Unit 9 · Acoustic Phenomena

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Waves and Optics (Units 6–13 together): 15 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** an MCQ: the quality of a sound depends on its waveform; in a short question (with Unit 8's flute): a flute played on a moving bus: a passenger on the bus hears no change (no relative motion), a listener on the road hears it higher as the bus comes, lower as it goes
- **MCQ (1 mark)**
  - intensity $\propto a^2$; pitch on frequency
  - intensity × 100 $\rightarrow$ +20 dB
  - Doppler: source or listener moving, both moving, two trains
  - original frequency from the one heard
  - speed of a car from the shift
  - reflection from a moving car or cliff (echo)
- **Short and long (5 or 8 marks, in parts)**
  - pressure amplitude; intensity from it
  - intensity vs loudness; Weber–Fechner; decibels
  - pitch and quality; instruments
  - inverse square law
  - derive the Doppler formulas: source moving, listener moving, both
  - Doppler: applications, when there is no shift
  - numericals: $I = (\Delta P)^2/2\rho v$, dB changes, $I = P/4\pi d^2$, f'

Key terms

Acoustics: the physics of sound (architectural, musical, bio-, medical acoustics).

Displacement amplitude a: greatest distance a layer of air moves from its place.

Pressure amplitude $(\Delta P)_{\max}$: greatest rise or fall of pressure from normal; what the ear and microphones respond to.

Intensity I: average sound energy a second through unit area at right angles to the wave; W/m^2; objective.

Threshold of hearing I_0: 10^{-12} W/m^2 at about 1000 Hz (0 dB).

Threshold of pain: about 1 W/m^2 (120 dB).

Loudness: how strong a sound seems; a sensation, subjective.

Intensity level β: $10\log(I/I_0)$ in decibels; one bel = $10 \times I_0$.

Pitch: how high or low a sound seems; set mainly by frequency.

Quality (timbre): what tells two sounds of the same pitch and loudness apart; set by the overtones, the **waveform**.

Infrasound / audible / ultrasound: below 20 Hz / 20 Hz–20 kHz / above 20 kHz.

Mach number: speed of an object ÷ speed of sound; above 1 supersonic, above 5 hypersonic.

Shock wave / sonic boom: waves piled on a cone behind a supersonic object / the bang as the cone passes.

Doppler effect: apparent change in frequency from the relative motion of source and observer.

Red / blue shift: light from a receding / approaching source, wavelength longer / shorter.

Formulas

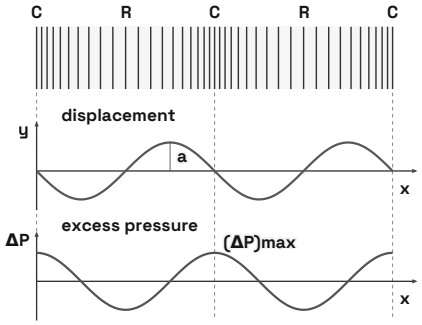
$\Delta P = -B\frac{dy}{dx}$	B bulk modulus **Use:** pressure change
$(\Delta P)_{\max} = Bak = \rho v \omega a$	$\propto a$ **Use:** pressure amplitude
$I = 2\pi^2 f^2 a^2 \rho v$	$\propto a^2, \propto f^2$ **Use:** intensity
$I = \frac{(\Delta P)^2_{\max}}{2\rho v}$	from a microphone **Use:** intensity
$I = \frac{P}{4\pi d^2}$	$I \propto 1/d^2$ **Use:** point source
$\beta = 10\log_{10}\frac{I}{I_0}$	$I_0 = 10^{-12}$ W/m^2 **Use:** decibels
$\Delta\beta = 10\log\frac{I_2}{I_1} = 20\log\frac{d_1}{d_2}$	double distance −6 dB **Use:** two levels

$f' = \frac{v}{v - v_s} f$	source towards (away: +) **Use:** moving source
$f' = \frac{v + v_l}{v} f$	listener towards (away: −) **Use:** moving listener
$f' = \frac{v \pm v_l}{v \mp v_s} f$	upper signs for towards **Use:** both moving
$f' = \frac{v + u}{v - u} f$	moving towards the wall at u **Use:** echo
$v_s = \frac{\Delta\lambda}{\lambda} c$	$v_s \ll c$; red shift: receding **Use:** light
$\sin\theta = \frac{v}{v_s} = \frac{1}{M}$	half-angle **Use:** Mach cone

