4.6. MEASUREMENT OF HEARING SENSITIVITY

Purpose of experiment
To examine a person’s hearing.

Tasks of experiment
- Record your hearing audiogram.
- Analyse and explain your hearing sensitivity curve and its dependence on sound frequency and outside noise.

Theoretical topics
- Sound waves and sources.
- Detection of sound.
- Structure of the human ear.
- Human audiogram.
- Loudness, measurement units.
- Weber and Fechner law.

Equipment and materials
Personal computer, loudspeaker and/or earphones, MATLAB and custom registration software, printer.

Theoretical part
Every day, many different sounds can be heard around us and we communicate with each other through sound waves: that is through speech and hearing. Hearing has an extremely important function in our life: when we lose our hearing or hear less well, the quality of our life decreases. One out of seven individuals does not have full hearing, and one out of ten hears very poorly. It is therefore very important to diagnose first hearing problems through the measurement of the main parameters of hearing quality. This is the objective of one of the branches of medical diagnostics called audiometry.

The full range of sound waves can be divided into three main parts (Fig. 4.6.1):
1. Sound, that part of the range between the frequencies of 20 Hz to 20,000 Hz that can be detected by the human ear with normal hearing. In practice, the ear responds best to a range of frequencies from about 1-6 kHz (the greatest sensitivity is in the range 2000-5500 Hz.).
2. Ultrasound – sound with frequencies above 20 kHz to 200 MHz. Dolphins and bats are well known natural sources that generate low frequency ultrasound. Artificial sources that generate ultrasound are called “ultrasound generators”. Ultrasound has a very wide use in medical diagnostics and therapy.
3. Infrasound – sound with frequencies below 20 Hz. It can be dangerous for the human body due to the fact that human body parts (the brain, muscles, heart etc.) vibrate at these frequencies (for
example, the heart vibrates at about 1 Hz), and infrasound can interfere or amplify these vibrations causing failures.

![Image of acoustic waves](image)

**Fig. 4.6.1.** The range of acoustic waves.

A sound wave is a mechanical wave. The generating of the mechanical wave is presented in Figure 4.6.2. The loudspeaker vibrates and causes the surrounding particles of the medium (in real case - air) to vibrate also. These vibrations are transferred through the medium because elasticity forces act between the particles. This process continues as a longitudinal progressive wave and transfers energy but not matter: air molecules do not actually travel from the loudspeaker to the ear. Each individual molecule moves only a small distance as it vibrates, but it causes the next molecules to vibrate in a rippling effect all the way to the ear. The black dots in Fig.4.6.2 represent air molecules: in some parts they create compressions, in other parts – rarefactions corresponding to pressure that is higher or lower than the normal atmospheric pressure.

The energy of the wave is expressed as sound intensity, which shows the average energy the wave transfers per square meter per second and which is proportional to the pressure (\(p\)) and inversely proportional to the density of the medium (\(\rho\)) and the speed of the wave (\(c\)):

\[ I = \frac{p^2}{2\rho c}. \]  
(4.6.1)
The product of density and speed of particles is called *acoustic resistance*. Acoustic resistance \((Z)\) is a property of the medium through which the sound wave is propagating. When two different mediums are in contact, the ratio of their acoustic resistances shows what portion of the acoustic wave is transmitted through the intersection.

**The main characteristics of a sound wave** are (Fig.4.6.3): *amplitude* \((A)\) - the maximum deviation of the particle from its equilibrium position; *wavelength* \((\lambda)\) – the smallest distance between two points of the wave with the same phase or the distance over which the wave’s shape repeats; *period* \((T)\) - is the duration of one cycle in a repeating event; *frequency* \((\nu)\) is defined as the number of vibrations during one second, and angular frequency \(\omega = 2\pi\nu\). One can see that the period is the reciprocal of the frequency. The *speed of sound* \((c)\) is the distance travelled during one period by a sound wave propagating through an elastic medium.

The wave propagating along the chosen direction, for example, \(x\) - axis, is described by the equation:

\[
s = A\cos[\omega(t - x/c)]; \quad \text{where} \quad c = \lambda\nu = \lambda/T.
\]

It describes the dependence of the displacement of the vibrating particle from the coordinate’s \(x\) position at any moment of time.

Sound wave travels at a different speed in different materials (Table 4.6.1): the lowest speed is in a gas medium, such as air. The speed increases with the increasing stiffness of the material, and it is highest in solids (human bone). Sound wave speed in the soft tissues of the human body is approximately equal to the speed in water. This property of sound is very important in ultrasound echoscopy.

