Bioacoustics. Biophysics of Hearing.

I. Theoretical Background

Basic Notions and definitions

I.1 Mechanical waves:

Mechanical wave is a periodic disturbance (vibration) that moves through an elastic medium

or

The process of oscillations transmitted from one point of medium (from the point of creation) to all others points of medium.

Mechanical waves are produced by vibrations and deformations in the elastic medium.

I.2. Waves can be classified into two types: Longitudinal Wave and Transverse Wave.

I.2.1 The wave is called a **transverse** or **shear wave** if the oscillations of individual particles of the medium are perpendicular to the direction the wave is propagating (the disturbance/vibration is perpendicular to the direction of propagation).

Transverse waves emerge as a result of shear deformation in elastic medium and therefore can be occurred only in solids and upon the surface of liquids.

Transverse wave causes the medium to vibrate at a right angle to the direction of wave propagation. Transverse waves have the crests and the troughs.

I.2.2 The wave is called a **longitudinal wave** or a **compression wave** if the oscillations of individual particles of the medium are parallel to the direction the wave is propagating (the disturbance/vibration is parallel to the direction of propagation).

Longitudinal waves emerge as a result of tensile and compression deformations in elastic medium and can occur in solids, fluids, and gases.

Longitudinal wave causes the medium to vibrate along the direction of wave propagation. Longitudinal waves are made up of the compressions and the rarefactions.

I.3. A wave motion can be described by the wave equation:

$$\frac{\partial^2 y(x,t)}{\partial t^2} = v^2\,\frac{\partial^2 y(x,t)}{\partial x^2}$$

Where y is the displacement of an element of medium (oscillating particle) from equilibrium position at point x and time t , v – is the speed at which the wave propagates (phase velocity).

I.4. The solution of the wave equation is:

$$y(x,t) = A\cdot\sin(kx - \omega t + \varphi_\circ)$$

where:

A is an amplitude — maximum displacement of individual oscillating particle from its equilibrium position;

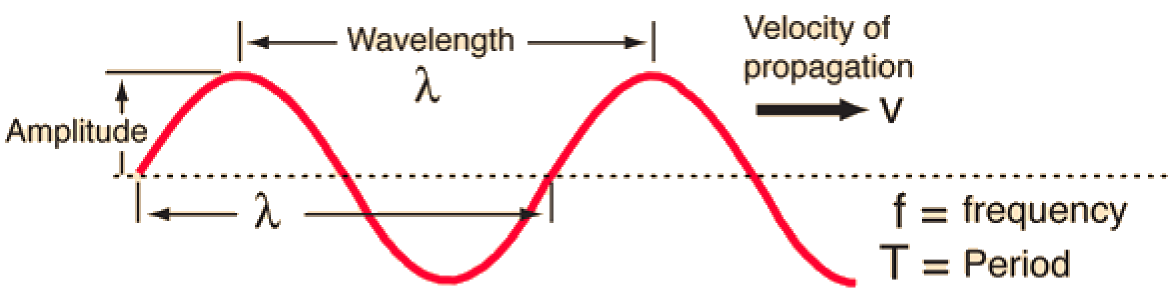
k is the **wavenumber**, $\mathbf{k} = \frac{2\pi}{\lambda}$;

λ is the **wavelength** — the distance between adjacent identical parts of the wave, or the distance between two points of medium which are oscillating in the same phase (for example – between two consequent crests);

ω is the **angular frequency** of the wave, $\omega = \frac{2\pi}{T} = 2\pi f$

T is the **period** of the wave — the time taken by the wave to complete one oscillation, or the time it takes one wavelength to pass a fixed point;

f is the **frequency** — the number of oscillations per unit of time, or the number of wavelength (waves) passing through fixed point per unit of time. The wave frequency f is the oscillation frequency of the individual particles of medium (atoms or molecules).

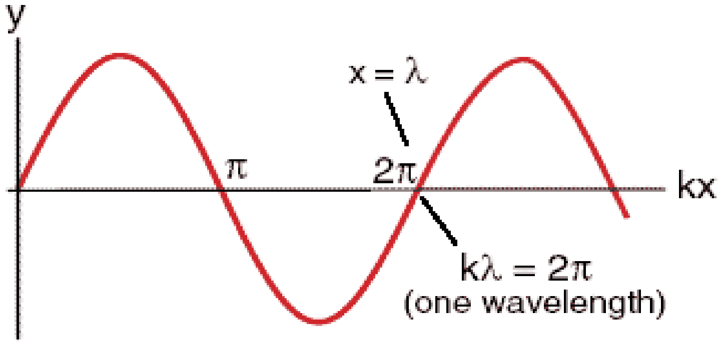


The quantity $\varphi = kx - \omega t + \varphi_\circ$ is called the phase.

