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COMPARISON OF SOUND TRANSMISSION IN HUMAN EARS AND COUPLER LOADED BY AUDIOMETRIC EARPHONES

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Invited paper

Abstract – *The thresholds of hearing are usually determined using audiometric earphones. They are calibrated by means of a standardized acoustical coupler. In order to have determined thresholds independent of the earphone type, the coupler should approximate the average human ear closely. Nevertheless, the differences among earphones as well as between human ears and the coupler affect the results of audiometric measurements inducing uncertainty. The influence of these differences is examined by investigating the sound transmission in both human ears and standardized coupler loaded by different audiometric earphones, which is related to coupling of these earphones to human ears and to the coupler. This is done by measurements of the transfer functions from input voltage of the earphone terminals to the entrance of the ear canal in two situations: open, and blocked. Similar measurements were carried out in the coupler, but since the "ear canal entrance" is not well-defined for the coupler, the mentioned measurements were done at different depths in the coupler. The sound transmission and coupling were described in terms of the pressure division at the entrance of the ear canal and the transmissions in human ears and the coupler were compared. The results indicate that they differ.*

1. INTRODUCTION

1.1. BACKGROUND AND PREVIOUS RESEARCH

Hearing thresholds are commonly determined by pure-tone audiometry, the sound field typically being generated by an earphone. It is assumed that the earphone produces a certain sound pressure level in the ear when controlled voltage is fed to the input terminals. The sound pressure level generated in the ear canal is supposed to be independent or nearly independent of individual characteristics of the ear. However, the response of the earphone is affected by the acoustic properties of the ear (pinna, ear canal, eardrum and ossicular chain) [1].

Variability of acoustic coupling between the earphone and the ear has been shown to be one of the important causes of unreliability of earphones in audiometry [2]. Two distinct factors are related to the variability, leakage at low frequencies and wave properties of the earphone and the external ear at higher frequencies. For some earphones such as supra-aural earphones, the connection between the cushion and the pinna is usually not effectively sealed and it depends on the position. This unstable coupling leads to variable amounts of sound pressure loss at low frequencies, usually below 500 Hz, accompanied by small variable amounts of increased sound pressure at somewhat higher frequencies [3]. On the other hand, the size and the shape of the cavity enclosed by the earphone, which are dependent on earphone and its positioning, geometry of the pinna and cartilaginous ear canal become very important at higher frequencies.

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The influence of individual differences, characteristics of the earphone or positioning of the earphone on the mentioned variability has been investigated [3-9]. In some cases, extreme differences of the ear canal sound pressures as much as 35 dB have been reported for the subjects with middle-ear pathologies present [3,4]. Such large uncontrolled variations in the ear canal sound pressure lead to the errors in audiometric test of the same amount of decibels, which could cause an incorrect interpretation of the observed effects on hearing, inappropriate use of hearing aids or unnecessary surgery.

Apart from variations of the sound pressure level in the ear, this level is not measured in the audiometric tests. The only control of sound stimulus level is adjustment of the input voltage to the earphone in order to give certain sound pressure level in the coupler [10,11]. This is carried out during calibration where the earphone is loaded acoustically with a coupler. The calibration procedure based on usage of either rigid couplers or so-called artificial ears has passed through different stages of development and standardization. Unfortunately, previous investigations have indicated that none of a number of designed couplers or artificial ears has a completely satisfactory performance for accurate calibration [6,7,12-15].

The basic purpose of an audiometric artificial ear or coupler is to enable determination of the voltage fed to an earphone required to just elicit the sensation of hearing for otologically normal listeners (on average) [12]. Besides, it should present to the earphone the same acoustic impedance as an average normal ear over the significant frequency range. It should also adequately simulate an effect of leakage between earphone and ear and permit the measurements of the sound pressure at a point in the artificial ear, which gives a 1:1 correspondence with the sound pressure developed in the human ear over the significant frequency range [16]. However, significant differences between the pressure generated in the ear canal of subjects and pressure generated at the position of the microphone in the coupler have been reported for different combinations of earphones and couplers [6,7,14,17,18].

1.2. MODELS OF SOUND TRANSMISSION

The sound transmission in the ear for earphone exposure may be represented by the analog model, Fig. 1 [19]. The sound pressure at the entrance of the ear canal is denoted $p_{EP,OE}$ (*EP* is used for *e*ar*p*hone and *OE* for *o*pen *e*ntrance), while the sound pressure at the eardrum is denoted $p_{EP,ED}$ (*ED* - *e*ar*d*rum). The *e*ar *c*anal (*EC*) is represented by an acoustical two-port terminated by the impedance of the eardrum, Z_{ED}. The excitation part comprising everything outside the ear canal is modeled by a Thévenin equivalent with generator sound pressure $p_{EB,BE}$ (*BE* - *b*locked *e*ntrance) and its impedance Z_{EP}.