Pressure amplitude

$(\Delta P)_{\max} = \rho v \omega a$

1. a cylinder of air $A\,\Delta x$; its ends move y_1, y_2: $\Delta V = A\,\Delta y$
2. $\Delta P = -B\frac{\Delta V}{V} = -B\frac{\Delta y}{\Delta x} \to -B\frac{dy}{dx}$
3. $y = a\sin(\omega t - kx) \to \frac{dy}{dx} = -ak\cos(\omega t - kx)$
4. $\Delta P = Bak\cos(\omega t - kx) \to (\Delta P)_{\max} = Bak$
5. $B = \rho v^2$, $k = \omega/v \to \rho v \omega a = 2\pi f \rho v a$



Layers, displacement y and excess pressure: ΔP is greatest where $y = 0$.

- pressure (cos) and displacement (sin) **90° out of phase**: at a compression's centre the air doesn't move

Intensity

1. power through A = force × particle velocity: $I = [\Delta P\, v_p]_{\text{avg}}$
2. $\Delta P = Bak\cos\theta$, $v_p = dy/dt = a\omega\cos\theta$
3. $\cos^2\theta$ averages ½: $I = \frac{1}{2}Ba^2k\omega$
4. $B = \rho v^2$, $k = \omega/v$: $I = \frac{1}{2}\rho v\omega^2a^2 = 2\pi^2f^2a^2\rho v$

- v (wave, 340 m/s) ≠ v_p (air swinging, under a mm/s)
- $I \propto a^2$ at a fixed frequency; same a, twice $f \to 4\times I$
- 0.5 Pa in air (1.2 kg/m^3, 340 m/s): $I = 0.25/816 = 3.06\times10^{-4}$ W/m^2

Intensity, loudness, decibels

- ear most sensitive at 2–5 kHz, so I_0 is quoted at 1 kHz; pain at 120 dB (some people 130)
- inverse square: power spread over $4\pi d^2$; twice as far, a quarter; 2 m → 8 m, 1/16

Intensity	Loudness
energy a second per area	how strong it seems
objective, a sound meter, W/m^2	subjective, the ear; compared in dB
depends on the wave and distance	also frequency, background noise, the listener

Weber–Fechner law: loudness $\propto \log I$

1. $L = k\log I$; unit chosen so $k = 1$
2. at the threshold $L_0 = \log I_0$
3. $\beta = L - L_0 = \log(I/I_0)$ bel $= 10\log(I/I_0)$ dB

- +10 dB = 10 × I; +20 dB = 100 ×; +3 dB ≈ 2 × (two equal machines: 80 → 83 dB)
- whisper 30, conversation 60–70, traffic 80, bus horn 110, concert 120, jet at 30 m 140 dB
- $10^{-8} \to 10^{-5}$ W/m^2: $10\log 1000 = +30$ dB

Loudness depends on

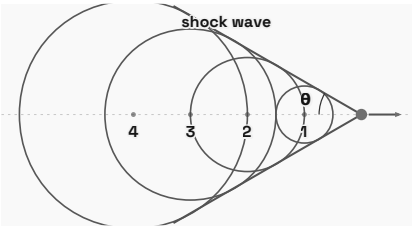
1. amplitude ($I \propto a^2$)
2. surface area of the vibrating body (a guitar's body)
3. distance
4. motion of the medium (wind)
5. reflecting or absorbing bodies nearby
6. frequency: at the same I, loudest at 2–5 kHz (not "rises with frequency" without limit)

Pitch and quality

Frequency	Pitch
vibrations a second	how high it seems
objective, Hz	subjective, by ear
any vibration	only audible sounds
doubled: twice the number	doubled: up one **octave**

- whistle high, bass drum low; women's and children's voices higher (shorter, lighter vocal cords)
- infrasound: earthquakes, storms; elephants (~15 Hz), whales
- ultrasound: bats and dolphins echolocate; uses: sea depth (sonar), scans of a baby, faults in metal, cleaning, welding plastics, killing bacteria
- **quality**: fundamental + which overtones and how strong → waveform; tells a violin from a bansuri on the same note; recognises voices (forensic acoustics)

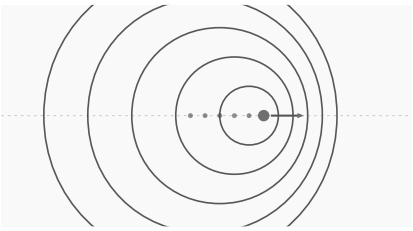
Supersonic



Mach 2: waves from points 1–4 pile onto the cone's edges; $\sin\theta = 1/M$.

