

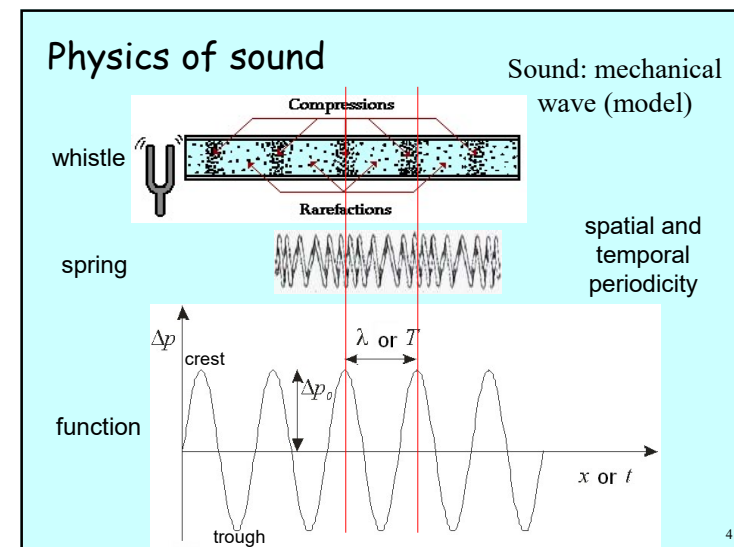
Physics of sound

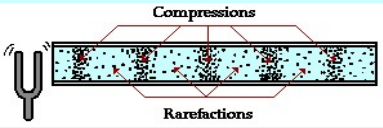
Longitudinal vs. Transverse wave

longitudinal wave
(in the interior of liquids and gases only this type)

transverse wave
can generated in solid materials and at liquid surfaces

3



whistle 


hydrostatic pressure pressure change, sound pressure

$$p_{\text{total}} = p_{\text{hydrostat}} + \Delta p$$

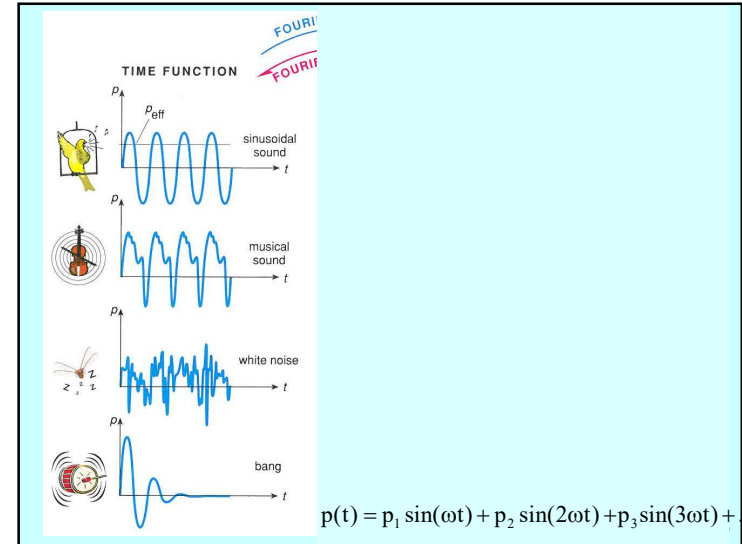
pressure DC + AC amplitude phase

$$\Delta p(t, x) = \Delta p_{\text{max}} \sin \left[2\pi \left(\frac{t}{T} - \frac{x}{\lambda} \right) \right]$$

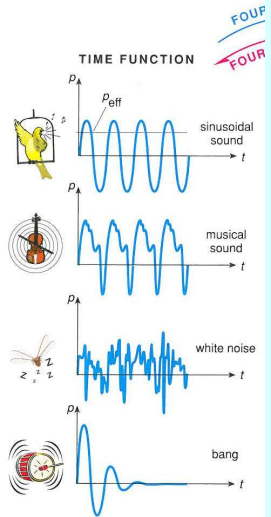
$c \cdot T = \lambda, \quad c = f \cdot \lambda$



