4. THE ACOUSTICS OF THE BODY

4.1. THE NATURE AND CHARACTERISTICS OF SOUND

"Although humans make sounds with their mouths and occasionally look at each other, there is no solid evidence that they actually communicate with each other."

For the human being sound is one of the most important ways to communicate by:

- expressing himself through speech
- obtaining information through listening
- obtaining stimulation (music)

Sound allows more complex information transfer than, for example, visual impressions.

Tools of information exchange through sound are:

- throat - mouth tract for producing and modulating speech sounds
- ear for listening and analyzing sounds

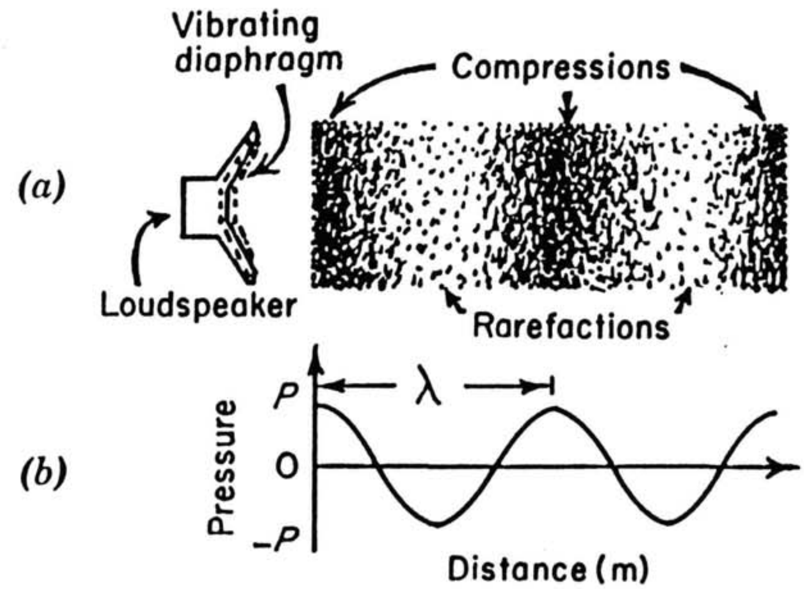
Sound can be used as a diagnostical tool:

- body as resonator $\Rightarrow$ stethoscope
- transmission and reflection of sound $\Rightarrow$ ultrasound imaging

Review of general principles of acoustics is necessary to appreciate the sensitivity of the human sound system.
It is also important for understanding acoustical diagnostics.

Transmission of sound requires matter (air, liquids, solids) as transmitting medium,
unlike light (e.m. waves) which can travel through matter free space!

Sound represents a longitudinal wave of wavelength λ and frequency f which is transmitted by pressure (density) changes with the speed of sound v in transmitting medium.



wave behaviour can be described by wave equation:

$$A = A_0 \cdot sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right) = A_0 \cdot sin 2\pi f\left(t - \frac{x}{v}\right)$$

A is displacement of molecules in transmitting medium at position x and time t, A_0 is maximum displacement of molecules.

Well known relation between speed of sound v, frequency of sound f, and wavelength λ

$$v = \lambda \cdot f$$

speed of sound is a material constant (depends on molecular structure, temperature, and density of material), therefore product of wavelength and frequency is constant.

Values of ρ, ν and Z for Various Substances

	ρ (kg/m^3)	v (m/s)	Z (kg/m$^2 \cdot$ s)
Air	1.29	3.31×10^2	430
Water	1.00×10^3	14.8×10^2	1.48×10^6
Fat	0.92×10^3	14.5×10^2	1.33×10^6
Muscle	1.04×10^3	15.8×10^2	1.64×10^6

Human sound system operates within a certain frequency range:

- range of human voice: 64 Hz (male bass) to 2050 Hz (2.05 kHz) (female soprano)
- range of human ear: 20 Hz to 20000 Hz (20 kHz)
- frequencies below audible range: infrasound
- frequencies above audible range: ultrasound

EXAMPLE

wavelengths of soprano and bass sound:

$$\lambda_{bass} = \frac{344\ m/s}{64\ Hz} = 5.38\ m \qquad \lambda_{soprano} = \frac{344\ m/s}{2050\ Hz} = 0.168\ m$$

The capability of hearing does not only depend on the frequency of sound but also on the intensity!

