ACOUSTIC IMPEDANCES OF EAR CANALS MEASURED BY IMPEDANCE TUBE

PACS: 43.64.Ha

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ABSTRACT
During hearing sensitivity tests, the sound field is commonly generated by an earphone placed on a subject ear. One of the factors that can affect the sound transmission in the ear is the acoustic impedance of the ear canal. Its importance is related to the contribution of other elements involved in the transmission such as the earphone impedance. In order to determine the acoustic impedances of human ear canals, the standardized method for measurement of complex impedances used for the measurement of the audiometric earphone impedances is applied. It is based on the transfer function between two microphone locations in an impedance tube. The end of the tube representing the measurement plane is placed at the ear canal entrance. Thus, the impedance seen from the entrance inward is measured on 25 subjects. Most subjects participated in the previous measurement of the ratio between the pressures at the open and blocked ear canal entrance related to the ratio of the earphone and ear canal impedance. The results from present investigation are in good agreement with the existing data and they are going to be further analysed together with the previously obtained results.

INTRODUCTION
In the test of the hearing sensitivity, the sound pressure level generated in an individual ear by an earphone can be affected by the factors such as the acoustic impedance of the ear canal and the impedance of the earphone [1]. Due to the mentioned influence, the levels generated differ considerably from one subject to another. The variability of the sound pressure level generation has been investigated observing the sound transmission in both human ears and the coupler [1]. The transmission is described by the pressure division representing the ratio of the pressures at the open and blocked ear canal entrance. This pressure ratio is equivalent to the ratio of the ear canal impedance and the sum of this impedance and the earphone impedance. The impedance of several audiometric earphones is already determined [2].

Since the human ear canal can is often assumed as a linear passive one-dimensional system, a complete description of such a system can be obtained by its acoustic impedance [3]. Unfortunately, measurement of the ear canal impedance is sensitive to the measurement conditions (measurement position) [3-5]. Some of the problems can be circumvented by focusing on the energy reflectance (the ratio of reflected and incident energy) or pressure reflection coefficient - pressure reflectance (the ratio of reflected to incident pressure) rather than on impedance. When energy losses due to the wave propagation in the ear canal are small and the ear canal area function is slowly varying, which is usually the case, the energy (pressure) reflectances measured at different positions in the ear canal are nearly equal [3, 4].

As a continuation of the previous investigations [1, 2], the pressure reflectance and impedance of the human ear canal were measured by the standardized method for measurement of complex impedance using the four-microphone impedance tube [2]. The transfer function method was applied for the measurements, and determination of the impedance was based on the sound pressure variation along the tube [6, 7]. The measurements were carried out on 25 subjects. The results for the pressure reflectance and the ear canal impedance are analysed.
MEASUREMENT OF EAR CANAL IMPEDANCE

Measurement method

The details of the developed four-microphone measuring tube, Fig. 1, are given in [2]. The tube consists of an inner brass tube of thickness of about 1 mm inserted in an external nylon tube in which the housings for the microphones (Sennheiser KE-4-211) are drilled. The pairs of microphones 4-1, 3-1 and 2-1 are intended to be used in the following frequency ranges, respectively 200-750 Hz, 750-3500 Hz, and 3500-16000 Hz. The distance of the first microphone from the tube end (l_x) is somewhat larger than the one used in the measurement of the earphone impedances [2] since the tube is somewhat extended by the additional plug fitted to the tube diameter to enable better and easier coupling of the tube to the human ear canal.

The stationary sound wave is generated by the loudspeaker (Audax TW010F) placed at one end of the tube, while the other end represents the measurement plane. Besides, the absorbing material is placed near the loudspeaker to reduce the effects of reflections and tube modes [2].

The details of the transfer function method used for determination of the pressure reflectance and ear canal impedance are given in [2, 6]. The pressure reflectance \( R \) is determined as

\[
R = e^{i2\pi l_x} \frac{P_i e^{ik\Delta l_x} - P_0}{P_i - P_0 e^{-ik\Delta l_x}} = e^{i2\pi l_x} \frac{H_{11} - H_i}{H_{11} - e^{-ik\Delta l_x}}, \quad \text{(Eq. 1)}
\]

where index \( i \) can be 2, 3 or 4 in the four-microphone tube, and \( H_{ij} \) is the transfer function of the pressures measured by the two microphones (\( p_i \) and \( p_j \)). The impedance of the tube termination \( Z \) and normalized impedance \( Z_n \) are determined as

\[
Z = \rho_c \frac{1+R}{1-R} = \rho_c Z_n, \quad Z_n = \frac{1+R}{1-R}. \quad \text{(Eq. 2)}
\]

Measurement system and procedure

The sound pressures required for the determination of the pressure reflectance and ear canal impedance were measured using PC-based maximum-length sequence (MLS) technique, that is, using WinMLS software. The measurement system was the same as for the measurement of the audiometric earphones’ impedances [2]. The sampling frequency was 48 kHz, and 11\textsuperscript{th} order MLS with 16 averages was chosen enabling sufficiently long excitation and still relatively short measurement of approximately 1.4 s. The stimulus amplitude was set in such a way to give a sound level of about 85 dB(A) at the microphone position in a head and torso simulator (Brüel & Kjær type 4128) when the measurement tube was coupled to the manikin ear by a specially made ear mould. The measurements were carried out in a listening room.