**The ear and hearing.** The ear serves as a transducer, converting the mechanical energy of the incoming sound wave into electrical signals for transmission to the brain. Sound waves are collected by the outer ear and travel through the external canal to the eardrum. Sound pressure causes the eardrum to vibrate in the same pattern as the incoming wave. The eardrum is a membrane oval in shape, which has a maximum diameter of about 8 mm and is about 0.1 mm thick. The vibrations of the membrane cause the 3 small middle ear bones (Hammer, Anvil and Stirrup) to
vibrate. These bones transmit and amplify the vibrations to a membrane that covers the entrance to the fluid-filled inner ear. The difference in area of the eardrum membrane and the oval window into the inner ear causes an increase of the transmitted sound pressure and therefore intensity. This amplifying effect is necessary to better detect low intensity sounds.

**Table. 4.6.1.** Sound speed and acoustic impedance.

<table>
<thead>
<tr>
<th>Material</th>
<th>( t ), °C</th>
<th>( c ), m/s</th>
<th>( Z ), kg/m²s</th>
<th>Material</th>
<th>( t ), °C</th>
<th>( c ), m/s</th>
<th>( Z ), kg/m²s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0</td>
<td>1403</td>
<td></td>
<td>Lungs</td>
<td>650</td>
<td>1.8 ( 10^5 )</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>20</td>
<td>1483</td>
<td>1.48 ( 10^6 )</td>
<td>Fat</td>
<td>1446</td>
<td>1.33 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>100</td>
<td>1543</td>
<td></td>
<td>Blood</td>
<td>1570</td>
<td>1.61 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>Salt solution (20%)</td>
<td>15</td>
<td>1650</td>
<td></td>
<td>Bone</td>
<td>(2070-5350)</td>
<td>7.8 ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>Brain</td>
<td>(1500-1610)</td>
<td>1.63 ( 10^6 )</td>
<td></td>
<td>Oxygen</td>
<td>-182.9</td>
<td>912</td>
<td></td>
</tr>
<tr>
<td>Muscle</td>
<td>(1540-1630)</td>
<td>1.64 ( 10^6 )</td>
<td></td>
<td>Air</td>
<td>18</td>
<td>342.4</td>
<td>413</td>
</tr>
</tbody>
</table>

The pressure wave propagating in the fluid stimulates and causes the deformation of the basilar membrane and this makes a shearing tension in the hair cell’s membrane initiating an action potential (AP). Sensitivity to sound frequency differs along the basilar membrane as shown in Figure 4.6.4. APs from the hair cells are transmitted to the nerve endings that convert mechanical vibrations to electrical signals (also called nerve impulses). They are sent from the hair cells along the auditory nerve to the brain.

![Fig. 4.6.4. Simplified anatomy of the ear.](image)

This raises the question of how sound is perceived. What does hearing depend on and how can the quality of hearing be evaluated?
Perception of sound. Many physicians and psychologists in the 19th century tried to answer these questions scientifically. E.H. Weber was the first to study the human response to different physical stimuli detected by ear in a quantitative fashion. His law states that the minimal difference between two stimuli (S) is proportional to the magnitude of the stimuli (I).

G.T. Fechner (another German philosopher and experimental psychologist, founder of psychophysics) later offered an elaborate interpretation of Weber’s findings and stated in Fechner’s law that subjective sensation is proportional to the stimulus intensity and inversely proportional to the absolute threshold in a logarithmic scale.

If to specify a reference intensity, which is taken to be $I_0 = 10^{-12}$ W/m², a measurable quantity sound intensity level ($L_I$) can be expressed:

$$L_I = \frac{\lg (I/I_0)}{[B]}; \quad L_I = 10\lg (I/I_0) \quad [\text{dB}]. \quad (4.6.3)$$

or sound pressure level:

$$L_I = 20\lg \left( \frac{p}{p_0} \right) \quad [\text{dB}], \quad (4.6.4)$$

where $p$ – sound pressure, $p_0$ – the reference pressure ($2 \cdot 10^{-5}$ Pa).

