gamma = 7/5$ gives 331.3 m s^{-1}, which is what NCERT uses (NCERT §14.4.2, pp. 286–287).
- Mixing up the harmonics of a closed pipe versus an open pipe: closed pipe has only odd harmonics (ν_1, $3\nu_1$, $5\nu_1 \cdots$) while an open pipe (or a string fixed at both ends) has all harmonics (ν_1, $2\nu_1$, $3\nu_1 \cdots$) (NCERT §14.6.1, pp. 291–292).

- In a standing wave, every particle oscillates with the same frequency and phase between two nodes but with different amplitudes — opposite to a progressive wave where amplitude is the same but phases differ (Points to ponder 5, p. 297).
- Beat frequency is the absolute difference $\nu_1 - \nu_2$, not the average; the average sets the pitch, the difference sets the waxing rate (NCERT §14.7, p. 294, Eq. 14.48).
- A common slip is treating "+" or "−" sign inside $(kx \pm \omega t)$ as cosmetic — the sign sets the direction of travel: $(kx - \omega t)$ propagates in +x, $(kx + \omega t)$ in −x (NCERT §14.3, p. 281).
- Mistaking k (angular wave number, rad m^{-1}) for the ordinary wave number $1/\lambda$ — only $k = 2\pi/\lambda$ enters the standard NCERT wave equation $y = a \sin(kx - \omega t)$.
- Forgetting that on a stretched string ν depends on length and tension/density of the wire — so changing string length (fretting a guitar) raises ν without altering v, whereas tightening the string raises v and hence ν together.
- Assuming the speed of sound in water or steel can be computed with Newton-Laplace $v = \sqrt{\gamma P/\rho}$: that formula is for gases only; in liquids and solids use $v = \sqrt{B/\rho}$ and $v = \sqrt{Y/\rho}$ (NCERT §14.4.2, p. 286).

2.5 Key formulas table

Quantity	Symbol / Formula	NCERT reference
Travelling wave (transverse)	$y(x, t) = a \sin(kx - \omega t + \phi)$	§14.3, Eq. 14.2, p. 282
Angular wave number	$k = 2\pi/\lambda$	§14.3.2, Eq. 14.6, p. 283
Angular frequency	$\omega = 2\pi/T = 2\pi\nu$	§14.3.3, Eq. 14.7, p. 283
Frequency	$\nu = 1/T = \omega/(2\pi)$	§14.3.3, Eq. 14.8, p. 283
Wave speed	$v = \omega/k = \lambda/T = \nu\lambda$	§14.4, Eqs. 14.11–14.12, p. 284
Speed on stretched string	$v = \sqrt{T/\mu}$	§14.4.1, Eq. 14.14, p. 285
Linear mass density	$\mu = m/L$	§14.4.1, p. 285
Speed in solid bar	$v = \sqrt{Y/\rho}$	§14.4.2, Eq. 14.19, p. 286
Speed in fluid	$v = \sqrt{B/\rho}$	§14.4.2, Eq. 14.20, p. 286
Newton's formula (isothermal)	$v = \sqrt{P/\rho}$	§14.4.2, Eq. 14.23, p. 287
Newton-Laplace (adiabatic)	$v = \sqrt{\gamma P/\rho}$	§14.4.2, Eq. 14.24, p. 287
Superposition principle	$y = \Sigma y_i = \Sigma f_i(x - vt)$	§14.5, Eq. 14.26, p. 288
Resultant of two waves (same a, ω, k)	$y = 2a \cos(\phi/2) \sin(kx - \omega t + \phi/2)$	§14.5, Eq. 14.32, p. 288
Standing wave on string	$y = 2a \sin(kx) \cos(\omega t)$	§14.6.1, Eq. 14.37, p. 290
Frequencies of string (both ends fixed)	$\nu_{?} = nv/(2L)$, n = 1, 2, 3 ⋯	§14.6.1, Eq. 14.41, p. 291

Quantity	Symbol / Formula	NCERT reference
Frequencies of pipe (closed one end)	ν? = (2n + 1)v/(4L), n = 0, 1, 2 ⋯	§14.6.1, Eq. 14.44, p. 292
Frequencies of pipe (open both ends)	ν? = nv/(2L), n = 1, 2, 3 ⋯	§14.6.1, p. 292
Beat frequency	ν_beat =	$\nu_1 - \nu_2$
Distance between adjacent nodes	λ/2	§14.6.1, p. 290
Distance node-to-nearest-antinode	λ/4	§14.6.1, p. 290

🎯 Practice MCQs

📊 PYQ Alignment

This chapter is a heavy-yield Class XI Physics chapter in CUET (UG): expect ~10–12 MCQs per year, dominated by (i) plug-and-chug wave-speed calculations on stretched strings v = √(T/μ), (ii) identification of allowed harmonics in open and closed pipes (the classic Example 14.5 / Exercise 14.17 pattern), and (iii) beat-frequency reasoning of the "tension is slightly increased/decreased — find the original frequency" type. Newton-Laplace formula, the y = a sin(kx − ωt + ϕ) parameter-reading questions, and the rigid-vs-open boundary phase change are also recurring NTA favourites.

CUET 2023–25 — Actual PYQs from this chapter

No PYQs from this chapter appeared in CUET 2023, 2024 or 2025.