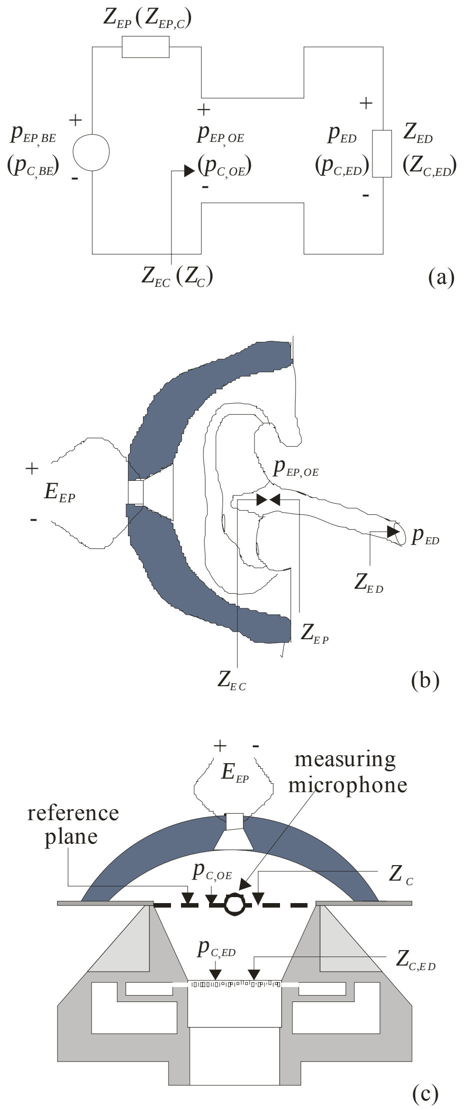

Fig.1. *Analog model for sound transmission in the ear and in the coupler (pressures and impedances are given in the brackets) for earphone exposure (a), illustration of transmission in the ear (b) and the coupler (c)*

The sound transmission in the coupler can be described by model similar to the one for the sound transmission in the ear. Relevant pressures and impedances for this transmission are also given in Fig. 1(a), but in the brackets, where the indices contain the same abbreviations as for transmission in the ear, except *C* meaning *c*oupler. Since the reference plane in the coupler that corresponds to the entrance of the ear canal is not so well-defined, then different planes in the coupler, that is, depths are used for measurements of corresponding transfer functions. The impedance of the Thévenin generator seen from the reference plane toward the earphone in this case is denoted $Z_{EP,C}$, while the impedance seen from the reference plane toward coupler's microphone is denoted as coupler impedance Z_C. The termination impedance of the coupler including the impedance of the coupler's microphone is denoted $Z_{C,ED}$, where the term *ED* (*e*ar*d*rum) in the coupler relates to the plane of the coupler's microphone membrane.

The Thévenin pressures ($p_{EP,BE}$ and $p_{C,BE}$) do not exist physically during listening or calibration, but can be measured at the entrance of the blocked ear canal (reference plane in the coupler), e.g. blocked by the earplug (blocking tip), since the acoustical two-port is considered as open circuit in such a condition. In order to yield the sound pressure at the entrance of the ear canal (reference plane), the Thévenin pressure is divided between the generator impedance and the impedance of the ear canal (coupler). Thus, the *p*ressure *d*ivision (PD) in the ear is given as

$$\frac{p_{EP,OE}}{p_{EP,BE}} = \frac{Z_{EC}}{Z_{EC} + Z_{EP}} . \qquad (1)$$

Similar, the PD for the sound transmission in the coupler is

$$\frac{p_{C,OE}}{p_{C,BE}} = \frac{Z_C}{Z_C + Z_{EP,C}} . \qquad (2)$$

The PDs are directly related to the ratios of the earphone impedance and the ear canal impedance, that is, coupler impedance. These impedance ratios can be determined by PDs from Eq. (1) and Eq. (2). Thus, PDs can be used for analyzing the impedance ratios and their significance.

1.3. PURPOSE OF INVESTIGATION

The hearing sensitivity is thus tested inseparably of the fit of earphone to the ear in spite of the known variability in the acoustical coupling of earphones to the ear. Besides, the calibration based on usage of a coupler does not enable that real acoustical output of earphones in the tested ear is directly controlled. This is the reason why the differences between earphones as well as between human ears and the coupler are observed here from an alternative perspective investigating sound transmission in human ears and in the standardized coupler both loaded by different earphones.

For that purpose, the transfer functions from input voltage of the earphone terminals to the entrance of the ear canal in two situations: 1) open (ear*p*hone *t*ransfer *f*unction with *o*pen *e*ntrance PTF_{OE}), and 2) blocked (ear*p*hone *t*ransfer *f*unction with *b*locked *e*ntrance PTF_{BE}) were measured. In order to compare the results for human ears with results for the coupler, similar measurements were done in the coupler. However, since the "ear canal entrance" is not well-defined for the coupler, the transfer functions were measured at different depths in the coupler. Based on the results, the PDs at the ear canal entrance are determined and used to describe the sound transmission and coupling of earphones to human ears and to the standardized coupler.

Five different audiometric earphones were included, while all coupler measurements were carried out using the IEC 60318-1 ear simulator type [20]. The transfer functions are analyzed including mean trends and individual variations, and impedance relations are discussed.

2. MEASUREMENT METHOD

2.1. MEASUREMENTS IN HUMAN EARS AND THE COUPLER

Transfer functions from voltage at the earphone terminals to the sound pressure at the entrance of the ear canal were measured, that is, impulse responses for that transmission. The center of the ear canal entrance is chosen as suitable measurement point. It enables measurements at two conditions, with the ear canal blocked (by an Aero Ear Classic earplug) and with the ear canal open, without considerable discomfort for the subjects.