Sound intensity, or pressure, level, is measured in bels [B] or decibels [dB]. The decibel is a logarithmic unit of sound level. The apparent loudness does not scale linearly with intensity, but instead a factor of 10 increase in intensity is perceived as an approximate doubling in volume, so a non-linear scale is more useful to describe the intensity of sounds instead of simply specifying the number of watts per square metre. Due to the logarithmic nature of the apparent loudness, the decibel is used to compare sound intensities and is not so much a unit as a way of specifying a ratio, and is used in other areas of physics. A decibel is one tenth of a bel. The absolute threshold is the smallest amount of stimulus energy necessary to detect a stimulus (sound, light, force, smell and other senses). The range between the lowest and highest intensity of sound that can be detected by a normal ear is about $10^{12}$ (ten to the power of twelve), and so for convenience a logarithmic scale is used. According to the definition of the decibel, the ear should register any sound intensity greater than 0 dB.

The human ear does not have the same sensitivity to all frequencies and, in practice; it is more sensitive to frequencies of about 1-6 kHz. The change in sensitivity of the human ear with frequency can be presented in equal loudness contours (Fig. 4.6.5). The variation of sound level is plotted as a function of frequency and gives the equal perceived loudness contour (called audibility curve for 0 dB). Loudness is measured in “phones”, but in practice very often is measured in bels or decibels. It is also very important to note that the loudness corresponds to the sound level only at 1 kHz, (the dB decibels reading is the same). Two frequencies, each with the same intensity (that is, carrying the same amount of energy), may be perceived as having different degrees of loudness. For example, a sound...
pressure level of 20 dB at 2 kHz can be heard, whilst a sound of the same level, but at 50 Hz, cannot be heard. These measurements have been made on a very large number of persons with normal hearing and the resulting average curves have been agreed internationally. It can be seen that the dynamic range and threshold of hearing are worst at the low frequency end of the spectrum. As the sound increases, the perceived loudness of different frequencies becomes more uniform.

The threshold of pain is approximately 130 dB. The threshold of hearing sensitivity is 0 dB, but it will vary amongst a group of normal people; it can also change from day to day and is affected by exposure to loud sounds. For these reasons, a variation of -10 to +15 dB is normally acceptable before a threshold measurement is considered to be abnormal.

Table 4.6.2 shows intensity and pressure levels for different sounds. For example, damage to the eardrum occurs immediately for sound levels of about 160 dB.

Table 4.6.2. Typical sound levels \( L \) (loudness) and corresponding sound pressure and sound intensity.

<table>
<thead>
<tr>
<th>Sound Sources (Noise) Examples with distance</th>
<th>Sound Pressure Level ( L_p ), dB SPL</th>
<th>Sound Pressure ( p ), N/m(^2), Pa</th>
<th>Sound Intensity ( I ), W/m(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet aircraft, 50 m away</td>
<td>140</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>130</td>
<td>63.3</td>
<td>10</td>
</tr>
<tr>
<td>Threshold of discomfort</td>
<td>120</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Chainsaw, 1 m distance</td>
<td>110</td>
<td>6.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Disco, 1 m from speaker</td>
<td>100</td>
<td>2</td>
<td>0.01</td>
</tr>
<tr>
<td>Diesel truck, 10 m away</td>
<td>90</td>
<td>0.63</td>
<td>0.001</td>
</tr>
<tr>
<td>Kerbside of busy road, 5 m</td>
<td>80</td>
<td>0.2</td>
<td>0.0001</td>
</tr>
<tr>
<td>Vacuum cleaner, distance 1 m</td>
<td>70</td>
<td>0.063</td>
<td>0.000001</td>
</tr>
<tr>
<td>Conversational speech, 1 m</td>
<td>60</td>
<td>0.02</td>
<td>0.000001</td>
</tr>
<tr>
<td>Average home</td>
<td>50</td>
<td>0.0063</td>
<td>0.0000001</td>
</tr>
<tr>
<td>Quiet library</td>
<td>40</td>
<td>0.002</td>
<td>0.0000001</td>
</tr>
<tr>
<td>Quiet bedroom at night</td>
<td>30</td>
<td>0.00063</td>
<td>0.000000001</td>
</tr>
<tr>
<td>Background in TV studio</td>
<td>20</td>
<td>0.0002</td>
<td>0.000000001</td>
</tr>
<tr>
<td>Rustling leaves in the distance</td>
<td>10</td>
<td>0.000063</td>
<td>0.0000000001</td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
<td>0.00002</td>
<td>0.00000000001</td>
</tr>
</tbody>
</table>

Most developed countries have adopted a limit of 90 dB for continuous exposure for industry workers over a normal 8 h working day, with higher levels allowed for short periods of time. In some countries, the level is set below 90 dB. There is a very important sound level for night-time periods; for example, if the sound level is higher than 55dB during the night then negative health effects can result.

