IB DP PHYSICS · THEME C WAVE BEHAVIOUR · C.4 · ~5 MIN READ

C.4 Standing waves and resonance

How standing waves form, nodes and antinodes, harmonics on strings and in open and closed pipes, natural and driving frequency, resonance, and light, critical and heavy damping.

Standing waves | Nodes & antinodes | Harmonics on strings | Open & closed pipes | Resonance | Damping

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- A **standing wave** forms when two identical waves travel in opposite directions and superpose. Energy is not transferred along it.
- **Nodes** have zero amplitude; **antinodes** have maximum amplitude. Adjacent nodes are **λ/2** apart. All points between two nodes oscillate in phase.
- Boundary conditions pick the allowed wavelengths: a **fixed end** or **closed pipe end** is a node; an **open end** is an antinode.
- Driving a system at its natural frequency gives **resonance**, a large amplitude. **Damping** reduces the amplitude and broadens the resonance peak.
- **C.4 is the same at SL and HL.**

BY THE END YOU CAN

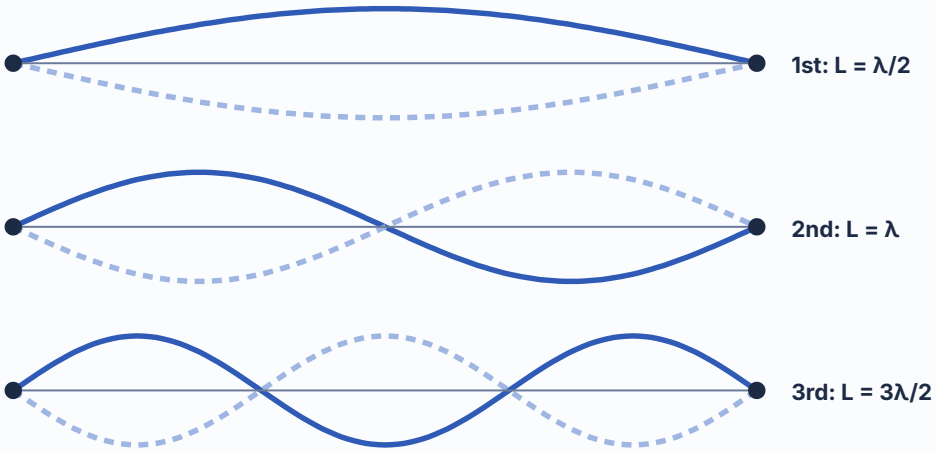
- Explain how standing waves form and compare them with travelling waves.
- Identify nodes and antinodes and the phase of points on a standing wave.
- Find the wavelength and frequency of the nth harmonic on strings and in pipes.
- Explain resonance, natural and driving frequency, with examples.
- Describe light, critical and heavy damping and their effect on resonance.

1 Standing waves

- **Formation:** a wave reflects at a boundary and the reflected wave superposes with the incoming one. Where they always cancel you get a node; where they always reinforce, an antinode.

	Travelling wave	Standing wave
energy	transferred along the wave	not transferred (stored)
amplitude	the same for all points	from zero (node) to maximum (antinode)
phase	changes steadily along the wave	same between adjacent nodes; flips by π across a node
wavelength	distance between points in phase	twice the node-to-node distance

2 Strings



string fixed at both ends: $f_n = nv/2L$ (N at ends)

A string fixed at both ends must have a node at each end, so a whole number of half-wavelengths fits.

$$\lambda_n = \frac{2L}{n}, \; f_n = \frac{nv}{2L}$$

string (or pipe open at both ends), n = 1, 2, 3, ...

- **First harmonic (fundamental)** n = 1: L = λ/2. Every harmonic is a whole-number multiple of the fundamental frequency.