The measurements in the coupler were carried out using the IEC 60318-1 ear simulator (Brüel & Kjær type 4153, here designated coupler). The coupler was used in its original form for supra-aural earphones, while it was supplied with a flat plate adaptor (type 1) for circum-aural earphone used as a rest for the earphone. The transfer functions from input voltage of the terminals of five earphones to the sound pressure at the reference plane/depth in the coupler were measured. In order to find the reference plane in the coupler that could be correlated with the entrance of the ear canal, nine planes were defined for measurements beginning from the plane almost at the top of the coupler's microphone (Brüel & Kjær type 4134), designated plane 1. Next eight planes separated approximately one millimeter from each other were defined above this plane 1. The last one, plane 9, was just above the plane of coupler's orifice. For each of the reference planes, the central point of circular opening of the coupler was defined as a measurement point.

2.2. EARPHONES AND SUBJECTS

The sound was reproduced by either one of 5 audiometric earphones: 4 supra-aural earphones (Telephonics TDH39, Telephonics TDH39 with noise capsules and cushions type ME70 (referred as TDH39C), Beyerdynamics DT48 and Holmberg 95-01) and 1 circum-aural (Sennheiser HDA200).

All 34 subjects participating in measurements had normal hearing that was tested by standard audiometry. Nineteen were males and 15 were females. The age ranged from 22 to 32 years (the mean age was 24.7). The absence of physical irregularities of subjects' ears such as perforated eardrum or presence of wax in the ear canal was examined by otoscope. Besides, none of the subjects had reported ear abnormalities that might affect the middle ear function.

2.3. MEASUREMENT SYSTEM

The general purpose maximum length sequence (MLS) measuring system (MLSSA – DRA Laboratories) was used. The MLS signal of order of 12 with 16 averages was chosen enabling sufficiently long excitation and still relatively short measurement (1.4 s). The sampling frequency was 48 kHz (provided by an external clock). In order to prevent frequency aliasing, the 20 kHz Chebyshev low pass filter of the MLSSA board and the 22.5 kHz low pass filter of the measuring amplifier were used. The stimulus amplitudes were 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). The signal from the MLSSA system was fed to the earphones through the power amplifier Pioneer A-616 with a calibrated gain of 0 dB. In addition, the signal from the power amplifier was attenuated approximately 25 dB by a custom made attenuator.

The sound pressure was recorded by a probe microphone Brüel & Kjær type 4182 with a 45 mm metal tube, which was bent at the end, and extended by a flexible tube. The length of the flexible tube varied from 9 to 15 mm depending on the shape of the pinna of the particular subject for measurements in human ears, that is, from 5 to 10.5 mm depending on the earphone and the reference plane for measurements in the coupler. The influence of the mentioned lengths of flexible tube on sensitivity and frequency response of the probe microphone was almost negligible. For circum-aural earphone, it was impossible to keep the same metal tube of the microphone since the flat plate adaptor was placed on the coupler, but another metal tube of the length of 100 mm bent on specific way was attached to the probe microphone. The curve of the bent part was not the same for different measurement planes, but the shape was adjusted for particular plane. The probe microphone with these different metal tubes (and attached flexible tubes) for supra and circum-aural earphones was calibrated separately. The signal from the probe microphone was sent to the measuring amplifier Brüel & Kjær type 2607 and then to the MLSSA system. Also transfer functions from input voltage of the earphone terminals to the pressure at the membrane of the coupler's microphone were measured by this microphone.

2.4. MEASUREMENT PROCEDURE

The subjects were seated on a seat with a headrest used as a support for the head to enable subjects to comfortably keep the head fixed during the measurements. In order to minimize the risk of displacement of the probe tube tip, special care was taken to place and fix the microphone and tube tip well. The tip of the tube was centered at the entrance of the ear canal, Fig. 2(a). A flexible metal strap, which was individually adjusted to fit the shape of the ear, was used for attaching the probe microphone to the subject's ear. The microphone arrangement was fixed by a surgical tape, but also by additional bandage and gauze with some subjects. The position of the flexible tube tip was assured with a special suspending wire used to prevent the occlusion of the tube tip in an easier way. The position of the probe tip was controlled before and after each measurement.

The Thévenin pressure $p_{EP,BE}$, that is the transfer function $\mathrm{PTF}_{\mathrm{EP,BE}}$, was measured first. For each earphone, the measurement was repeated five times for each of the two capsules (left and right), removing and repositioning the earphone after each measurement. Care was taken not to position the earphone awkwardly, but in a way similar to its position during audiometric tests with the subject. All measurements were done for the subjects' left ears. After the measurements with all five earphones, additional measurements were carried out for free-field exposure (results not presented here). Then, the earplug was carefully removed trying not to disturb the position of the probe tip. The next step was to repeat all the measurements, but measuring at the open ear canal entrance, $p_{EP,OE}$ ($\mathrm{PTF}_{\mathrm{EP,OE}}$). Some additional control measurements were included to check the repeatability of the measurement procedure and also to measure signal-to-noise ratio. During the measurements, the effects of physiological noise (caused by pulse, breathing etc) were monitored and care was taken to reduce their influence.