**Audiometry** is used for the measurement of hearing quality. It consists of recording sound level dependence on frequency for equal loudness, usually for 0 dB. Audiometry tests are used in which speech or sounds from a loudspeaker are presented to the person at a range of frequencies and their ability to detect different intensities is recorded. They are presented to the patient through headphones. Usually a loud sound is presented to patients and the intensity is reduced slowly until they can no longer hear the sound. In some clinics, a reverse model is used: the intensity is increased from zero to the point where it can first be heard. In a test situation, the patient is instructed to listen carefully and respond to every sound: usually by pressing a button.

Hearing-care professional tests are carried out in a quiet test environment with a specially calibrated audiometer (in our case loudspeaker and earphones), using specific procedures. In a room where hearing tests are carried out, a background noise level below 30 dB is preferred, so the experiment should be carried out in a soundproof room. Also, each ear is tested separately, since any damage may be different in each ear. The standard hearing test concentrates only on the range of frequencies relevant for understanding speech: 250 Hz to 8000 Hz. The result is presented in the
form of an audiogram. The hearing range of the test ear is compared to the normal hearing range. But it must be remembered that this can change with age: typical loss of hearing at 3 kHz is 5 dB at age 40, 10 dB – 50; 20 dB – 70; and with experimental conditions.

Methodology

The experiment is performed on a computer using the MATLAB package and specialized software created by Donatas Čiukšys (PhD). Similarly, (but clearly in greater depth and detail, with accurately calibrated instruments) hearing tests are carried out in medical diagnostic facilities using modern computerized audiometers.

The experiment measures the relationship between the physical characteristics of the sound wave, expressed by the intensity level, and the subjective quality of loudness as perceived by the student.

Procedures

Notes:
1. Do not press the button “Benchmark”, (lt. “Etalonas”), because it will create a new reference curve corresponding to your hearing.
2. The “Clear” button deletes the data in the study window < Hearing examination system > and allows you to start a new experiment.
3. Under no circumstances should you press the “Export” button, as it will restart the computer.

1. Switch on the computer, open MATLAB, <MATLAB Window>, click <Enter>. Print the word “Klausa” (“Hearing”) and click <Enter>. On the screen a new window will appear < Hearing examination system > (lt. „Klauso tyrimo sistema“) (Fig. 4.6.6.).
2. Click “Test hearing sensitivity” (lt.“Tikrinti klausos jautrumą”) (Fig. 4.6.6.). A small window with three icons: “No longer hear” (lt. „Jau nebegirdžiu“); “Increase loudness” (lt. “Pagarsinti”); and “End experiment” (lt. „Pabaigti eksperimentą“) will open (Fig. 4.6.7.).
3. Using these three icons you can determine your hearing limit at different frequencies.
4. Frequencies change randomly.
5. The loudness of the signal constantly decreases, and you should click the icon - “No longer hear” at the precise moment when the signal sound disappears.
6. If you fail to catch that moment, repeatedly click the icon “Increase loudness” until again you clearly hear the signal. Repeat step 5.
7. Continue the experiment until, for each frequency, at least three color dots of experimental values of hearing level appear on the screen.
8. Click “End experiment”.
9. Click - “Standard ” (lt. “Vartai”), to put standard hearing ranges on your audiogram (Fig. 4.6.8).
10. Print your name with the icon “Add text.”
11. Print the audiogram.

Figure 4.6.6 pav. Screen image of the <Hearing examination system> (Lt. <Klausos tyrimo sistema>).

Figure 4.6.7 Screen image of the <Hearing examination system> - <Klausos tyrimo sistema> with three icons.
12. When you have printed your audiogram, please, press the button “Clear” which deletes the data in the study window and allows another student to start an experiment.

13. Compare your audibility curve with standard hearing curve.

14. Click “End” (lt. “Pabaiga”) to close the window <Hearing examination system> or exit window <MATLAB Command Window>.

**Note.** If you do the experiment in a noisier environment, your loudness contour will be at a higher range of sound level in dB, especially in the case of high frequency sounds.

**References**

1. Irving P. Herman, Physics of the human body, Berlin; Heidelberg: Springer (2007).