5



TIME FUNCTION

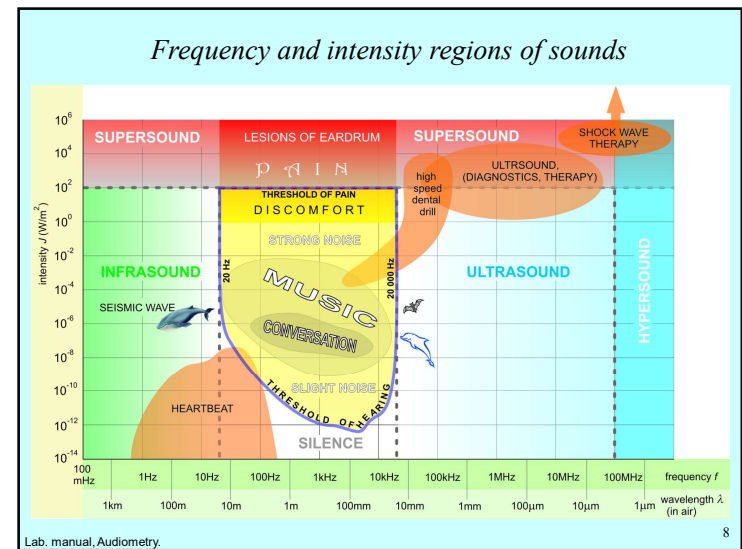


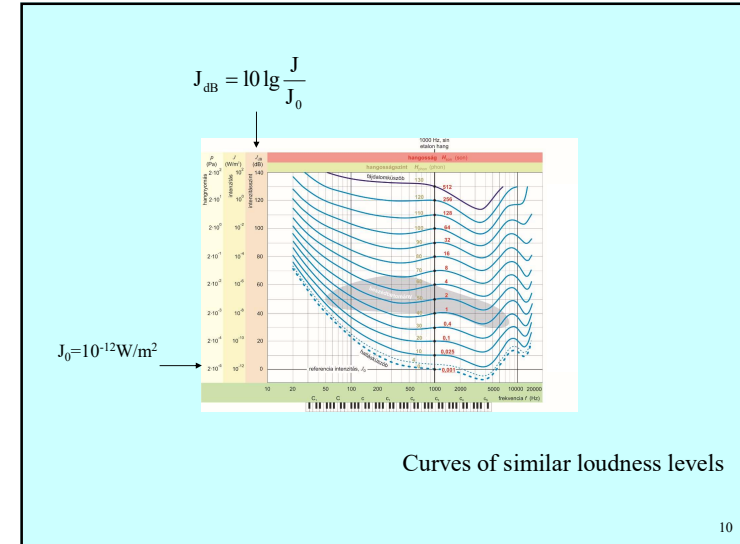
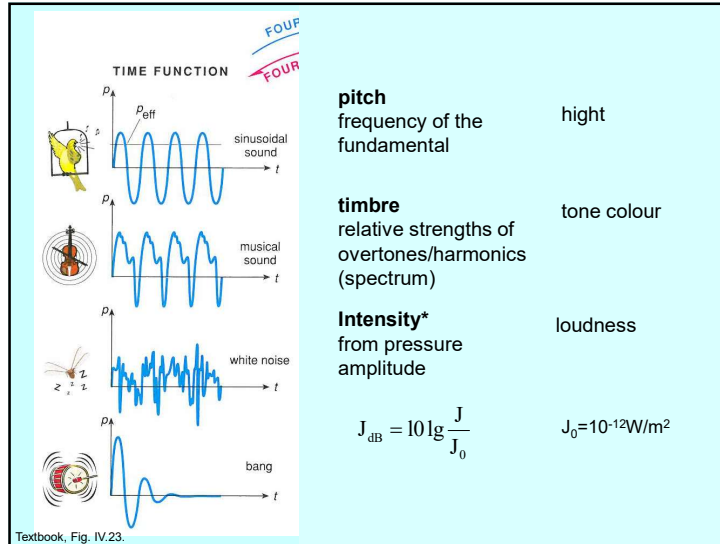
pitch
frequency of the fundamental high

timbre
relative strengths of overtones/harmonics (spectrum) tone colour

Intensity*
from pressure amplitude loudness

Textbook, Fig. IV.23.