The measurements in the coupler were also carried out in two conditions, open and blocked coupler. Thus, pressure $p_{C,BE}$ ($PTF_{C,BE}$) was measured first. For that purpose, the coupler was blocked with a blocking tip of conical shape fitted the shape of the coupler's cavity and made of plastic. Different blocking tips were used for different measurement planes. The tip of the probe microphone tube was positioned at the center point on the top surface of the blocking tip representing the particular measurement plane, which is shown in Fig. 2(b). Care was given to avoid occlusion of the tube tip. The body of probe microphone was firmly fixed by a screw-clamp.


(a)

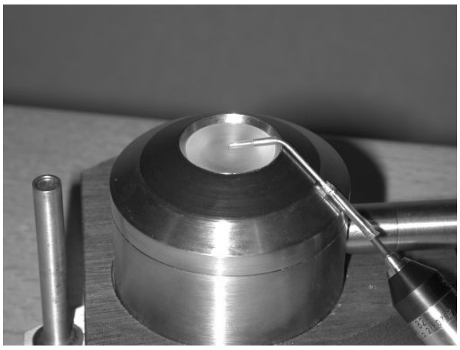
(b)

Fig.2. *Placement of probe microphone on human subject (a) and positioning of the tip of probe microphone tube in the blocked coupler for supra-aural earphones (b)*

For the blocked condition, the transfer function was measured three times for each of the capsules, repositioning the earphone on the coupler each time. The force that should be applied on an earphone in calibration procedure [10] was applied during coupler measurements for both conditions. After measurements in the blocked coupler, the blocking tip was removed and the probe microphone was placed back in the same position in the coupler. The displacement of tube tip position for open condition from corresponding one for blocked condition was negligible. The transfer function was again measured three times for each of the capsules with repositioning the earphone. Then, the whole procedure with blocked and open coupler was repeated for the next measurement plane. Additional measurements were carried out in order to check the repeatability and signal-to-noise ratio.

2.5. DATA PROCESSING

In order to determine the transfer functions and PDs, the measured impulse responses were post processed in MATLAB. They contain the aimed information, that is, the transfer function from input voltage of the earphone terminals to the sound pressure at the measurement point (H_{tf}), but also they contain the response of electrical part of measurement system and the contribution of measurement microphone. For the determination of PDs, the contribution of the measurement system cancels out since the same system was used for measurements in both conditions, blocked and open. Thus, the PDs could be simply determined by Fourier transformation of the measured impulse responses for open and blocked conditions, and complex division in frequency domain. Since all responses were very short, only the first 256 samples were used for post processing.

The determination of transfer functions requires a calibration between voltage and sound pressure, that is, determination of the contribution of the measurement system. The contribution of the electrical part of the measurement system was taken into account by its frequency response (H_{EL}) obtained by measurement of the electrical part of the system while short-circuited. The microphone frequency response (H_{MIC}) was found by comparison of the response of the probe microphone used to a reference microphone (Brüel & Kjær type 4136 having a flat pressure frequency response up to approximately 50 kHz) in the dedicated coupler. So, the transfer function for both conditions could be determined as

$$\left|H_{TF}\right| = \frac{\left|H_M\right|}{\left|H_{EL}\right|\left|H_{MIC}\right|}\frac{V_{MIC}}{V_{EP}\rho_{MIC}}, \qquad (3)$$

where H_M represents the frequency response of the measured impulse response, V_{EP} the input voltage to the earphone, V_{MIC} the output voltage of the microphone and ρ_{MIC} its sensitivity.

3. MEASUREMENT RESULTS

3.1. EARPHONE TRANSFER FUNCTIONS IN HUMAN EARS

The signal-to-noise ratio was measured for some subjects. For that purpose, the total noise was obtained by repeating the measurement, but replacing the earphone by an appropriate resistor and having all gain settings the same as during the measurement with earphone exposure. The results showed that the signal-to-noise ratio was dependent on particular features related to the measured transfer function (e.g. the physiological noise was different for different subjects, but also for the same subject and different earphones). This ratio was typically about 40 or 45 dB, but in the worst case, in the frequency range where the earphone transfer function had a low amplitude and/or where the background noise level was high, the ratio was about 20 or 25 dB.

The PTF_{BE}s of one of the supra-aural earphones together with those ones of circum-aural earphone for one randomly chosen subject are presented in Fig. 3. The variability in the earphone's response caused by its positioning depends on subject, earphone and frequency. Thus, greater differences among the transfer functions exist at low and high frequencies while the functions are closer to each other at mid frequencies. Besides, the differences are greater for supra-aural earphones than for circum-aural earphone.

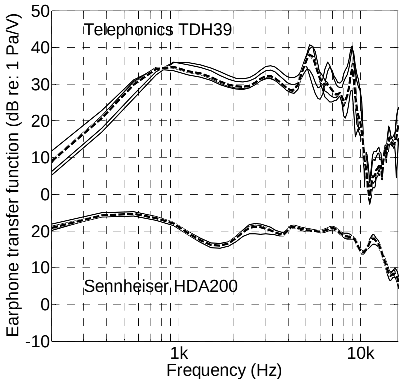

Fig.3. *PTF_{BE}s for one subject (JG) and five placements of the earphones (—) for the left capsule together with the average curve (---)*

The difference between average transfer functions for left and right capsule of a particular earphone is relatively small in comparison to other differences found in the results. The average transfer functions for both capsules are further averaged to give the mean transfer function for that measurement condition and each earphone. The mean PTF_{BE}s of all earphones measured on one subject are presented in Fig. 4. They are rather different. However, there is some similarity in PTF_{BE}s of supra-aural earphones at frequencies between 3 and 7 kHz. Also, the reduction of PTF_{BE}s at low frequencies is common for supra-aural earphones.

