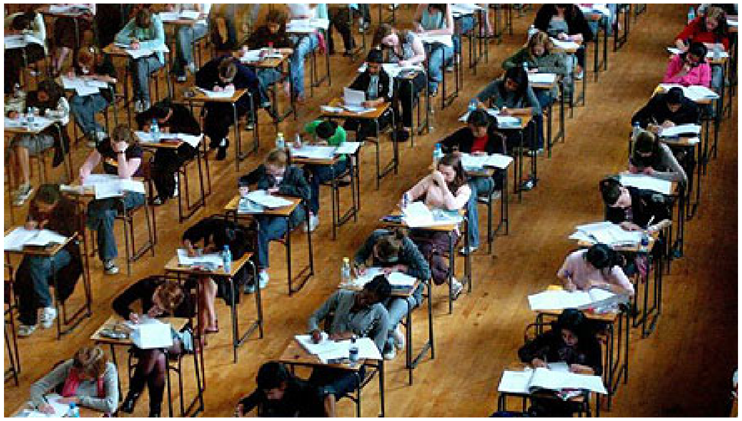
EE1.el3 (EEE1023): Electronics III

Acoustics lecture 21
Revision notes

Dr Philip Jackson



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Overview of Acoustics

- Lecture 12: Principles of sound
- Lecture 13: Human hearing, loudness & pitch
- Lecture 14: Measurement of sound & noise
- Lecture 15: Sound wave behaviour
- Lecture 16: Standing waves & room modes
- Lecture 17: Resonators and waveguides
- Lecture 18: Room acoustics
- Lecture 19: Musical acoustics
- Lecture 20: Sound localisation
- *Lecture 21: Revision notes*
- *Lecture 22: Glossary*

Lecture 12: Principles of sound

The 1-D wave equation for transverse vibration on a string:

$$\rho_L \frac{\partial^2 y}{\partial t^2} = T \frac{\partial^2 y}{\partial x^2} \qquad \Rightarrow \qquad \boxed{\frac{\partial^2 y}{\partial t^2} - v^2 \frac{\partial^2 y}{\partial x^2} = 0}$$

where waves travel along the string with speed $v = \sqrt{T/\rho_L}$

The 1-D plane wave equation for sound in a medium:

$$\frac{\partial^2 p}{\partial t^2} = c^2 \frac{\partial^2 p}{\partial x^2} \qquad \Rightarrow \qquad \boxed{\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial x^2} = 0}$$

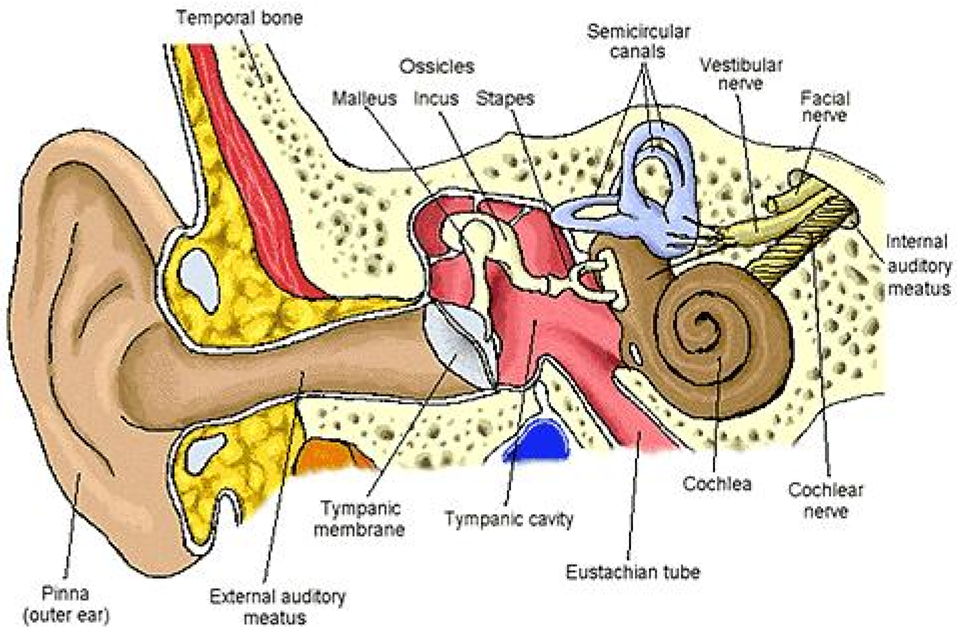
where waves propagate longitudinally with speed $\boxed{c = \sqrt{\gamma r T}}$