The **phase constant $\varphi_\circ$** (initial phase) is determined by the initial conditions of the motion. If at t = 0 and x = 0 the displacement y is zero, then $\varphi_\circ = 0$ or π. If at t = 0 and x = 0 the displacement takes on its maximum value, then $\varphi_\circ = \frac{\pi}{2}$

At a fixed time t the displacement y varies as a function of position x as:

$$\mathbf{y(x,t) = A \sin kx = A \sin \frac{2\pi}{\lambda} x}$$

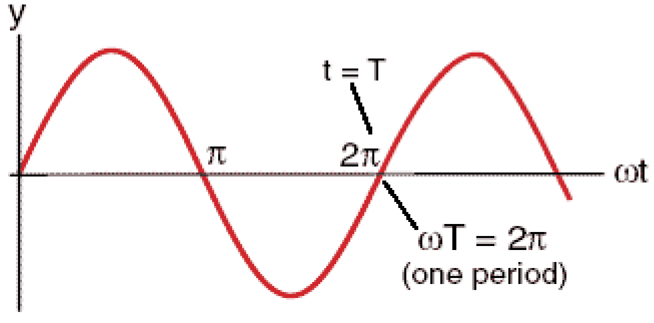


Space: sin(θ) = sin(kx)

At a fixed position x the displacement y varies as a function of time as :

$$\mathbf{y(x,t) = A \sin(\omega t) = A \sin \frac{2\pi}{T} t}$$

with a convenient choice of origin



Time: sin(θ) = sin(ωt)

I.5. The wave speed (velocity), frequency, period and wavelength can be expressed through each other:

$$V = \frac{\lambda}{T} = \lambda \cdot f = \frac{\omega}{k}$$

The wave speed is a speed at which the wave peak (crest) moves.

I.6. Energy and intensity of the wave.

Wave motion transfers energy from one location to another without transfer the medium's substance – waves carry energy, not substance. The energy transferred by wave is called wave energy.

I.6.1 The wave energy is the energy of oscillating particles of the medium. In the case of simple harmonic oscillations:

$$E = \frac{m\omega^2 A}{2}$$

where **m** is a mass of substance undergoing the oscillatory motion in a certain region of space, **ω** - angular frequency of oscillations, **A** - an amplitude.

I.6.2 The intensity of the wave is the wave energy transferred per unit area and per unit time in direction of the wave propagation:

$$I = \frac{E}{St}$$

The intensity is measured in $[I] = [\frac{E}{St}] = \frac{1\,J}{1m^2 \cdot 1s} = 1\,\frac{W}{m^2}$ watt per square meter

I.6.3 Traveling through some region of space of volume V = $S \cdot l$ and mass Δm wave carries energy:

$$\Delta E = \frac{\Delta m\omega^2 A}{2} = \frac{\rho V\omega^2 A}{2} = \frac{\rho Sl\omega^2 A}{2}$$

Where Δm is a mass of substance of density ρ oscillating in volume V:

$$\Delta m = \rho \cdot V = \rho \cdot S \cdot l$$

Hence the equation for the intensity can be written:

$$I = \frac{\Delta E}{St} = \frac{\rho S l \omega^2 A}{2St} = \frac{\rho l \omega^2 A}{2t};$$

Since $\frac{l}{t} = v$ — the wave speed, then:

$$I = \rho \cdot v \ \frac{\omega^2 A}{2} \quad \text{or} \quad I = 2\pi^2 f^2 A \rho \cdot v$$

The product of density and wave speed is called the acoustic impedance Z which is the characteristic of the medium: $Z = \cdot v$, therefore: $I = Z \frac{\omega^2 A}{2}$ **or** $I = 2\pi^2 f^2 A Z$

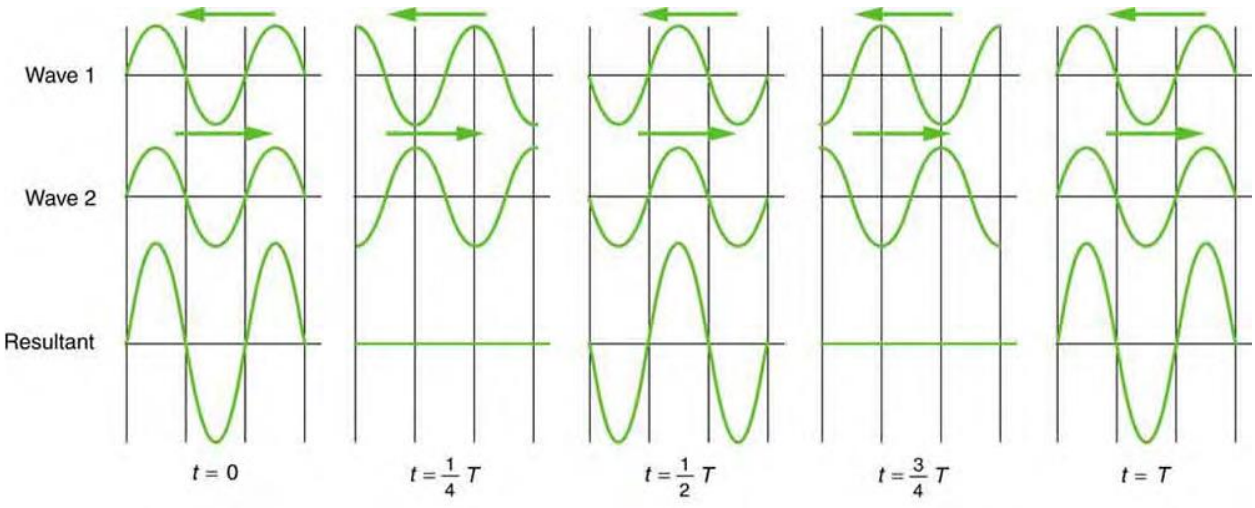
The general conclusions from the above given formula for intensity.