The PTF_{BE}s for different subjects and different earphones are considerably different, but there is a common pattern for each earphone, Fig. 5. However, the patterns for different earphones are rather different. The differences among individual PTF_{BE}s depend on frequency range and earphone. The largest variability caused by individual characteristics for a particular supra-aural earphone exists at low and high frequencies. This is not completely the case for the circum-aural earphone, where the larger variability is found only at high frequencies. Besides, the variability is generally smaller for the circum-aural earphone than for the supra-aural earphones.

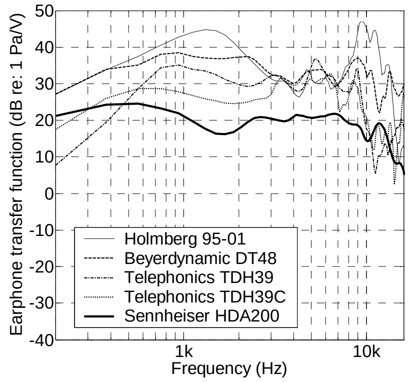

Fig.4. *The mean transfer functions (PTF_{BE}s) of all earphones measured on one subject (JG)*

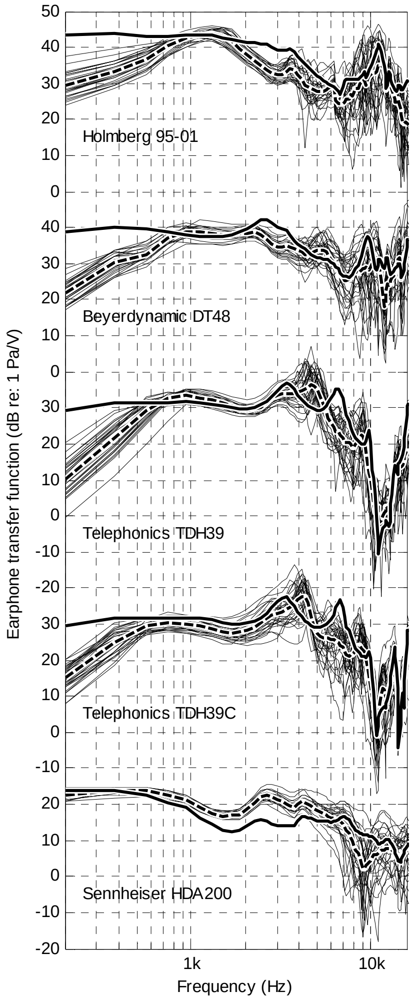

Fig.5. *Individual PTF_{BE}s for all subjects and left capsule (thin lines - individual functions, dashed line - average) together with the earphone transfer functions measured in the coupler by coupler's microphone (thick solid line)*

Together with individual PTF_{BE}s, the transfer function for each of the earphones measured in the coupler by its microphone is given in the same figure, Fig. 5. There is significant difference between individual transfer functions measured in the ear and that one measured in the coupler, but also between the average function of individual PTF_{BE}s and the function in the coupler.

The inter-subject variability in earphone transfer functions is even larger for open ear canal entrance (in PTF_{OE}s), which is in agreement with some other investigations [21]. For illustration, the individual transfer functions measured at the blocked and the open ear canal entrance for only one earphone are shown in Fig. 6.

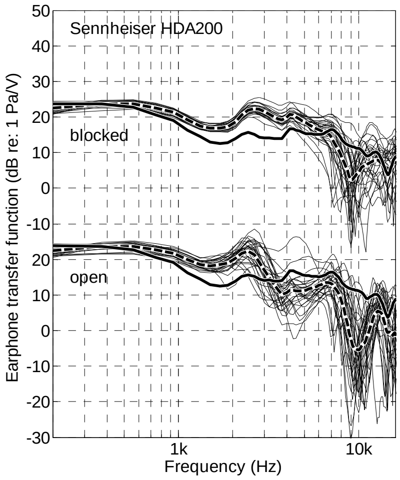

Fig.6. *Individual PTF_{BE}s and PTF_{OE}s for all subjects and left capsule (thin lines are individual functions and dashed ones are averages) together with the earphone transfer function measured in the coupler by its microphone (thick solid line)*

3.2. EARPHONE TRANSFER FUNCTIONS IN THE COUPLER

The influence of repositioning the earphone for the measurements in the coupler is not equally important as for measurements in human ears. However, for supra-aural earphones, the repositioning can result in differences in the transfer functions especially at low (below 800 Hz) and high frequencies (above 8 kHz) in some cases. One of the worst examples is shown in Fig. 7. Apart from supra-aural earphones, the repositioning does not cause any change of transfer function for circum-aural earphone.