General solutions exist of the form:

$$p(x,t) = g\left(t - \frac{x}{c}\right) + h\left(t + \frac{x}{c}\right)$$

where $g(\cdot)$ and $h(\cdot)$ can be arbitrary waveforms

Lecture 13: Human hearing, loudness & pitch

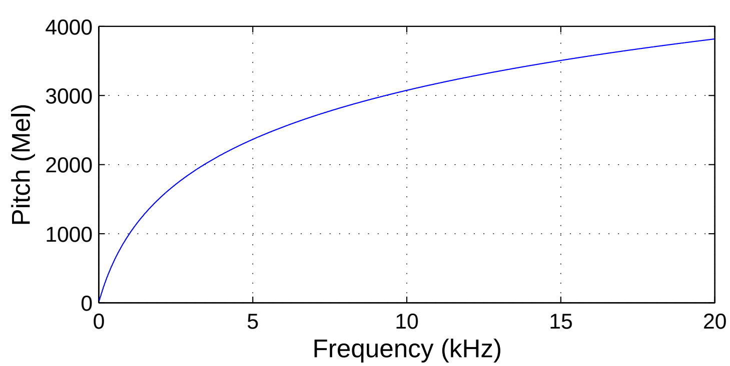


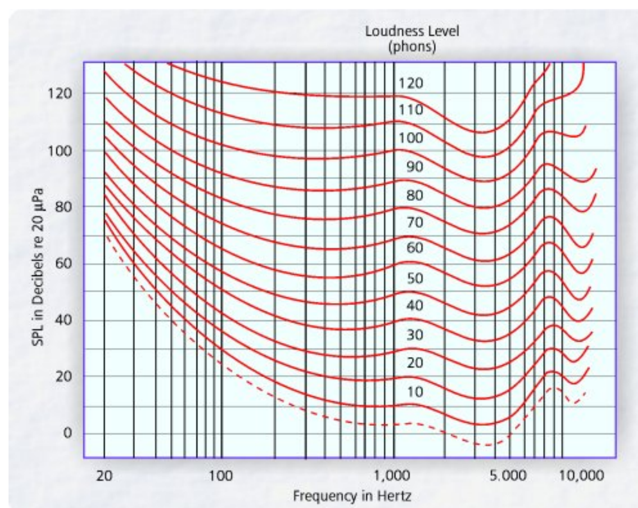
Frequency range ≈ {20 Hz to 20 kHz}

Frequency resolution determined by **critical bands**

Pitch perception

Loudness perception





Lecture 14: Measurement of sound & noise

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

$$\boxed{p = uz}$$

where $z = \rho_0 c$ for plane waves.

Sound from a **point source** with spherical wavefronts:

$$p(r,t) = \frac{1}{r} g\left(t - \frac{r}{c}\right)$$

Sound **power** is the integral of **intensity**, $\boxed{\mathbf{I}(t) = p(t)\,\mathbf{u}(t)}$, over area

$$\boxed{W = \oint_S \mathbf{I}.dS}$$

At radius r from point source, we integrate over a sphere:

$$I = \frac{W}{4\pi r^2}$$

Sound pressure, intensity and power levels

Sound intensity level: $$\text{SIL} = 10\log_{10}\left(\frac{I}{I_{\text{ref}}}\right)$$

where $I_{\text{ref}} = 10^{-12}\,\text{W}\,\text{m}^{-2}$ is the threshold of hearing for humans in the free field

Sound power level: $$\text{SWL} = 10\log_{10}\left(\frac{W}{W_{\text{ref}}}\right)$$

where $W_{\text{ref}} = 10^{-12}\,\text{W}$ is the equivalent intensity over one square metre

Sound pressure level: $$\text{SPL} = 20\log_{10}\left(\frac{p_{\text{rms}}}{p_{\text{ref}}}\right)$$

where $p_{\text{ref}} = 2 \times 10^{-5}\,\text{Pa}$ corresponds to $I_{\text{ref}} \approx p_{\text{ref}}^2/\rho_0 c$ for plane wave propagation in air

Lecture 15: Sound wave behaviour

Soundfield of a **sinusoidal point source** in complex form:

$$\boxed{\mathbf{p}(r,t) = \frac{Q}{r}\,\mathbf{e}^{j(\omega t - kr)}}$$

with source strength Q, and wave number is $k = \omega/c = 2\pi/\lambda$

Diffraction of the wavefronts occurs at wavelengths above (frequencies below):

$$\boxed{D \approx \frac{\lambda_{\text{crit}}}{2}}$$

where D is characteristic dimension of the obstacle or gap.