What is the intensity of a 300 Hz sound that a person, who has 25 dB hearing loss at this frequency can hear? (The average hearing threshold at this frequency is $3 \cdot 10^{-11} \text{ W/m}^2$)

$$J_{dB} = 10 \lg \frac{J}{J_0}$$

$$25 = 10 \lg \frac{J}{3 \cdot 10^{-11}}$$

$$10^{2.5} = \frac{J}{3 \cdot 10^{-11}}$$

$$J = 9,5 \cdot 10^{-9} [\text{Wm}^{-2}]$$

11

Propagation of sound/ultrasound

The role of elastic medium – *speed* of propagation

$$c = f\lambda$$

$$c = \frac{1}{\sqrt{\rho\kappa}}$$

ρ : density of medium



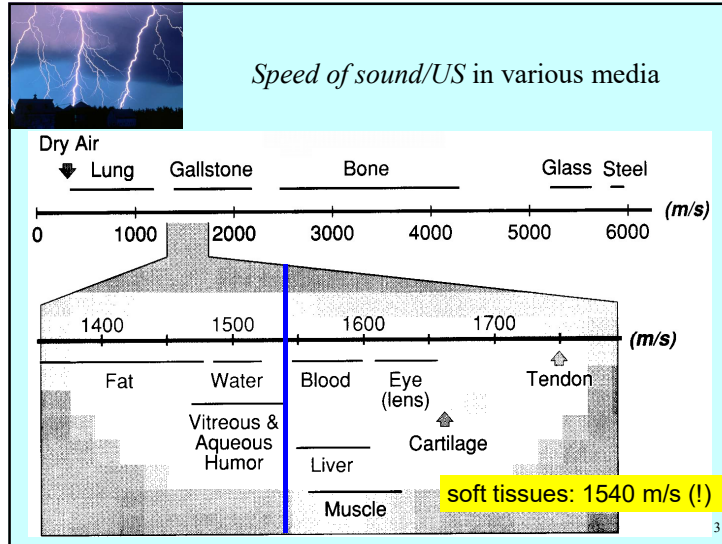
$$\kappa = -\frac{1}{V} \left(\frac{\Delta V}{\Delta p} \right) [\text{Pa}^{-1}]$$

compressibility
relative volume decrease
over pressure

Speed of propagation is higher in solids than in liquids.

$$\rho \uparrow \quad \kappa \downarrow$$

12



Propagation of sound/ultrasound

$$c = \frac{1}{\sqrt{\rho\kappa}}$$



$$\kappa = \frac{-\Delta V/V}{\Delta p} \quad [\text{Pa}^{-1}]$$

$$Z = \frac{p}{v} = \frac{p_{\max}}{v_{\max}} \quad \text{acoustic impedance (definition)}$$

$$Z_{\text{el}} = \frac{U}{I}$$

$$Z = c\rho = \sqrt{\frac{\rho}{\kappa}} \quad \text{acoustic impedance (useful form)}$$

$$[\text{kg} / \text{m}^2 \text{s}]$$

Propagation of sound/ultrasound

$$c = \frac{1}{\sqrt{\rho\kappa}}$$

$$\kappa = \frac{-\Delta V/V}{\Delta p}$$

$$Z = c\rho = \sqrt{\frac{\rho}{\kappa}}$$

material	ρ [kg/m ³]	κ [1/GPa]	c [m/s]	Z [kg/(m ² s)]
air	1,3	7650	331	$0,00043 \cdot 10^6$
water 20°C	998	0,45	1492	$1,49 \cdot 10^6$
aluminum	2700	0,009	6400	$17,28 \cdot 10^6$
quartz	2650	0,011	5736	$15,2 \cdot 10^6$