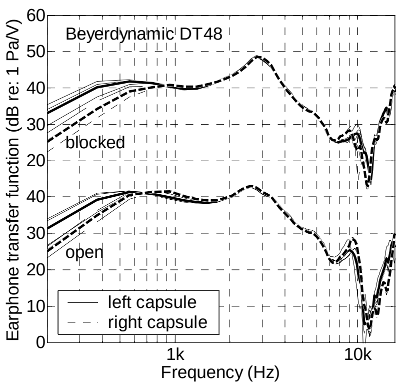

Fig.7. *Earphone transfer functions for repeated measurements in blocked and open coupler (measurement point was approximately 3 mm below the coupler's orifice)*

A change of measurement position (depth) affects the earphone transfer functions measured in both blocked and open coupler, Fig. 8. For supra-aural earphones, the shortest blocking tip, that is, the measurement position closest to the coupler's microphone, gives the lowest amplitude of the transfer function at frequencies up to 5 or 7 or even 8 kHz depending on the earphone. Moving the measurement point toward the coupler's orifice and reducing the volume of the coupler by bigger blocking tips, the amplitude of the transfer function in the mentioned frequency range is increased. However, the pattern is not completely regular for all measurement depths and earphones.

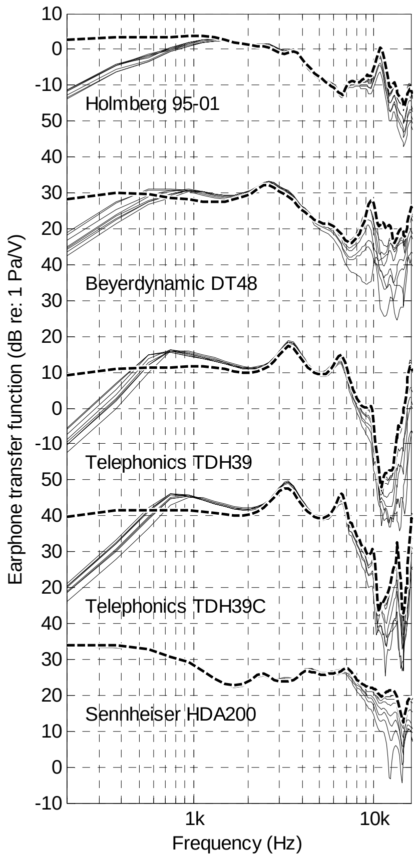

Fig.8. *Earphone transfer functions measured by probe microphone in blocked coupler at 8 depths (from the plane 1 - coupler's microphone surface to the plane 8 - just below the coupler's orifice) (—), together with the function measured by coupler's microphone in open coupler (---)*

On the other hand, the pattern at higher frequencies (above 5 or 8 kHz) is opposite to the mentioned one at low and mid frequencies. Thus, the shortest tip yields the highest amplitudes of transfer function here. But, this pattern is not that regular for most of the supra-aural earphones. The situation is different for the circum-aural earphone. The pattern found for the supra-aural earphones at low and mid frequencies is not prominent for the circum-aural earphone. On the contrary, the pattern at high frequencies giving higher amplitude for shorter blocking tip is very prominent and regular.

The differences among the earphone transfer functions measured at different depths in the open coupler at low frequencies for supra-aural earphones, Fig 9, are not related to the different measurement positions but to leakage, which may vary slightly from measurement to measurement. This is not the case for the circum-aural earphone where the transfer functions for different depths coincide since there is no leakage. The differences among the functions caused by different measurement positions become prominent above 5 or even 7 kHz depending on earphone. The measurement position closest to the coupler's microphone yields the function with the smallest deviation from the function obtained by the coupler's microphone. Shifting of the position toward the coupler's orifice reduces the amplitude of the earphone transfer function. Thus, the smaller the depth of the measurement position in the coupler, the lower the amplitude at high frequencies. This is similar to the pattern found with the blocked coupler.

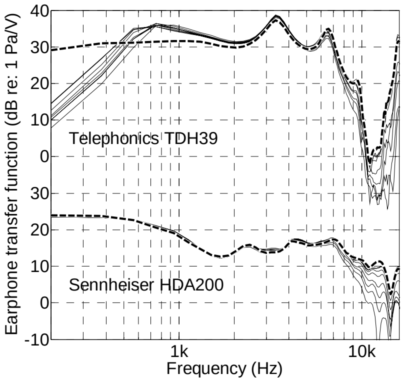

Fig.9. *Earphone transfer functions measured by probe microphone in open coupler at 8 depths (—) together with the function measured by coupler's microphone (---)*

3.3. PRESSURE DIVISION IN HUMAN EARS

The complex division of corresponding average earphone transfer functions PTF_{OE} and PTF_{BE} gives the PD. Typical example of PD for one subject and two earphones is presented in Fig. 10. Such a pattern exists for most subjects. Nevertheless, the pattern is a bit different for some subjects especially regarding the first peak, which is almost negligible in some cases.

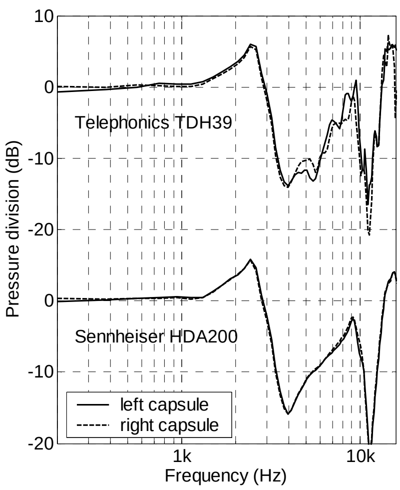

Fig.10. *Average PD for one subject (JG)*

Individual PDs together with average PD taken across all subjects are given in Fig 11, while mean PDs together with standard deviations are presented in Fig. 12. A similar pattern exists for all earphones. The PD is equal to or very close to 0 dB at low frequencies. There is a peak between 2 and 3 kHz with an average value of a few dB. The next two dips and a peak are also common for the pattern for the PD, where the first dip appears around 4 kHz and the second one around 10 kHz, while the peak appears between 7 and 8 kHz. The difference between earphones is very small and it could be in the order of a few dB.