whisper - scream

The intensity of sound I is correlated to energy E [J] per time t [s] and area $[m^2]$:

$$I = \frac{E}{t \cdot area}\ [\frac{J}{s \cdot m^2}] = [\frac{W}{m^2}]$$

The mechanical energy of a sound wave with frequency f and speed v necessary to move a single molecule by a maximum distance A_0 is:

$$E = 1/2 \cdot m \cdot v^2\ \ [J] \quad \rightarrow \quad E = 2\pi^2 m A_0^2 f^2\ \ [J]$$

The total intensity can be expressed in terms of density ρ

$$I = \frac{1}{2} \cdot \rho \cdot v\ A^2\ (2\pi \cdot f)^2\ \ [W/m^2]$$

The product of density and speed of sound is a material constant and is called the acoustic impedance Z.

$$I = \frac{1}{2} \cdot Z \, (A \cdot \omega)^2 \;\; [W/m^2]$$

with $\omega = 2\pi \cdot f$ as angular frequency.
The intensity can be expressed in terms of change of pressure P in transmitting medium:

$$I = \frac{1}{2} \cdot \frac{P^2}{Z}$$

Audible sound intensities at ≈1000Hz range from 10^{-12} [W/m^2] (quiet) to 1 [W/m^2] (loud)!

Audible range covers twelve orders of magnitude: unsurpassed in sensitivity!!!

EXAMPLE

What is the displacement range for air molecules corresponding to the audible intensity range at an average frequency f = 1000 Hz?

$$A_{loud} = \frac{1}{2\pi \, f} \left(\frac{2 \cdot I}{Z} \right)^{1/2} = \frac{1}{6280} \sqrt{\frac{2 \cdot 1}{430}} = 1.1 \cdot 10^{-5} \; [m] = 10 \; [\mu m]$$

displacement corresponds to size of a cell!

$$A_{quiet} = \frac{1}{2\pi \, f} \left(\frac{2 \cdot I}{Z} \right)^{1/2} = \frac{1}{6280} \sqrt{\frac{2 \cdot 10^{-12}}{430}} = 1.1 \cdot 10^{-11} \; [m] = 10 \; [pm]$$

displacement corresponds to the size of the atom!

What is the displacement range for the ear drum diaphragm corresponding to the audible intensity range?

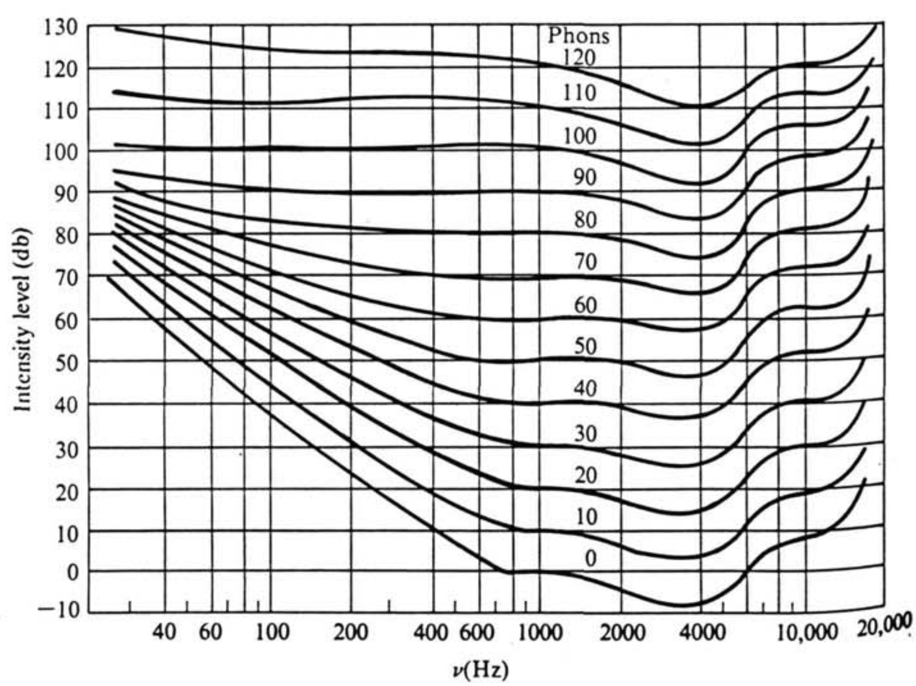
$$Z = \rho \cdot v = 1.64 \cdot 10^6 \quad [kg/(m^2 \cdot s)]$$