1) $I \propto \rho$: intensity is directly proportional to the density of the medium — the denser the medium, the more intense the wave. A dense medium contains more mass into any volume than a rarefied medium and therefore can possess the greater kinetic energy.
2) $I \propto \omega^2 \ (f^2)$: intensity is directly proportional to the square of frequency — the more frequently a wave vibrates the medium, the more intense the wave is.
3) $I \propto v$: intensity is directly proportional to the wave speed — the faster the wave travels, the more quickly it transmits energy. Intensity measures the rate at which energy is transferred.
4) $I \propto A$: intensity is directly proportional to the wave amplitude — the greater the amplitude, the more intense the wave.

I.7. Standing Waves

A standing wave is a wave in a medium in which each point on the axis of the wave has an associated constant amplitude. The locations at which the amplitude is minimum are called ***nodes***, and the locations where the amplitude is maximum are called ***antinodes***.

Standing waves are created by the superposition of two identical waves moving in opposite directions. The oscillations are at fixed locations in space and result from alternately constructive and destructive interference.



II. Sound and Hearing

II.1. Sound: A sound wave is a mechanical wave that moves through a medium as particles in the medium are displaced relative to each other.

II.1.1 The nature of sound: the sound waves are mechanical waves which are created from vibrations between the particles of the medium. When it is moved through the medium of air then the air particles are displaced by the moving energy of sound waves and wave is travelled.

On the atomic scale, it is a disturbance of atoms that is far more ordered than their thermal motions. In many instances, sound is a periodic wave, and the **atoms undergo simple harmonic motion**.

Sound represents a longitudinal wave of wavelength λ and frequency *f* which is transmitted by density (pressure) changes through elastic medium with a certain speed *v* which depends on medium properties and the external conditions.

II.1.2 The speed of sound:

In gaseous medium the speed of sound is:

$$\mathbf{v} = \sqrt{\frac{\gamma RT}{M}}$$

where: $\gamma = \frac{c_p}{c_v}$ is the ratio of the specific heat at constant pressure to that at constant volume — adiabatic index in polytropic process equation pV^{γ} = constant;

R = 8,31 $\frac{J}{molK}$ - the *universal gas constant*; M - the molar mass.

$$v = v_\circ \sqrt{\frac{T}{273}} = v_\circ \sqrt{1 + \frac{t}{273}} \approx 331 + 0.6\,t\ (\frac{m}{s})$$

$v_\circ$ - is the speed of sound at temperature t = 273K (0 ℃), t – is a temperature expressed in Celsius. At room temperature (293 K = 20 ℃), the speed of sound in air is approximately $\approx 340\ \frac{m}{s}$

Values of densityρ, sound speed v, and acoustic impedance Z for some selected substances

	$\rho\ \frac{kg}{m^3}$	$v\ \frac{m}{s}$	$Z = (\rho \cdot v)\ \frac{kg}{m^2 s}$
Air	**1.29**	**3.31x 10^2= 331**	**430**
Water	**1.00 x 10^3**	**14.8 x 10^2= 1480**	**1.48 x 10^6**
Fat	**0.92 x 10^3**	**14.5 x 10^2= 1450**	**1.33 x 10^6**
Muscle	**0.04 x 10^3**	**14.8 x 10^2= 1480**	**1.64 x 10^6**
Blood	**1.06 x 10^3**	**15.7 x 10^2=1570**	**1.66 x 10^6**
Bone (varies)	**(1.40-1.90) x 10^3**	**40.8 x 10^2=4080**	**(5.7 - 7.8) x 10^6**

II.1.3 The intensity of sound is the rate at which sound energy passes through a unit area held perpendicular to the direction of propagation of sound waves.

The intensity can be expressed through the change of pressure in transmitting medium.

Since $p = \rho \cdot v \cdot \omega \cdot A \sin \omega t = P \sin \omega t$ then

$$I = Z\ \frac{\omega^2 A}{2} = \frac{P^2}{2\rho \cdot v} = \frac{P^2}{2Z}$$

where $P = \rho \cdot v \cdot \omega \cdot A$ - is the pressure amplitude in the sound wave.

II.2. Hearing is the perception of sound. (Perception is commonly defined to be awareness through the senses, a typically circular definition of higher level processes in living organisms.)

Normal human hearing encompasses frequencies from **20 to 20,000 Hz**, an impressive range. Sounds below 20 Hz are called **infrasound**, whereas those above 20,000 Hz are **ultrasound**. Neither is perceived by the ear, although infrasound can sometimes be felt as vibrations.

Audible sounds intensities at frequency f = 1000 Hz (10^3Hz) range from $\boldsymbol{I_\circ = 10^{-12}\,\frac{W}{m^2}}$ (very quiet) to $\boldsymbol{I_{max} = 1\,\frac{W}{m^2}}$ (very loud).

The lowest audible intensity $\boldsymbol{I_\circ = 10^{-12}\,\frac{W}{m^2}}$ is called ***the threshold of hearing***.

