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Acoustics

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- Principles of sound
  - Definition
  - Wave mechanism
  - Plane waves
  - Point sources
- Properties of sound
  - acoustic pressure
  - acoustic velocity
  - acoustic impedance
- Reflection of sound

from Do Science

Definitions of sound

“Sensation caused in the **ear** by the **vibration** of the surrounding air or other **medium**”, Oxford English Dictionary

“Disturbances in the **air** caused by **vibrations**, information on which is transmitted to the brain by the sense of **hearing**”, Chambers Pocket Dictionary

“Sound is **vibration** transmitted through a **solid, liquid, or gas**; particularly, sound means those vibrations composed of frequencies capable of being detected by **ears**”, Wikipedia

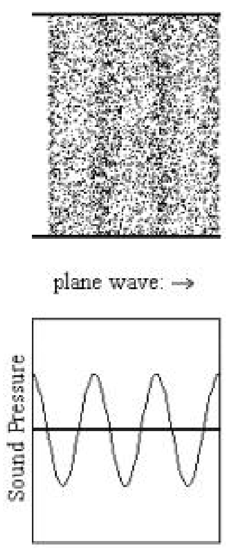
Sound wave fundamentals

- What?
  - small perturbation of particles
- How?
  - adiabatic process with (almost) no loss of entropy
  - propagates longitudinally in a medium
- Effect
  - measurable pressure and velocity fluctuations
  - waves travel at the medium's speed of sound
  - vibrations in the ear perceived by the cochlea

Sound propagating in 1D (plane waves)

Consider a **planar source** (e.g. piston) that emits sound in a normal direction:

- infinite source of pressure or velocity fluctuation
- uniform continuous medium without boundaries to the direction of wave propagation
  e.g., in pipes, vocal tract, exhaust, ducting, far field
- plane wave propagation of the wavefronts



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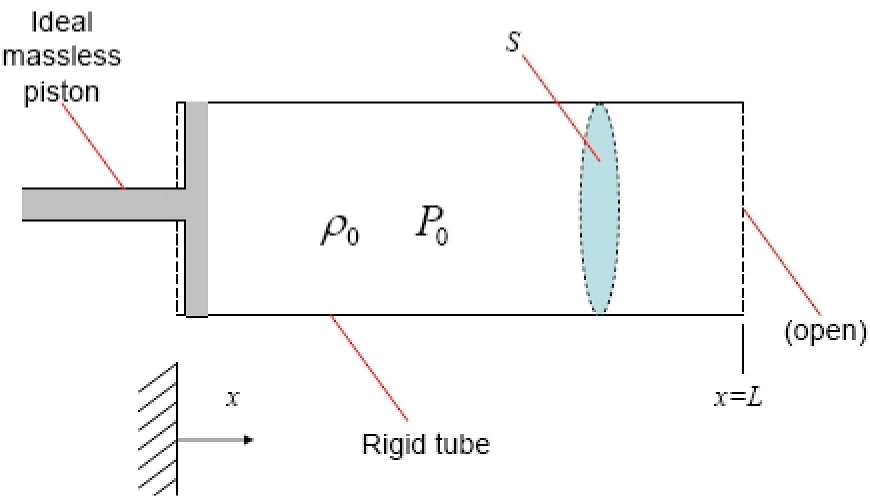


Plane wave equation

In a perfect gas medium, the pressure $P = P_0 + p$ of a given volume depends on density ρ, specific gas constant $r = R/M$, and absolute temperature T: $P = \rho r T$

Adiabatic wave propagation specifies

$$\frac{P}{P_0} = \left(\frac{P_0 + p}{P_0}\right) = \left(\frac{\rho}{\rho_0}\right)^{\gamma} \tag{1}$$

where γ is the ratio of heat capacities for the medium.

Considering continuity of matter and simple forces, we get the 1D plane wave equation (Kinsler et al. 2000, pp. 114-121):

$$\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial x^2} = 0 \tag{2}$$

where $c = \sqrt{\gamma r T}$, which has solutions $f(t \mp (x/c))$, e.g.,

$$p(x,t) = A \cos\left(\omega\left(t - \frac{x}{c}\right) + \phi\right) \tag{3}$$

[L.E. Kinsler et al., *Fundamentals of acoustics*, 4th ed., New York: Wiley, 2000.]

Speed of sound, c

Sound speed depends on medium's inertia and stiffness, which are functions of ambient temperature and pressure (cf. natural frequency of SHM).