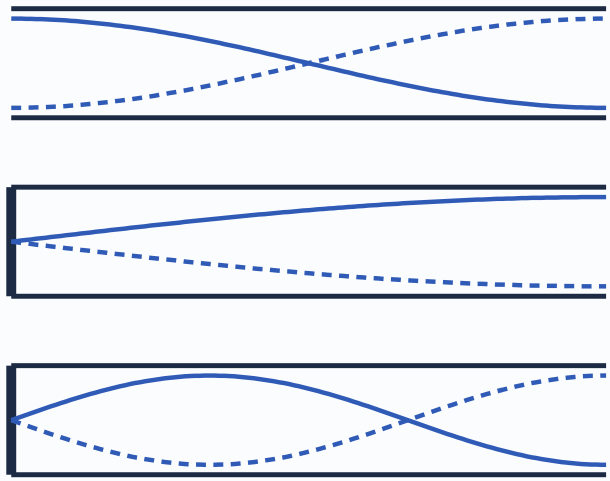
WORKED EXAMPLE

A guitar string 0.65 m long has fundamental frequency 196 Hz. Find the wave speed on the string and the frequency of its third harmonic.

1. $v = f\lambda = 196 \times 2 \times 0.65$ M1
2. $= \mathbf{255\ m\ s^{-1}}$ A1
3. **$f_3 = 3 \times 196 = 588$ Hz** A1

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3 Pipes



Open end = antinode, closed end = node. Closed pipes: odd harmonics only.

Open ends are displacement antinodes; a closed end is a displacement node.

$$\text{open–open: } f_n = \frac{nv}{2L}$$

n = 1, 2, 3, … (all harmonics)

$$\text{closed at one end: } f_n = \frac{nv}{4L}$$

n = 1, 3, 5, … (odd harmonics only)

WORKED EXAMPLE

A pipe 0.30 m long is closed at one end (v = 340 m s^{-1}). Find its fundamental and the next harmonic. Repeat for an open pipe.

1. closed: f_1 = v/4L = 340/1.2 = **283 Hz**; next is $3f_1$ = **850 Hz** M1 A1
2. **open: f_1 = v/2L = 340/0.60 = 567 Hz; next $2f_1$ = 1130 Hz** A1

COMMON MISTAKE

Counting the "second harmonic" of a closed pipe. Closed pipes only have odd harmonics, so the next one after the first is the **third**.

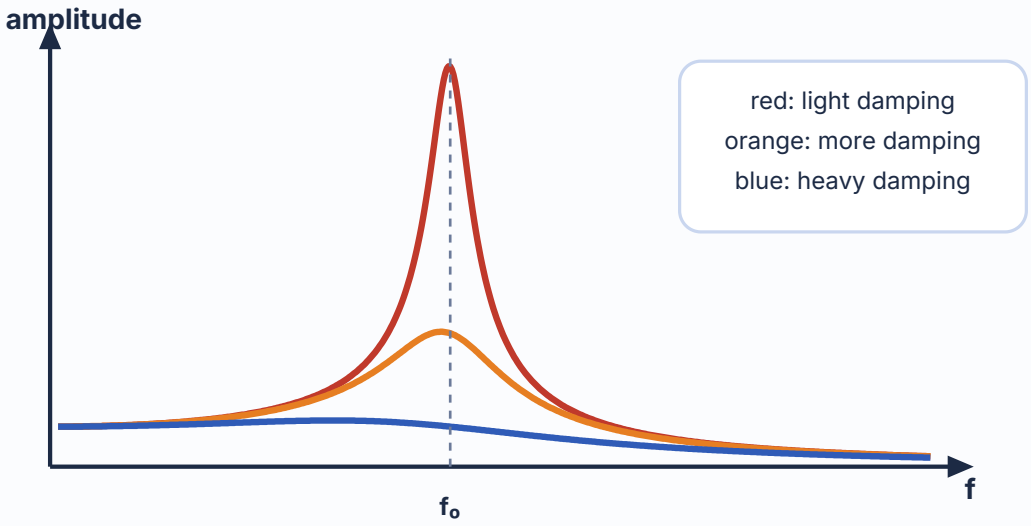
EXAM TIP

In pipe diagrams, sketch displacement (antinode at an open end). If a question talks about pressure, swap them: pressure nodes sit at displacement antinodes.