This is the minimum sound level of a pure tone that an average human ear with normal hearing can hear with no other sound present.

The maximum sound intensity perceived by human ear $\boldsymbol{I_{max} = 1\,\frac{W}{m^2}}$ is called ***the pain threshold of hearing***. This is the sound intensity that produces pain.

II.3. The sound intensity level *β* in bel (B) is defined to be:

$$\beta = \log_{10}\frac{I}{I_\circ}$$

The sound intensity level is measured in Bels and decibels

The intensity level of 1 Bel corresponds to 10 times change in intensity relatively to the threshold of hearing.

The sound intensity level ***β*** in decibels (dB) is defined to be:

$$\beta\,(db) = 10\,\log_{10}\frac{I}{I_\circ}$$

- The decibel is actually a measure of the relative intensity of the sound compared with a reference intensity;
- The reference intensity is taken as $\boldsymbol{I_\circ = 10^{-12}\,\frac{W}{m^2}}$, which is the lowest intensity sound (at frequency of 1 kHz) that the average human ear can hear.

If $I = I_\circ$, $\beta = 0$; *if* $I = 10\,I_\circ$, $\beta = 1\ B = 10\ dB$

The smallest increments of sound that the human ear can differentiate as being "louder" are typically two decibel increases – more likely.

Ratios of Intensities and Corresponding Differences in Sound Intensity Levels

$\frac{I_1}{I_2}$	$\beta_1 - \beta_2$
2.0	**3.0 dB**
5.0	**7.0 dB**
10.0	**10.0 dB = 1.0 B**

II.4. Perception of sound intensity is called loudness:

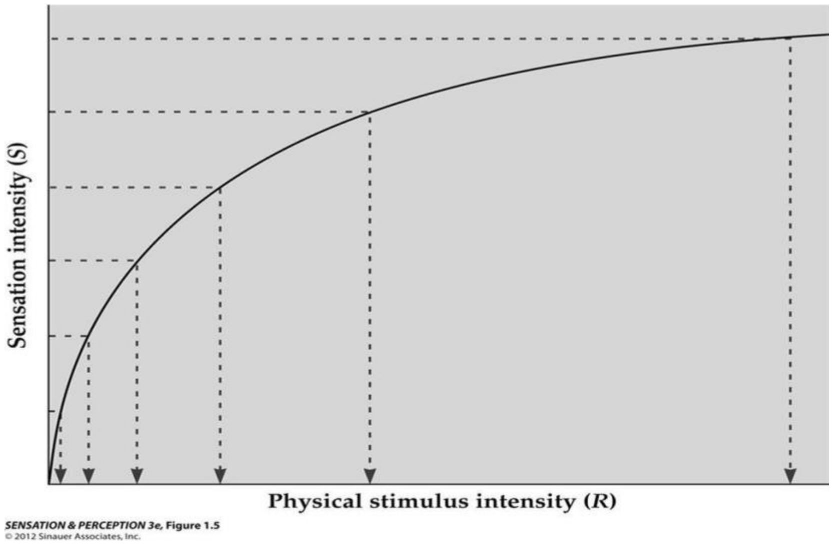
$$L = k(f) \cdot \beta = k(f) \cdot \log_{10}\frac{I}{I_\circ}$$

Where k is a coefficient depends on frequency and sound intensity. For the standard human ear:

$$k\ (1\ kHz) = 1\ (\ k \text{ is } 1 \text{ at frequency of } 1 \cdot 10^3\ Hz)$$

It means that loudness and intensity level are the same at that frequency.

The above given regularity is known as **Weber – Fechner Law**:



The loudness of the given sound is proportional to the logarithm of intensity of the sound.

A unit of loudness perception is *phon*. A unit called a ***phon*** is used to express loudness numerically. Phons differ from decibels because the phon is a unit of loudness perception, whereas the decibel is a unit of physical intensity.

II.5. The perception of frequency is called *pitch*. Pitch perception is directly related to frequency and is not greatly affected by other physical quantities such as intensity.

II.6. Sounds can be classified into music sounds and noise.

Music sound is a steady periodic sound which can be represented as superposition of sinusoidal waves with multiple frequencies. It means that music sound has discrete frequency spectrum.