In air, eq. 2 gives

$$c_{\text{air},0^\circ\text{C}} = \sqrt{1.4 \times 287 \times 273} \approx 331\,\text{m}\,\text{s}^{-1}$$

$$c_{\text{air},20^\circ\text{C}} = \sqrt{1.4 \times 287 \times 293} \approx 343\,\text{m}\,\text{s}^{-1}$$

For calculations at room temperature, the speed of sound is usually taken as $c_{\text{air}} = 340\,\text{m}\,\text{s}^{-1}$

Sound speed in helium, $c_{\text{He}} = 972\,\text{m}\,\text{s}^{-1}$

Sound speed in water, $c_{\text{H}_2\text{O}} = 1500\,\text{m}\,\text{s}^{-1}$

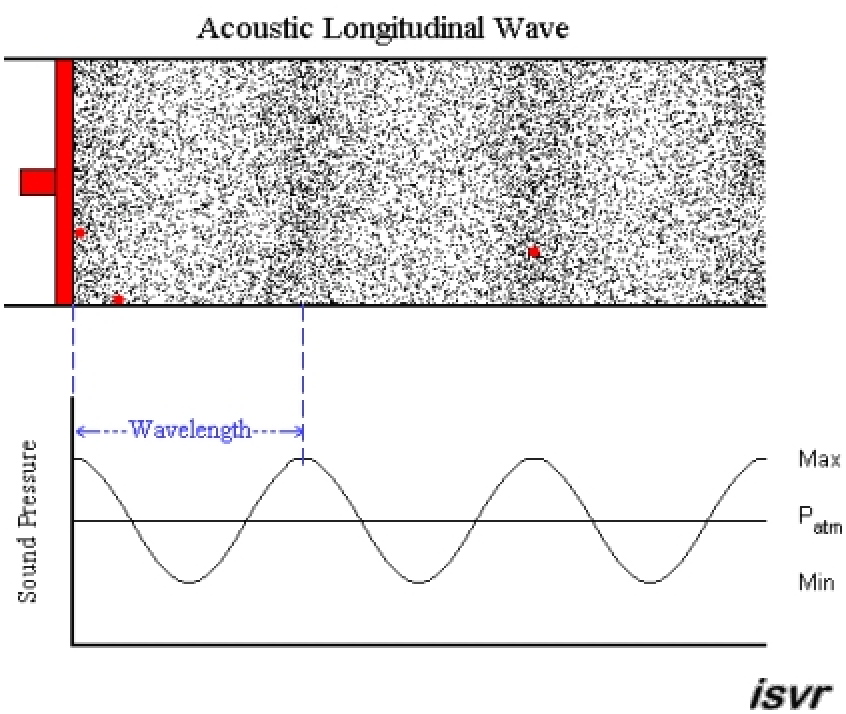
Sound pressure and particle velocity

Like Ohm's law ($V = IR$), **acoustic impedance** z is defined

$$p = uz \quad (4)$$

Unit of impedance is rayl (after Lord Rayleigh):

$$1\,\text{rayl} = 1\,\text{Pa}\,\text{s}\,\text{m}^{-1}$$



For plane waves, the impedance is $z = \rho_0 c$ and so

$$\boxed{p = u\rho_0 c} \quad (5)$$

The impedance in air is $z_{\text{air},20^\circ\text{C}} = 415\,\text{rayl}$

Sound pressure and SPL

For any sound energy, whether propagating as in free field or diffuse as in reverberant field, we calculate equivalent free-field sound level in air from a point measurement.

Sound pressure level (SPL) is defined in dB:

$$\boxed{\mathrm{SPL} = 10\log_{10}\left(\frac{p_{\mathrm{rms}}^2}{p_{\mathrm{ref}}^2}\right)} \tag{6}$$

where $p_{\mathrm{rms}} = A/\sqrt{2}$ and $p_{\mathrm{ref}} = 2\times10^{-5}$ Pa or 20 μPa, which corresponds to the threshold of hearing, approximately.

Note that this can also be written

$$\mathrm{SPL} = 20\log_{10}\left(\frac{p_{\mathrm{rms}}}{p_{\mathrm{ref}}}\right)$$

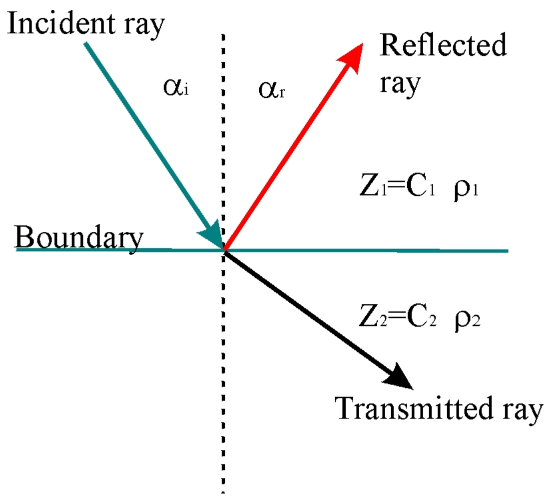
Typical readings are in the range from 0 dB to 140 dB.