$$A_{loud} = \frac{1}{2\pi\ f} \left(\frac{2 \cdot I}{Z}\right)^{1/2} = 1.8 \cdot 10^{-7} [m] \quad for \;\; I = 1\ [W/m^2]$$

$$A_{quiet} = \frac{1}{2\pi\ f} \left(\frac{2 \cdot I}{Z}\right)^{1/2} = 1.8 \cdot 10^{-13} [m] \quad for \;\; I = 10^{-12}\ [W/m^2]$$

molecular structure of diaphragm allows less displacement.

Correlation of sensitivity range of human ear with respect to frequency and intensity of sound waves!



UNITS OF SOUND INTENSITIES FOR AUDITORY SYSTEMS

It is difficult to assign absolute intensity units for auditory systems because absolute values always depend on medium and pressure conditions. In air they also depend on atmospheric pressure which changes with height and weather conditions.
Therefore relative intensity units have been established which depend on intensity ratios.
Typically intensity is normalized to lowest audible intensity
$I_0 \; = \; 10^{-12} \; [W/m^2]$

International standard unit corresponding to an intensity ratio of 10:
I_2/I_1=10 corresponds to 1 bel

(in honor of Graham Bell)

$$1[bel] = log_{10}\frac{I_2}{I_1}$$

The bel unit represents a rather crude scale, therefore the introduction of decibels: **1db = 0.1 bel**

$$1db = 10 \cdot log_{10}\frac{I_2}{I_1}$$

As shown before, sound intensity is directly related to pressure change:
$I \propto P^2$

$$1db = 10 \cdot log_{10}\frac{I_2}{I_1} = 10 \cdot log_{10}\left(\frac{P_2}{P_1}\right)^2 = 20 \cdot log_{10}\frac{P_2}{P_1}$$

If a sound wave causes a pressure difference of two: $20 \cdot log2 = 6$ db
if sound wave causes a pressure difference of ten: $20 \cdot log10 = 20$ db

Audible intensities are referenced to lowest audible intensity

$$I_0 = 10^{-12} \ [W/m^2]$$

$$P_0 = \sqrt{I_0 \cdot 2 \cdot Z} = 3 \cdot 10^{-5} \ [Pa]$$

the most intense sound which can be heard without inflicting pain or damage is $I = 1 \ [W/m^2]$;
this corresponds to intensity in decibels:

$$10 \cdot log_{10} \frac{10^{12}}{1} = 120 \ [db]$$

$$120 \ [db] = 20 \cdot log_{10} \frac{P}{P_0} \rightarrow \frac{P}{P_0} = 10^6 \rightarrow P = 30 \ [Pa]$$

Approximate intensities of day-to-day sounds humans are exposed to!

Approximate Intensities of Various Sounds

	Intensity (W/m^2)	Level (dB)
Sound that is barely perceptible	10^{-12}	0
Whisper	10^{-10}	20
Average dwelling	10^{-9}	30
Business office	10^{-7}	50
Speech at 1 m	10^{-6}	60
Busy street	10^{-5}	70
Subway or automobile	10^{-3}	90
Sound that produces pain	10^{0}	120
Jet aircraft	10^{1}	130
Rocket on launch pad	10^{5}	170

EXAMPLE

Intensity levels of 160 db can cause damage of the ear drum diaphragm. What is the displacement of the diaphragm at such an intensity adopting an average frequency of $f = 1000$ Hz?

$$A = \frac{1}{2\pi\, f} \cdot \sqrt{\frac{2 \cdot I}{Z}} \qquad with\ \ Z = 1.64 \cdot 10^6\ \ [kg/m^2 s]$$

$$10 \cdot log \frac{I}{I_0} \;=\; 160\ db \qquad log \frac{I}{I_0} \;=\; 16 \quad I \;=\; 10^{-12} \cdot 10^{16} \;=\; 10^4 \quad [W/m^2]$$

$$A = \frac{1}{2\pi\ 1000\ Hz} \cdot \sqrt{\frac{2 \cdot 10^4}{1.64 \cdot 10^6}} \;=\; 1.76 \cdot 10^{-5}\, [m] \;=\; 0.018\, [mm]$$