C.4 Standing waves and resonance

International Baccalaureate · IB Diploma · Physics · HL

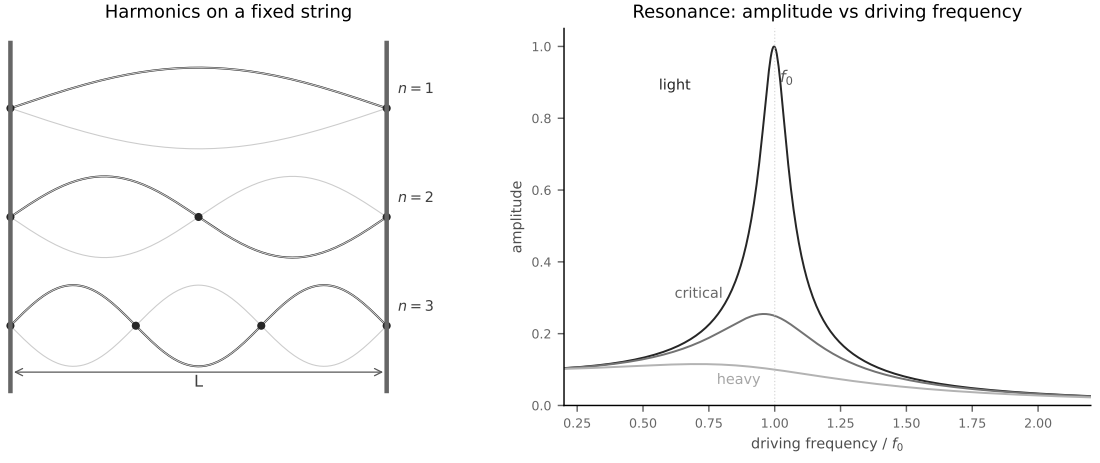
Scope and prerequisites

Full guide C.4 scope (Standing waves and resonance), first assessment 2025. Read directly from the Physics guide, pages 48–49. Prerequisites: C.1 (oscillation vocabulary) and C.3 (superposition).

These are original teaching examples, not actual measurements or completed assessed learner investigations.

Standing waves: superposition of opposites

Two **identical waves travelling in opposite directions** – usually a wave and its reflection – superpose into a **standing wave** : the pattern stays put while the medium oscillates inside it. Where the two always cancel there is a **node** (zero displacement); where they always reinforce there is an **antinode** (maximum amplitude). Two points between neighbouring nodes oscillate **in phase** ; points on opposite sides of a node are in **antiphase** – unlike a travelling wave, the phase does not march along.



First three harmonics on a string fixed at both ends, and the resonance curves of a driven oscillator under light, critical and heavy damping.

Boundary conditions: strings and pipes

The ends decide which wavelengths fit. A fixed string end (or the closed end of a pipe) must be a displacement **node**; a free string end (or the open end of a pipe) must be an **antinode**. Pipes are described in displacement terms only (pressure nodes are not required, and no end corrections).

Boundaries	Allowed wavelengths	Harmonic frequencies
Fixed–fixed string; closed–closed pipe (node–node)	$\lambda_n = 2L/n$	$f_n = nv/2L$
Fixed–free string; closed–open pipe (node–antinode)	$\lambda_n = 4L/(2n-1)$	$f_n = (2n-1)v/4L$ – odd harmonics only
Free–free string; open–open pipe (antinode–antinode)	$\lambda_n = 2L/n$	$f_n = nv/2L$

The lowest-frequency mode is the **first harmonic** (the terms "fundamental" and "overtone" are not used in this course). Determining the wavelength and frequency of the nth harmonic from the length and wave speed is a required skill.

Worked check (string). A string of length 0.60 m carries waves at 240 m/s. First harmonic: $\lambda_1 = 2L = 1.2$ m, $f_1 = v/2L = 240/1.2 = 200$ Hz; the second harmonic doubles to 400 Hz, the third to 600 Hz.

Worked check (closed–open pipe). A pipe closed at one end, open at the other, length 0.40 m, air at 340 m/s: $f_1 = v/4L = 340/1.6 = 213$ Hz; the next harmonic is the third, $f_3 = 3f_1 = 638$ Hz – even harmonics cannot form.

Worked check (open–open pipe). The same pipe opened at both ends: $f_1 = v/2L = 340/0.80 = 425$ Hz, an octave above the closed–open first harmonic, and every harmonic is allowed.

Resonance and damping

Every elastic system has a **natural frequency** – the rate at which it oscillates when left alone. Drive it with a periodic force and the response depends on the **driving frequency** : when the driving frequency approaches the natural frequency the amplitude grows sharply – **resonance** . Energy arrives at exactly the rate the system can absorb it, so the amplitude at resonance is limited only by how fast energy dissipates.

Damping – the removal of oscillation energy – reshapes the response: it lowers the maximum amplitude, shifts the resonant peak slightly below the natural frequency, and broadens it.

- **Light damping** – a tall, sharp peak; large resonant amplitude (a swing pushed gently at its natural frequency).
- **Critical damping** – the oscillation dies away in the shortest time without passing the equilibrium point; the resonance peak has effectively vanished (car suspension).

- **Heavy damping** – slow, sluggish return; the system barely responds at any driving frequency (a heavy door closer).

Resonance is wanted and engineered (musical instruments, radio tuning, MRI) and unwanted or destructive (the Tacoma Narrows bridge, machinery shaking itself apart, soldiers breaking step on a bridge) – the guide asks for both sides.

Check yourself

1. State how a standing wave forms, and why nodes stay fixed while the medium between them moves.
2. Two points on a standing wave lie either side of a node, each 0.15 m from it. State their phase difference.
3. A string fixed at both ends is 0.75 m long and carries waves at 150 m/s. Calculate the first and second harmonic frequencies.
4. Explain why a closed–open pipe produces only odd harmonics.
5. A pipe of length 0.50 m is open at both ends; the air speed is 340 m/s. Calculate the first harmonic frequency and the wavelength of the second harmonic.
6. Sketch or describe how the resonance curve of a lightly damped system changes as damping increases.
7. Give one useful and one destructive effect of resonance, with the physical reason each happens.

Answers: 1 two identical waves travelling in opposite directions superpose; at a node their displacements always cancel, so it never moves, while between nodes the superposition oscillates; 2 antiphase – 180° (π rad) apart; 3 $f_1 = v/2L = 150/1.5 = 100$ Hz, $f_2 = 200$ Hz; 4 the closed end must be a node and the open end an antinode, so only an odd number of quarter-wavelengths fits – even harmonics cannot meet both conditions; 5 $f_1 = v/2L = 340/1.0 = 340$ Hz; $\lambda_2 = L = 0.50$ m; 6 the peak falls, broadens, and shifts slightly below the natural frequency; 7 useful – a radio circuit tuned to resonance picks one station out of many because it responds only near its natural frequency; destructive – driving at the natural frequency feeds energy in faster than it dissipates, so the amplitude grows until the structure fails.