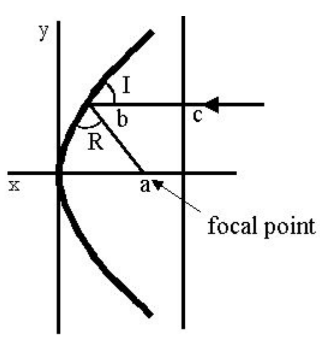
Properties of sound waves

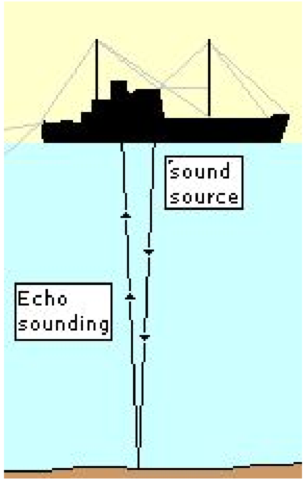
- particle **displacement**, x
  - perturbation from equilibrium position
  - x_{rms} from 0.1 nm to 5 mm
- particle **velocity**, u
  - acoustic velocity or sound velocity
  - u_{rms} from 50 nm s^{-1} to 250 mm s^{-1}
- perturbation **pressure**, p
  - acoustic pressure or sound pressure
  - p_{rms} from 20 μPa to 100 Pa
- **speed** of propagation, c
  - speed of sound or phase velocity
  - $c \approx 340$ m s^{-1} in air
- audible **frequency range** 20 Hz to 20 kHz

Reflection of sound

Sound is reflected at any **interface** between two media, at an **opening** in a baffle, at a **rigid** boundary: wherever there is a *change in the acoustic impedance*:

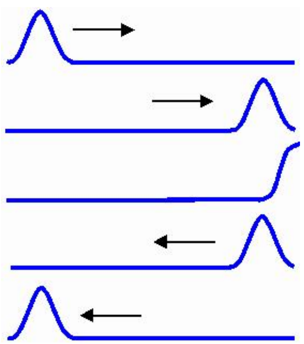


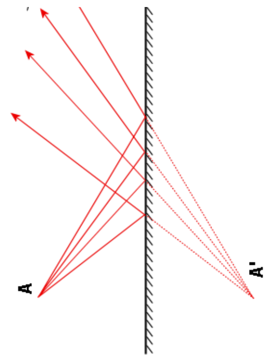


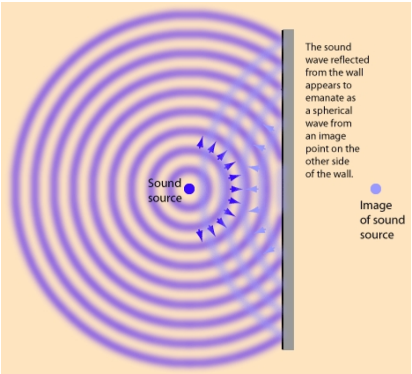


Reflection at a rigid boundary (zero velocity, free pressure)

E.g., at a wall or interface between two fluids



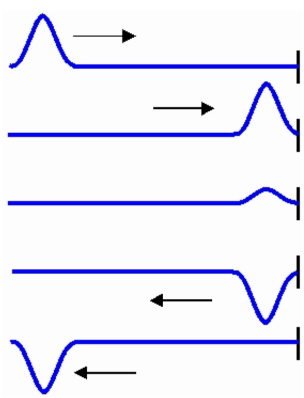


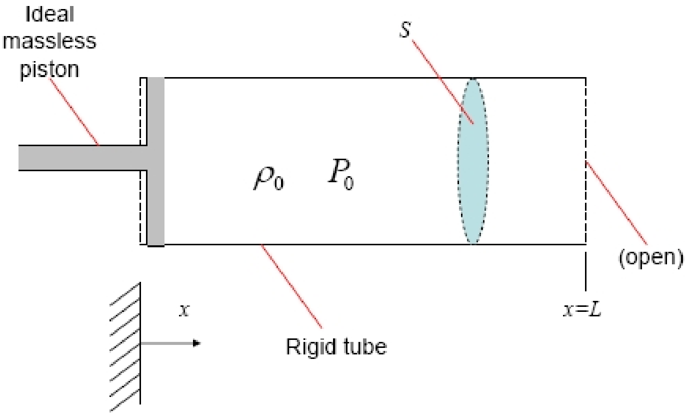


Effect can be modeled by **in-phase** virtual source

Reflection at an opening (tiny pressure, free velocity)

E.g., an exhaust pipe, woodwind instrument, your mouth





Effect can be modeled by **anti-phase** virtual source

Introduction to acoustics

- Principles of sound
  - defined as pressure perturbation in a medium
  - longitudinal waves that propagate isentropically
- Plane (1D) wave equation
  - speed of sound
- Properties of sound waves
  - sound pressure, velocity and SPL
  - acoustic impedance
- Reflection of sound
  - at fixed and free boundaries