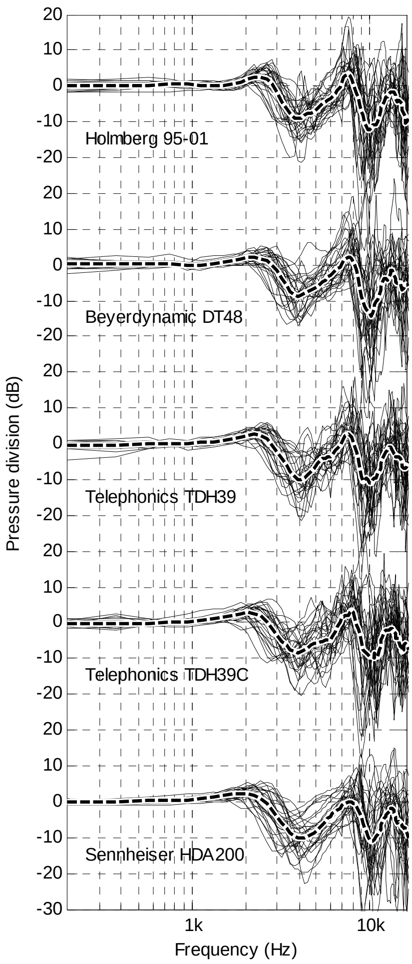

Fig.11. *Individual PDs (—) and corresponding average PD (---) for left capsule of all earphones*

3.4. PRESSURE DIVISION IN THE COUPLER

The differences between the earphone transfer functions measured in an open and a blocked coupler are not the same as corresponding differences found for human ears. This is reflected in the PD for the coupler, Fig. 13. The pattern seen in all earphones for measurements in human ears does not exist in any of the presented PDs for the coupler, that is, for none of the measurement depths. Different blocking tips and in that way different measurement positions affect the PD so that bigger blocking tips give PDs with lower amplitudes, especially at mid and high frequencies for the supra-aural earphones, and at high frequencies for the circum-aural earphones.

When the PDs in the coupler for different earphones are compared, then a similar pattern could be found for the supra-aural earphones, except that PD for Beyerdynamic DT48 earphone has some specific features in the part of the observed frequency range. On the other hand, the PD for the circum-aural earphone is almost equal to 0 dB up to 5 kHz for all depths. The amplitude of the PD depends on depth above that frequency. Besides, there is a dip above 10 kHz, which is prominent for bigger blocking tips.

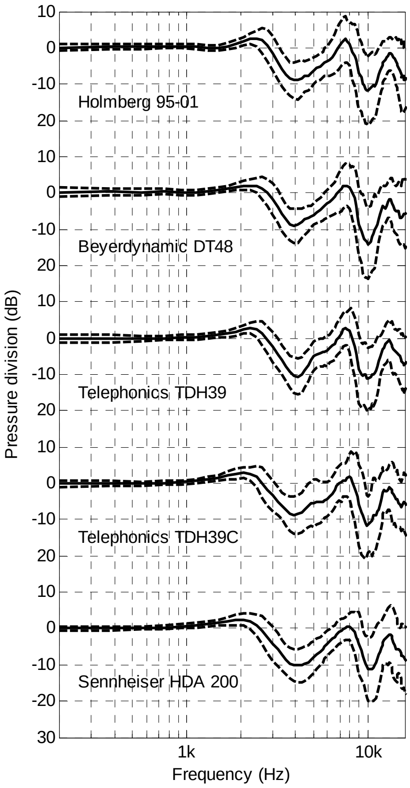

Fig.12. *Means and standard deviations of PDs calculated across all subjects and both capsules, mean is given by solid line (—), while mean ± one standard deviation is given by dashed lines (---)*

4. DISCUSSION

4.1. ASSESSMENT OF MEASUREMENTS IN THE COUPLER

Since the earphone transfer functions in the coupler were measured using both the probe microphone and the coupler's microphone, it is possible to determine and take into account the possible influence of the probe microphone. The metal tube of the probe microphone placed at the edge of coupler's orifice impedes perfect contact of earphone and coupler and may thus introduce leakage. This possible influence is approximately the same in the two measurement conditions, blocked and open coupler, since the position of the tube was the same. It does, however, influence the Thévenin impedance, and is as such in principle an error. Nevertheless, generally speaking, the transfer functions measured by both microphones coincide well at mid and high frequencies. Thus, it is assumed that the PD for the coupler is reliably determined.

4.2. VARIABILITIES AND DIFFERENCES IN EARPHONE TRANSFER FUNCTIONS

The intra-subject variability of PTF_{BE}s and PTF_{OE}s caused by repositioning the earphone on the human ear depends on the earphone but also on the frequency range. The main contributor of this variability at low frequencies is the leakage, which differs from one trial to another, because of the unstable fit of the earphone cushion to the complex geometry of the ear. The supra-aural earphones tend to have considerably larger variability at low frequencies than circum-aural earphone and leakage is more prominent for that type of earphone. The transducer could also be inclined in a certain direction, which may differ after repositioning. In that case, some differences in response could appear in a wider frequency range, including higher frequencies. The results obtained for intra-subject variability for the audiometric earphones included are in the range of already presented results for these earphones, but also for some other headphones although this variability differs from one investigation to another [7,8].