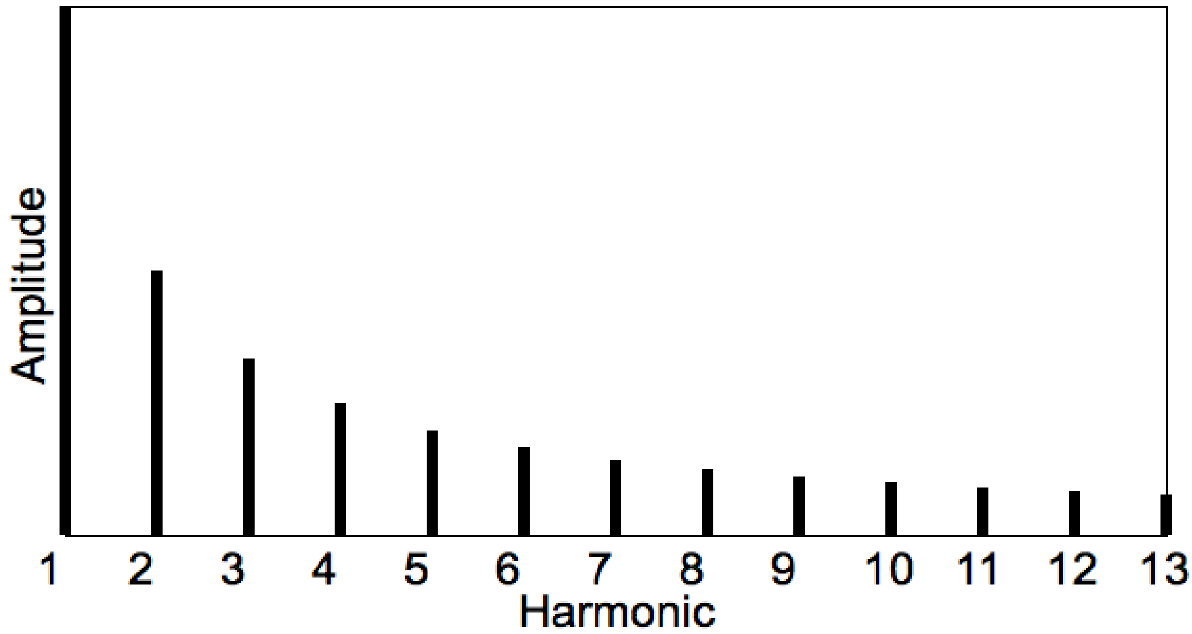
The Fourier theorem states that any periodic function $f(t)$ with a period T *such as* $f(t) = f(t+T)$ could be represented by a trigonometric series of the following form:

$$f(t) = a_\circ + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)$$

where:

$$a_\circ = \frac{1}{T}\int_0^T f(t)\,dt\ ;\ a_n = \frac{2}{T}\int_0^T f(t)\cos n\omega t\,dt;\ b_n = \frac{2}{T}\int_0^T f(t)\sin n\omega t\,dt$$

The lowest frequency in the frequency spectrum is called the ***fundamental frequency*** and determines the ***pitch of the tone***.



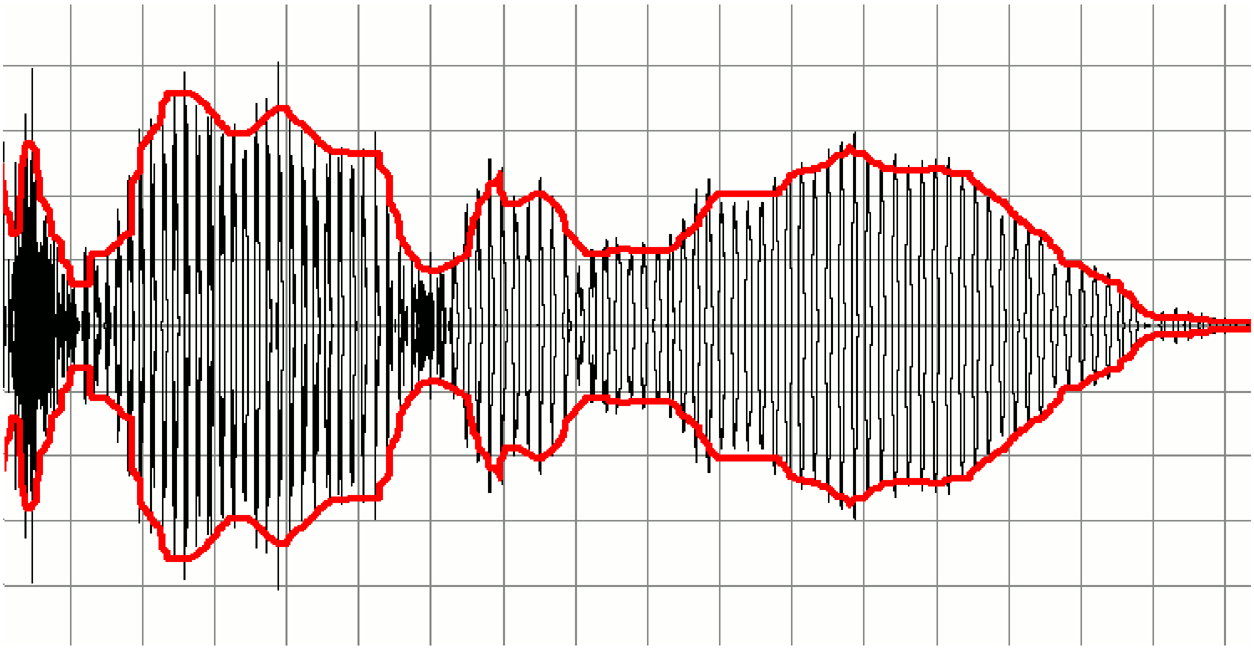
A pure tone is a tone with a sinusoidal waveform corresponds to a certain frequency

A complex tone is any musical tone that is not sinusoidal, but is periodic, such that it can be described as a sum of simple tones with harmonically related frequencies (pure tones) called overtones.

A musical sound contains fundamental frequency and series of overtones.

The perception of frequency spectrum is called *timbre*.