Before the measurements, the calibration of the microphones’ sensitivities was done so that the microphones’ responses were measured when each of them was placed in the same position (hole) in the tube. The equipment and method were verified by the measurement of two known impedances – a rigid termination and open tube, where similar results were obtained as in [7].

There were 25 subjects participating in the measurements, 14 males and 11 females. The age ranged from 22 to 34 years (the mean age was 26.6). More than a half of the subjects (13
subjects) participated in the previous experiment – the measurements of the pressure division [1]. The left ear (the only one used for the measurements) of all 25 subjects was checked by a tympanometer and in some cases by an otoscope before the measurements. None of the subjects had reported ear abnormalities that might affect the middle ear function.

The subjects were lying down on the dentist chair placed in a horizontal position as shown in Fig. 2. Their heads were supported by the headrest enabling subjects to comfortably keep the heads fixed during the measurements. The tube was fixed by the supporting mechanical arrangement consisting of a heavy stand and several special clips, Fig. 2. This supporting arrangement allowed the tube to be moved and inclined at different angles in order to find the best coupling of the tube to the entrance of the ear canal of each individual. The correct tube position was found with help of the subject since it was possible to feel the occlusion when the tube was tightly fitted. The tube geometry enabled tight fit for almost all subjects without any additional coupling device. In only one subject with wider entrance of the ear canal, the ear mould was made and inserted in the ear to prevent the leakage between the tube and the tissue surrounding ear canal entrance. Additionally, the initial measurements were performed to check that the tube was positioned correctly and that the leakage was minimized.

Figure 2.- Measuring tube coupled to the ear canal of one of the subjects

When the tube was positioned and fixed, the sound pressures were measured by all four microphones in two measuring conditions: single channel measurements (one microphone at the time) and multi channel measurements (simultaneously all four microphones at the time). For single channel measurements, the sound pressure was measured using one by one microphone and stability of the measurement was checked by an additional control measurement [2]. In the case of instability, the measurements for that repositioning were repeated. When the measurements for particular repositioning were finished, the tube was removed and repositioned again. The measurements for each measuring condition and each subject were repeated five times (five repositions). Additionally, the measurements for another five repositions were carried out using not direct coupling of the tube to the ear canal entrance but the silicone ring placed on the measuring end of the tube. The length of this silicone ring was a few millimetres. The measurements for each subject lasted for approximately one hour. Besides, the reliability of the measurements was checked from time to time measuring the reference impedance, i.e. the rigid termination of the tube.

PRESSURE REFLECTANCES AND EAR CANAL IMPEDANCES

Results of some individuals
The signal-to-noise ratio was typically more than 40 dB in the greatest part of the observed frequency range in most subjects. The smallest signal-to-noise ratio existed at low frequencies (below 100 Hz or 200 Hz) and it was usually between 10 and 30 dB.

Since the results for single and multi channel measurements are very similar, only the results for single channel measurements are shown here. The repositioning of the tube has certain influence in some subjects. An example where this influence is relatively small in both the
magnitude and phase of the pressure reflectance is presented in Fig. 3(a) and (b). In some other subjects, certain difference appears among the pressure reflectances especially at lower frequencies (below 1 kHz or even 2 kHz in some cases). This difference is primarily the consequence of the leakage between the measuring tube and surrounding tissue of the pinna. In some other subjects, certain difference exists in a wider frequency range, which could be the consequence of different positions of the tube relative to the ear canal.

Figure 3.- Pressure reflectance (magnitude (a) and phase (b)) from five repositions (black solid lines) together with the mean (blue dashed line) for direct coupling of the tube, and mean pressure reflectance (magnitude (c) and phase (d)) for two couplings and one subject (JKV)

The influence of the coupling of the tube to the ear canal (direct coupling and coupling by the silicone ring) is reflected in certain difference in the pressure reflectance, Fig. 3(c) and (d). In some subjects, there is certain difference in the reflectance magnitude (an example is shown in Fig. 3(c)): However, in most subjects there is a difference in the reflectance phase, where the phase for the silicone ring coupling reaches the value of $-\pi$ at lower frequency than the phase for the direct coupling, as it is shown in Fig. 3(d). The reason for this is a small shift of the tube from the ear canal entrance and in this way from the ear drum due to the coupling ring.