- source outruns its waves → shock wave on a cone; boom heard as the cone sweeps past, all along the path
- Mach 2: $\sin\theta = \frac{1}{2}$, $\theta = 30°$

Doppler effect



Source at half the speed of sound: crowded ahead ($\lambda' = (v - v_s)/f$), spread behind.

Source moving, listener still

1. f waves a second; the first goes v, the source v_s behind it
2. they fill $v - v_s$: $\lambda' = \frac{v - v_s}{f}$ (wavelength changed)
3. still arrive at v: $f' = \frac{v}{\lambda'} = \frac{v}{v - v_s} f > f$
4. away: $\lambda' = \frac{v + v_s}{f}$, $f' = \frac{v}{v + v_s} f < f$

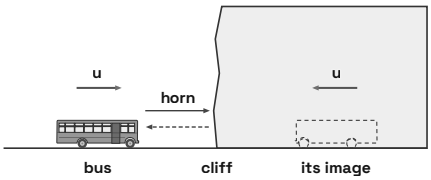
Listener moving, source still

1. λ unchanged; waves pass the listener at v_R
2. towards: $v_R = v + v_l \rightarrow f' = \frac{v + v_l}{\lambda} = \frac{v + v_l}{v} f$
3. away: $v_R = v - v_l \rightarrow f' = \frac{v - v_l}{v} f$

Both moving: $f' = \frac{v_R}{\lambda'}$

1. towards each other: $\frac{v + v_l}{v - v_s} f$; apart: $\frac{v - v_l}{v + v_s} f$
2. source following: $\frac{v - v_l}{v - v_s} f$; listener following: $\frac{v + v_l}{v + v_s} f$
3. same speed, same way: $f' = f$

- source moving changes λ; listener moving changes the **speed relative to him**: 30 m/s each way, 500 Hz → 548.4 vs 544.1 Hz
- signs: ask "towards or away?" for each; towards always raises f'; speeds relative to the air
- siren drops at the moment it passes; a flute on a bus: same note for the passengers



The echo comes from the bus's image behind the cliff, approaching at u.

- echo, approaching: $\frac{v + u}{v - u} f$; receding: $\frac{v - u}{v + u} f$
- bat at 10 m/s, 40 kHz: echo $40 \times 350/330 = 42.4$ kHz

No shift, or the formula fails, when

1. both still, or same speed same way; motion at right angles to the line
2. the medium changes (temperature, wind)
3. source faster than sound (shock wave instead)
4. motion not steady or not along the line: use the part along it

- light: $\lambda' = (1 + v_s/c)\lambda \rightarrow v_s = \frac{\Delta\lambda}{\lambda} c$; galaxies red-shifted → the universe is expanding
- uses: speed guns, Doppler ultrasound of blood and the heart, stars' and galaxies' speeds, weather radar, sonar, GPS, a cricket ball's speed

COMMON MISTAKES

✗ pitch depends on amplitude
✓ on **frequency**; loudness on amplitude.

✗ quality depends on loudness
✓ on the **waveform** (the overtones).

✗ $2 \times$ intensity $= 2 \times$ loudness
✓ only +3 dB; loudness $\propto \log I$.

✗ loudness always rises with frequency
✓ only up to 3–4 kHz.

✗ pressure and displacement peaks together
✓ 90° apart.

✗ source and listener moving alike give the same f'
✓ source changes λ, listener changes v_R.

✗ source towards: $f' = \frac{v}{v + v_s} f$
✓ $\frac{v}{v - v_s} f$: towards raises it.

✗ a flute on a moving bus sounds higher to the passengers
✓ no relative motion, no shift.

Science Playground, Katunje, Bhaktapur
https://science-playground.com/learn/grade-12-physics/acoustic-phenomena