Intensity of US

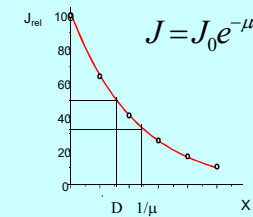
$$J = \frac{1}{Z} \Delta p_{\text{eff}}^2$$

intensity = energy/current density

$$P_{\text{el}} = \frac{1}{Z_{\text{el}}} U_{\text{eff}}^2$$

electric analogy

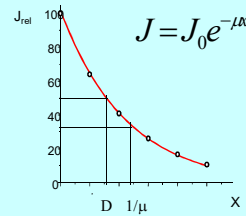
Loss of energy during propagation (absorption)



$$\text{attenuation: } \alpha = 10 \cdot \lg \frac{J_0}{J} \text{ dB}$$

$$\alpha = 10 \cdot \mu \cdot x \cdot \lg e \text{ dB}$$

Loss of energy during propagation (absorption)



At $f = 1$ MHz

$D_{\text{air}} \sim 1$ cm

$D_{\text{water}} \sim 1$ m

attenuation: $\alpha = 10 \cdot \lg \frac{J_0}{J}$ dB

$$\alpha = 10 \cdot \mu \cdot x \cdot \lg e \text{ dB}$$

μ is proportional to frequency in the diagnostic range

Specific attenuation: $\frac{\alpha}{f \cdot x}$

17

μ is proportional to frequency in the diagnostic range

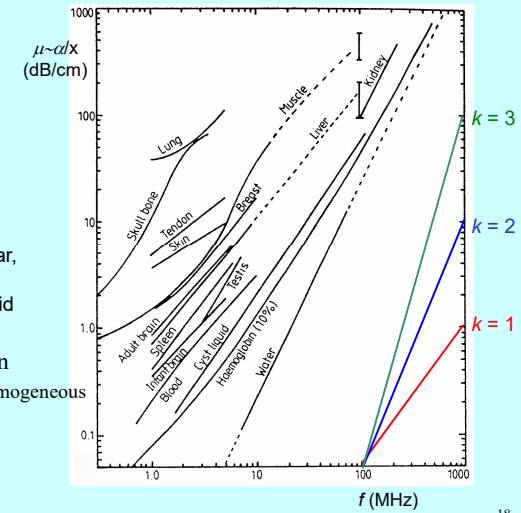
$$\mu \sim f^k, \quad k \sim 1(?)$$

$$\lg \mu \sim k \lg f$$

if the graph is a linear, the power function approximation is valid

specific attenuation for soft tissues (homogeneous tissue model):

$$\frac{\alpha}{f \cdot x} \sim 1 \frac{\text{dB}}{\text{cm MHz}}$$



18

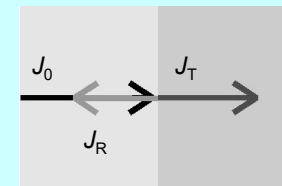
$$\frac{\alpha}{f \cdot x} \sim 1 \frac{\text{dB}}{\text{cm MHz}}$$

tissue	Specific attenuation
liver	0,6 – 0,9
kidney	0,8 – 1,0
fat	1,0 – 2,0
blood	0,17 – 0,24
bones	16 – 23