Noise is aperiodic sound with continues or chaotic frequency spectrum.



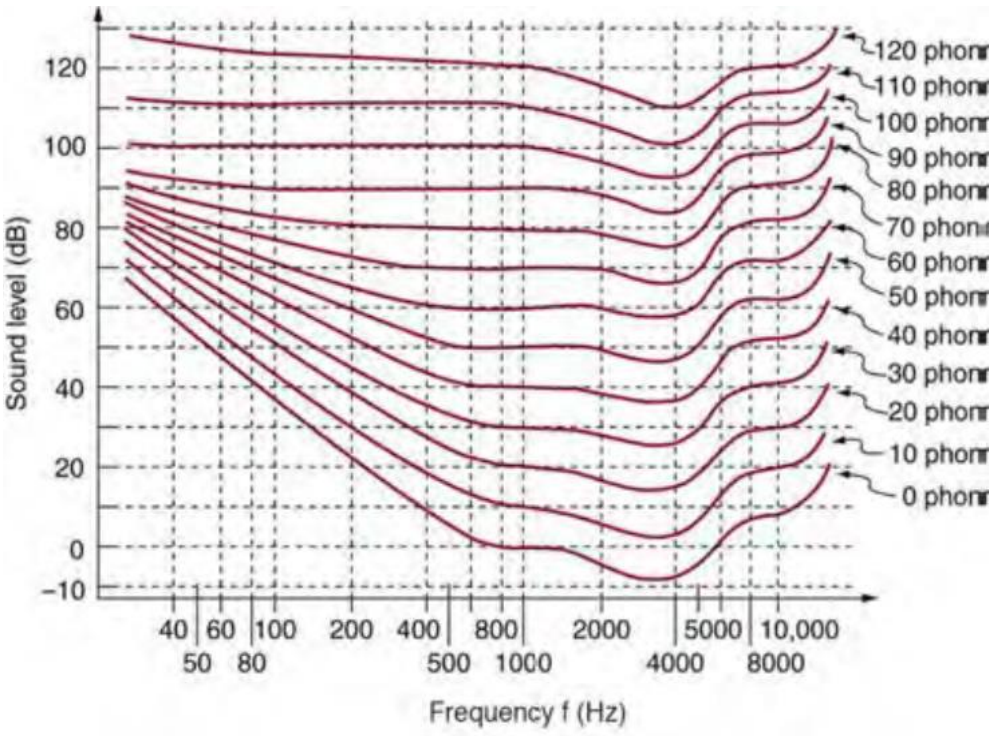
II.7.

The objective and subjective characteristics of sound

Objective characteristic – Physical quantity	Subjective characteristic - Perception
Intensity and Frequency	Loudness
Frequency	Pitch
Frequency spectrum	Timbre
Number and relative intensity of multiple frequencies in is a steady periodic sound	Tone

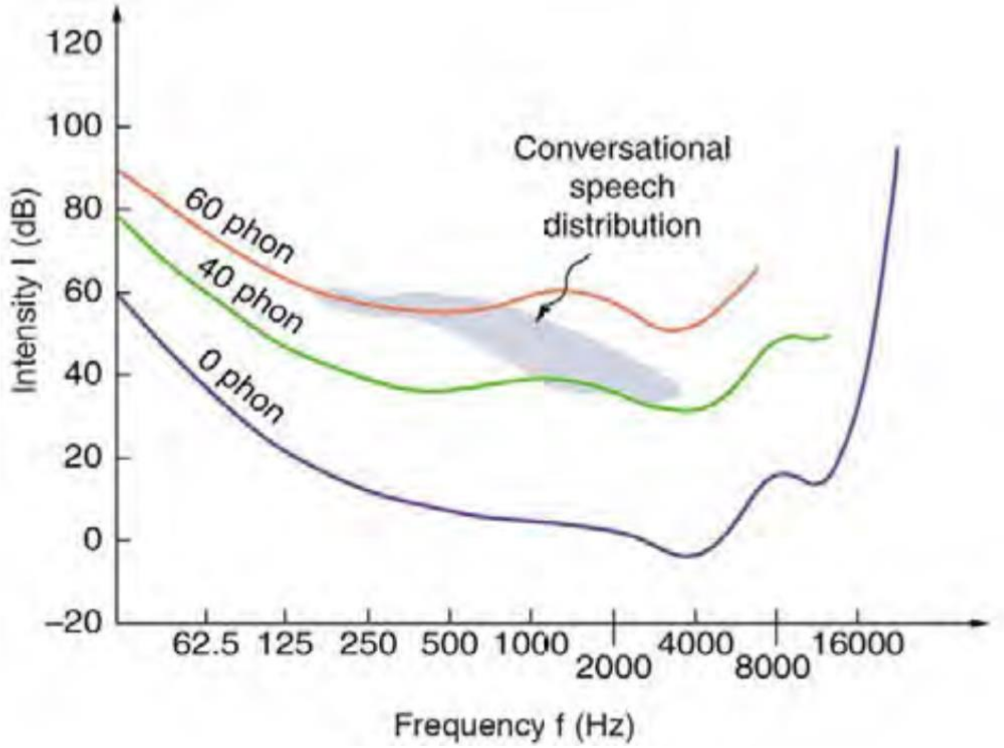
II.9. Correlation of sensitivity range of standard human ear with respect to frequency and intensity of sound

At a given frequency, it is possible to discern differences of about 1 dB, and a change of 3 dB is easily noticed. But loudness is not related to intensity alone. Frequency has a major effect on how loud a sound seems. The ear has its maximum sensitivity to frequencies in the range of 2000 to 5000 Hz, so that sounds in this range are perceived as being louder than, say, those at 500 or 10,000 Hz, even when they all have the same intensity. Sounds near the high- and low-frequency extremes of the hearing range seem even less loud, because the ear is even less sensitive at those frequencies.