Refraction occurs at the interface between two media, with sound speeds c_1 and c_2

$$\boxed{\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}}$$

where angles from the normal are θ_1 and θ_2 respectively.

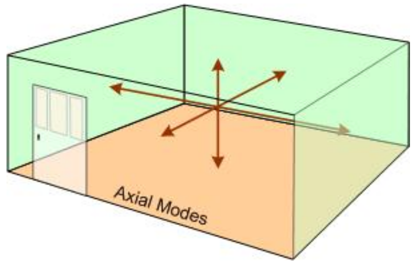
Lecture 16: Standing waves & room modes

The room modes occur at frequencies:

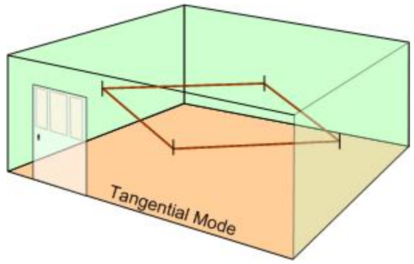
$$f(l,m,n) = \frac{c}{2}\sqrt{\left(\frac{l}{X}\right)^2 + \left(\frac{m}{Y}\right)^2 + \left(\frac{n}{Z}\right)^2}$$

with the mode number (l, m, n) in 3D, for $l, m, n \in \{0, 1, 2, \ldots\}$, which count the number of **nodal planes** along each axis.

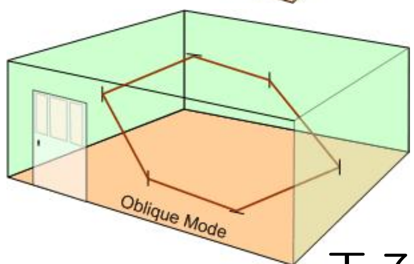
Axial modes have one non-zero dimension and two zeros, e.g., (1-0-0).



Tangential modes have two non-zero dimensions and one zero, e.g., (1-2-0).



Oblique modes have all three non-zero dimensions, e.g., (1-1-1).



Lecture 17: Resonators and waveguides

Resonance frequencies of standing-wave modes

in an open pipe:

$$\boxed{f(n) = \frac{n\,c}{2L_O}}$$

in a semi-closed pipe:

$$\boxed{f(m) = \frac{(2m-1)c}{4L_S}}$$

For **transverse modes**, the longitudinal wavenumber k_z depends on the transverse wavenumbers, but is only real above the **cut-on frequency**:

$$\boxed{f_{\text{cut-on}} = \frac{c}{2\pi}\sqrt{k_x^2 + k_y^2}}$$

Lecture 18: Room acoustics

As $t \to \infty$, the **energy density** reaches equilibrium:

$$\boxed{\mathcal{E}^{\infty} = \frac{4W}{S\alpha c}}$$

The **reverberation time**, T_{60}, is the time for the SPL in a room to drop by 60 dB:

$$\boxed{T_{60} = \frac{KV}{S\alpha}}$$

where $K = 24/(c \log_{10} \mathrm{e}) \approx 0.16\,\mathrm{s\,m^{-1}}$ gives Sabine's Eq.

The **critical distance** is defined as:

$$\boxed{d_c = \frac{1}{4}\sqrt{\frac{R_A}{\pi}}}$$

where $R_A = S\alpha/(1-\alpha)$ is the room absorption constant.

Lecture 19: Musical acoustics

Acoustic wave-guide model of musical instruments

The **Helmholtz resonance frequency**:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S}{LV}}$$

Revision summary

- Read and digest lecture notes
  - summarise topics
  - identify areas for further study

- Practise on examples
  - review worked examples
  - complete exercises
  - do additional exercises in books

- Rehearse exam technique
  - attempt past exam paper