4 Resonance and damping

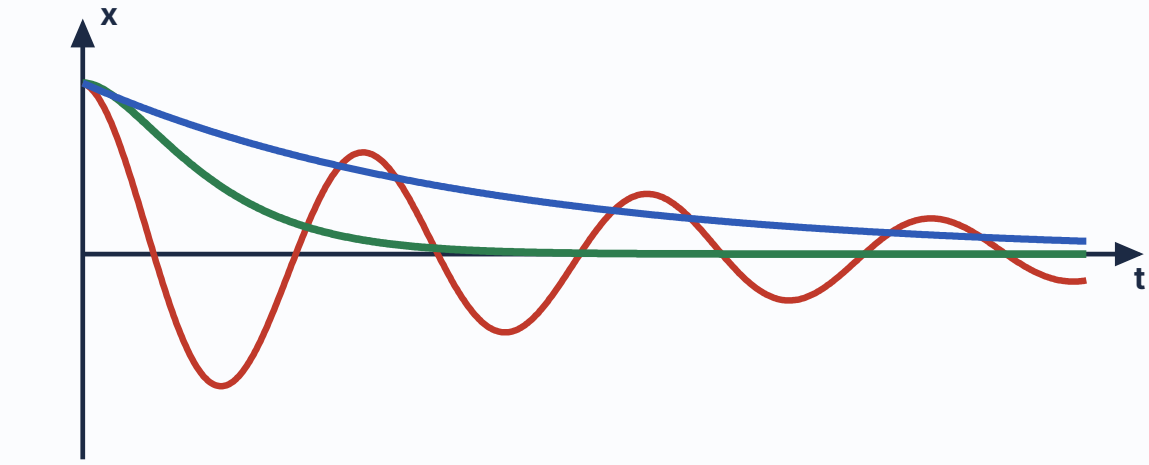
Natural frequency — the frequency at which a system oscillates when displaced and left alone.

Resonance — a large amplitude of oscillation when the driving frequency equals the natural frequency; energy is transferred most efficiently.



More damping: lower, broader peak, shifted slightly below f_o.

The same system driven over a range of frequencies, with three levels of damping.



light: decaying oscillation **critical: fastest return** **heavy: slow return**

Displacement against time after one push.

Light damping — oscillations continue with slowly decreasing amplitude.

Critical damping — the system returns to equilibrium in the shortest time without oscillating (car suspension, door closers).

Heavy damping — no oscillation, but a slow return to equilibrium.

- **Useful resonance:** musical instruments, microwave ovens (water molecules), radio tuning, MRI. **Harmful resonance:** bridges in wind or crowds, engine vibrations, buildings in earthquakes; damping and changing natural frequency are the cures.

LINKING QUESTION

A standing wave on a string is the superposition of C.2 travelling waves; the same quantisation idea (only certain wavelengths fit) appears for electrons in atoms (E.1, E.2).

IDEA FOR YOUR IA / EXPLORATION

Investigate how the fundamental frequency of a vibrating string depends on tension (with a signal generator and vibration generator), and test $f \propto \sqrt{T}$.

Test yourself — cover the answers first

QUICK CHECK

1. What is the distance between two adjacent nodes?
2. Does a standing wave transfer energy along its length?
3. A string's length is halved (same tension). What happens to its fundamental?
4. Which harmonics does a pipe closed at one end have?
5. What is critical damping?
6. What happens to the resonance peak when damping increases?

EXAM-STYLE

7. A tube closed at one end resonates at 425 Hz and next at 1275 Hz ($v = 340$ m s^{-1}). Find its length.
8. A standing wave on a 1.2 m string fixed at both ends has 4 loops at 100 Hz. Find the wave speed.

Show answers

1. $\lambda/2$
2. no
3. it doubles
4. odd harmonics only
5. return to equilibrium in the shortest time without oscillating
6. lower and broader (and slightly lower frequency)
7. 1275/425 = 3, so 425 Hz is the fundamental
   $L = v/4f = 340/(4 \times 425)$
   = **0.20 m**
8. 4 loops = 4 half-wavelengths, so $\lambda = 2 \times 1.2/4 = 0.60$ m
   $v = f\lambda = 100 \times 0.60$
   = **60 m s^{-1}**

Stuck on a question?

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