The relationship of loudness in phons to intensity level (in decibels) for persons with normal hearing. The curved lines are **equal-loudness curves (isophones)** − all sounds on a given curve are perceived as equally loud. Phons and decibels are defined to be the same at 1000 Hz.

The dips in the isophones at frequencies around 3000 Hz and 8000 Hz signalize that lower intensities correspond to higher loudness. This results from the increased sensitivity of the ear due to the resonance effect in the outer ear canal.

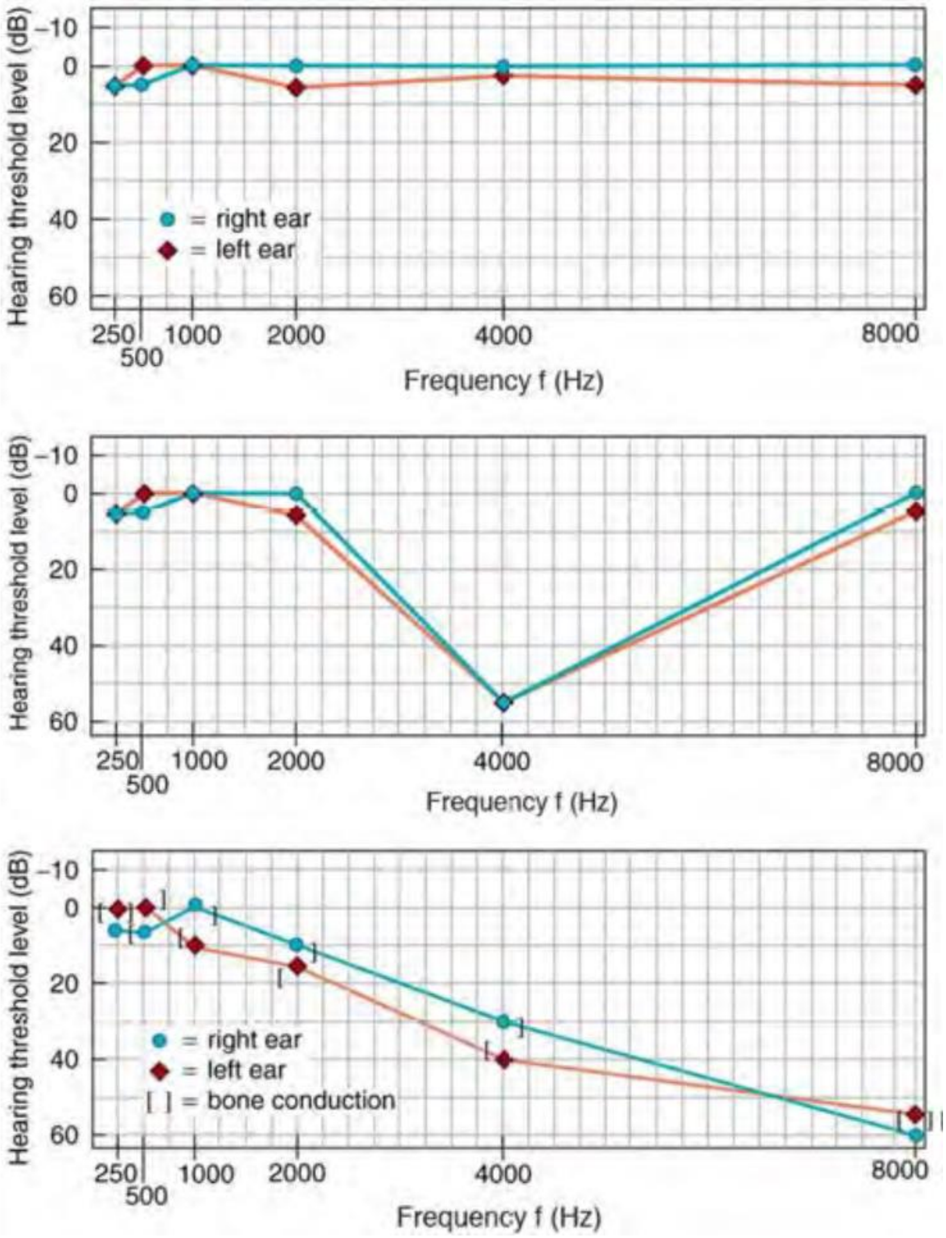


The shaded region represents frequencies and intensity levels found in normal conversational speech. The 0-phon line represents the normal hearing threshold, while those at 40 and 60 represent thresholds for people with 40- and 60-phon hearing losses, respectively.