The pattern of the reflectance from Fig. 3 is typical for most subjects. The reflectance magnitude has value close to 1 at low frequencies, when there is no leakage between the tube and the ear canal entrance in the measurement. By increasing the frequency, the reflectance magnitude decreases and it has a dip between 1 and 2 kHz. This dip is more prominent with some subjects, and it usually appears between 2 and 3 kHz, as shown in Fig. 4(a). Besides, there is a peak of the reflectance magnitude usually between 7 and 9 kHz, Fig 3(a) and 4(a). Some more dips and peaks can appear at higher frequencies. In some subjects, these extremes are more prominent, such as the dip above 10 kHz in Fig. 4(a).

On the other hand, the pressure reflectance phase approaches 0 at low frequencies. Actually, this was one of the criteria for correct positioning of the tube - to have the reflectance phase as close as possible to 0 at low frequencies. Some of the measurements not satisfying this criterion were discarded. By frequency increasing, the reflectance phase decreases. The slope of this decrease depends on a particular subject and the distance of the tube end from the ear canal termination (the ear drum). Thus, the reflectance phase reaches $-\pi$ at around 3 kHz in Fig. 3, while this is the case at around 4 kHz in Fig. 4.
The normalized ear canal impedance for one subject is presented in Fig. 4(c) and (d). The impedance magnitude has the value close to 10 at 200 Hz, and it decreases up to around 4 kHz, where there is a prominent dip. At higher frequencies, there is a prominent peak at around 9 kHz, and one more dip above 10 kHz. The ear canal impedance phase has an almost constant value (somewhat around 1 radian) up to approximately 4 kHz. Above that frequency, it changes the value between approximately -1 and 1 radian.

Individual and mean results

Common patterns of the pressure reflectances and normalized ear canal impedances shown in Fig. 4 exist in most subjects, Fig. 5. However, the amplitudes of the magnitude dips and peaks and their frequency positions depend on a particular subject. Moreover, individual reflectances and impedances usually have some additional characteristics. Thus, the declination of the reflectance magnitude from low frequencies toward the first dip around 2 or 3 kHz, and the dip itself are not that prominent in some subjects or even do not exist, Fig. 5(a). At higher frequencies, the reflectance magnitude fluctuates without any particular rule and prominent extremes in some subjects. On the other hand, all individual reflectance phases decrease by frequency increasing, starting from approximately 0 radians at low frequencies, Fig. 5(b). The unwrapped phase for only two individuals does not follow the relatively regular pattern found in other subjects, since their phase jumps are smaller than the default jump tolerance of $\pi$, so that the "unwrap" function does not correct the phase, and it remains to fluctuate around 0.

The declination of the impedance magnitude up to the first dip located around 3 or 4 kHz is seen in almost all subjects, Fig. 5(c). Also, the peaks and dips of the impedance magnitude are relatively prominent for almost all subjects. Thus, the pattern for this magnitude is more regular than the one for the reflectance magnitude. The main cause for the differences among the impedance magnitudes is a relative shift of the dips and peaks in frequency and the difference of amplitudes of the extremes. Similarly, the pattern of individual impedance phases is relatively regular, Fig. 5(d). The individual phases are similar to each other, with some fluctuations and some differences, especially in the regions of the transition from a negative to a positive phase (of approximately $\pm 1$ radian) and vice versa.

The patterns seen in individual characteristics exist also in the means determined separately for the magnitude (based only on individual magnitudes) and phase (based only on individual phases), but some of the important features of the individual characteristics become smeared.
DISCUSSION

The presented results for both the pressure reflectance and ear canal impedance are in relatively good agreement with the published data [3-5]. This gains special importance taking into consideration that different methods were used for the measurements. Moreover, in the present method, there were certain disturbances, such as the area discontinuity at the intersection of the measurement tube and the ear canal, and the leakage that was very difficult to be avoided for some subjects. Certain differences between the results found here and elsewhere are the consequence of different location of the measurement plane (e.g. the difference in the slope of the reflectance phase declination).

Initial analysis of the obtained ear canal impedances and the impedances of the audiometric earphones from [2] validates the assumption made in [1] that the impedances of the human ear canals are considerably larger than the earphone impedances at frequencies below 1 kHz. However, mutual relationship between these two impedances requires more thorough analysis of all results obtained in the overall research, which is planed to be made in the near future.

ACKNOWLEDGEMENTS

Financial support from the Danish Technical Research Council and Aalborg University is greatly acknowledged since all the measurements were carried out at Aalborg University. The authors would like to thank all our subjects for participation.