19

Phenomena at the boundary of different media

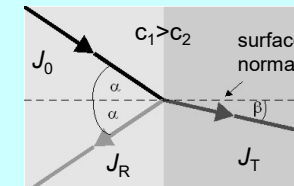
normal/perpendicular incidence



$$J_0 = J_R + J_T$$

reflection and transmission (penetration)

skew incidence

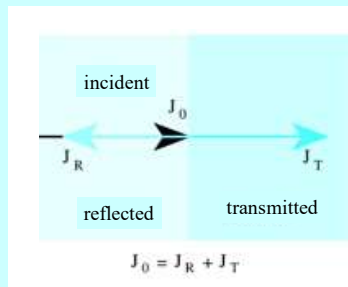


$$\frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2}$$

Snellius-Descartes

20

Reflection of ultrasound



$$R = \frac{J_R}{J_0}$$

$$R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2$$

If $R \approx 1 \longrightarrow$ Total reflection

21

Detection/Generation of US

Piezoelectric effect



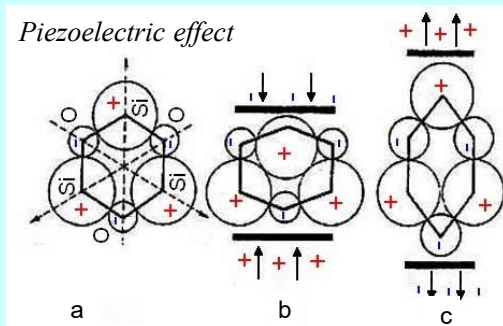
Pressure change

Mechanical deformation of crystal

Electric potential difference

22

Piezoelectric effect



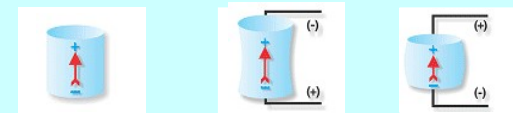
(a) Center of charge of positive and negative charges coincides.

(b) and (c) As a result of pressure, the charge centers are separated, i.e. a potential difference arises

23

Detection/Generation of US

Inverse piezoelectric effect



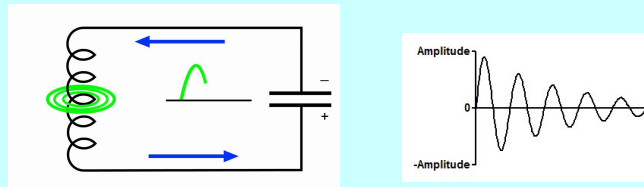
Periodic electric potential difference

The crystal is deformed when voltage is applied

Mechanical vibration

24

Oscillator circuit – LC circuit



L : self inductance [$\text{S} \cdot \Omega^{-1}$]

$$L \sim A N^2$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

25

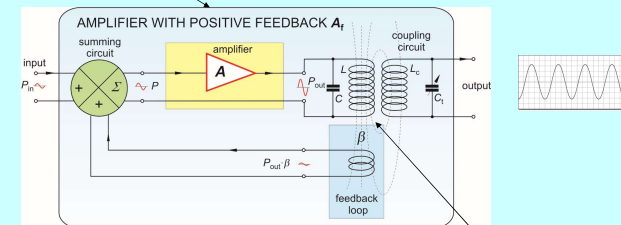
Source of electric signal: sine wave oscillator

$$A_{\text{feedback}} = \frac{U_{\text{out}}}{U_{\text{in}}} = \frac{A}{1 - A \cdot \beta}$$

$$A\beta = 1$$

amplification = „infinity“

no input signal, output signal: sine voltage



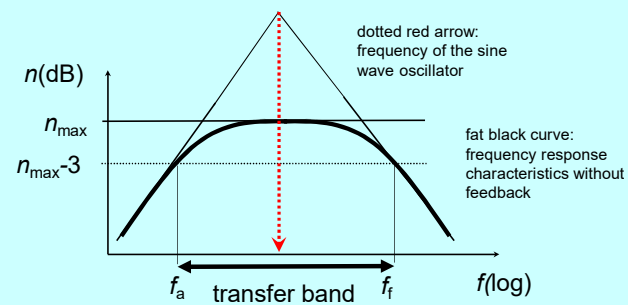
$$f = \frac{1}{2\pi\sqrt{LC}}$$

26

Source of electric signal: sine wave oscillator

amplifier with positive feedback

$$A_{U, \text{feedback}} = \frac{A_U}{1 - \beta A_U}$$



27

Detection/Generation of US - Ultrasound transducer