A 40-phon hearing loss at all frequencies still allows a person to understand conversation, although it will seem very quiet. A person with a 60-phon loss at all frequencies will hear only the lowest frequencies and will not be able to understand speech unless it is much louder than normal. Even so, speech may seem indistinct, because higher frequencies are not as well perceived. The conversational speech region also has a gender component, in that female voices are usually characterized by higher frequencies. So the person with a 60-phon hearing impediment might have difficulty understanding the normal conversation of a woman.

II.8. Hearing tests are performed over a range of frequencies, usually from 250 to 8000 Hz, and can be displayed graphically in an **audiogram**.

The hearing threshold is measured in dB *relative to the normal threshold*, so that normal hearing registers as 0 dB at all frequencies. Hearing loss caused by noise typically shows a dip near the 4000 Hz frequency, irrespective of the frequency that caused the loss and often affects both ears. The most common form of hearing loss comes with age and is called *presbycusis*–literally elder ear. Such loss is increasingly severe at higher frequencies, and interferes with music appreciation and speech recognition.



Audiograms showing the threshold in intensity level versus frequency for three different individuals. Intensity level is measured relative to the normal threshold. The top left graph is that of a person with normal hearing. The graph to its right has a dip at 4000 Hz and is that of a child who suffered hearing loss due to a cap gun. The third graph is typical of presbycusis, the progressive loss of higher frequency hearing with age. Tests performed by bone conduction (brackets) can distinguish nerve damage from middle ear damage.

II.9. Biophysical Mechanism of Hearing:

The ear is divided into the outer (external), the middle, and the inner ear. Each of these three parts performs an important function in the process of hearing.

1. Sound travels along the ear canal of the outer ear and causes the ear dram to vibrate.

2. The three small bones of the middle ear conduct this vibration from the eardrum to the cochlea.

3. Fluid waves in the cochlea, initiated by movement of the three small ear bones, stimulate the more than sixteen thousand delicate hair cells.

4. Movement of these hair cells generates an electrical current in the auditory nerve fibers.

5. Finally, this current is transmitted through various complicated interconnections in the brain stem to the auditory cortex, which recognizes this electrical stimulation as sound.

II. Test Problems

1. What is the intensity in watts per meter squared of 85.0-dB sound?

2. What sound intensity level in dB is produced by earphones that create an intensity of 4.00 × 10 −2 W/m2 ?

3. Show that if one sound is twice as intense as another, it has a sound level about 3 dB higher.

You are given that the ratio of two intensities is 2 to 1, and are then asked to find the difference in their sound levels in decibels. You can solve this problem using of the properties of logarithms. Solution: (1) Identify knowns: The ratio of the two intensities is 2 to 1, or: $\frac{I_2}{I_1}$ = 2.00. We wish to show that the difference in sound levels is about 3 dB. That is, we want to show: $\beta 2 - \beta 1 = 3$ dB. $\beta 2 - \beta 1 = 10 \log \frac{I_2}{I_1}$

4. (a) What is the decibel level of a sound that is twice as intense as a 90.0-dB sound? (b) What is the decibel level of a sound that is one-fifth as intense as a 90.0-dB sound?

5. (a) What is the intensity of a sound that has a level 7.00 dB lower than a 4.00 × 10-9 W/m2 sound? (b) What is the intensity of a sound that is 3.00 dB higher than a 4.00 × 10-9 W/m2 sound?

6. (a) How much more intense is a sound that has a level 17.0 dB higher than another? (b) If one sound has a level 23.0 dB less than another, what is the ratio of their intensities?

7. People with good hearing can perceive sounds as low in level as ⁻8.00 dB at a frequency of 3000 Hz. What is the intensity of this sound in watts per meter squared?

8. An 8-hour exposure to a sound intensity level of 90.0 dB may cause hearing damage. What energy in joules falls on a 0.800-cm-diameter eardrum so exposed?

9. Find the range of an eardrum displacement with respect to the range of audible sound intensity and frequency. The acoustic impedance of the eardrum muscle is Z($\boldsymbol{\rho} \cdot \boldsymbol{v}$) = **1.64** x $\mathbf{10^6}$ $\frac{\boldsymbol{kg}}{\boldsymbol{m^2 s}}$

Reading:

- Medical and Biological Physics. Textbook for students of higher medical education institutions / V.I. Fediv, O.I. Olar, V.V. Kulchynskyi, H. Y. Rudko. – Chernivtsi: BSMU Publishing House, 2017. - 342 p. – English. pp. 68 – 99.

- Irving P. Herman. Physics of the Human Body. / Springer – Verlag. Berlin, Heidelberg 2007. Brown B.H. Medical Physics and Biomedical Engineering

3.4 Audition; 13.3. Representation of deterministic signals; 15. Audiology

- The Acoustics of the Body
https://www3.nd.edu/~nsl/Lectures/mphysics/Medical%20Physics/Part%20I.%20Physics%20of%20the%20Body/Chapter%204.%20Acoustics%20of%20the%20Body/Chapter%204.%20Acoustics%20of%20the%20Body.pdf

Watching:

https://www.youtube.com/watch?v=H-iCZElJ8m0

https://www.youtube.com/watch?v=3G5jiXl2LSM