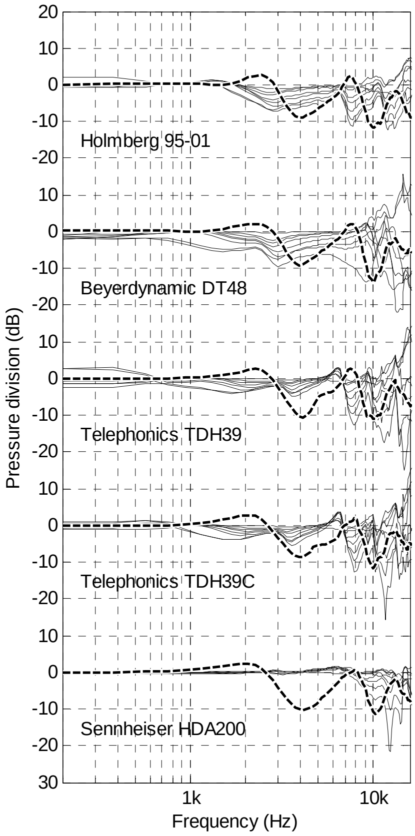

Fig.13. *PDs for 8 depths in the coupler (—) together with mean PDs in human ears (---)*

Even stronger frequency dependency exists for the inter-subject variability of earphone transfer functions in human ears. Due to the leakage and wave propagation influence, the variability for supra-aural earphones is larger at low and high frequencies, while for the circum-aural earphone, this increased variability exists only at higher frequencies. Also, the presented results reveal that inter-subject variability is generally considerably larger than intra-subject variability. The inter-subject variability that has been reported in other publications varies from one investigation to another depending on the earphone, number of subjects, etc. However, the results from present investigation are in the range of already reported variabilities.

The inter-subject variability found for all earphones stresses the differences of the sound pressure level that could be obtained in the ears of different subjects feeding calibrated input voltage to the earphone. Thus, the difference between mean sound pressure level (associated with the average human ear) and the level for a particular individual could be in the order of 5 or 7 dB at lower frequencies, but even in the order of 20 dB at higher frequencies for supra-aural earphones. At the same time, the difference between the sound pressure levels in the ears of two individuals for the same input voltage fed to a particular earphone could be even greater than 35 dB at higher frequencies in extreme cases. The situation is somewhat better for the circum-aural earphone, but still the mentioned difference could be fairly large. This individual difference is of direct consequence for the difference in determined hearing thresholds.

Earphone transfer functions in human ears have been compared to corresponding functions in different couplers in several studies [5,6,13,14,17,18]. In all of them, it has been shown that these functions are different, especially at low (for some earphones) and high frequencies (for almost all earphones). The amplitude reduction caused by leakage seen in the functions measured in human ears for the supra-aural earphones does seldom exist in the transfer functions measured in the coupler. The agreement between the transfer functions is the best at mid frequencies. At higher frequencies, some of the trends are similar in both transfer functions, but also some of them are unique for a particular function. Concerning the circum-aural earphone, the difference between the functions measured in human ears and in the coupler is in the same range of values as the differences for the supra-aural earphones, except that the trends are different for this earphone. There is almost no difference at low frequencies since the leakage is not common for circum-aural earphones. The difference at mid frequencies is of the same order as the difference at high frequencies.

On the other hand, the earphone transfer functions measured in the coupler exhibit some specific characteristics. So, the reduction of coupler's volume by bigger blocking tip leads to the increase of the amplitude of the transfer function for the supra-aural earphones at low and mid frequencies. However, this tendency is not prominent for the circum-aural earphone. The reason could be a bigger volume between the coupler and the cushion of the circum-aural earphone than the corresponding volume of the coupler when enclosed by a supra-aural earphone. Thus a change of the volume by the blocking tip has less relative importance. However, the mentioned effect of increased transfer function amplitudes at low and mid frequencies is opposite at higher frequencies for all earphones. On the contrary, different measurement depths in the open coupler do not affect the earphone transfer function for any of the earphones at low and mid frequencies where the wavelength of sound is great compared to the dimensions of the coupler, and the sound pressure is uniform inside the coupler. At higher frequencies, the influence of changing the measurement position (depth) in the open coupler on the earphone transfer function is similar to that in the blocked coupler.

4.3. INDIVIDUAL AND MEAN PRESSURE DIVISIONS

Comparison of PTF_{OE}s and PTF_{BE}s reveals that the mean transfer functions for open and blocked ear canal entrance coincide well at low frequencies (below 1 kHz). Thus, for all earphones investigated, the mean PD in human ears is almost equal to 0 dB in the frequency range mentioned. This indicates that the Thévenin impedance of each of the earphones Z_{EP} is considerably smaller here than the impedance of the ear canal Z_{EC} according to the Eq. (1). For such a ratio of impedances, the earphone could be considered as a nearly ideal sound pressure source. The influence of individual differences is significantly reduced for such a source meaning that similar sound pressure could be obtained in the ears of different individuals.

At frequencies above 1 kHz, the mean PD fluctuates showing prominent peaks and dips. In that region, the relation between the impedances of the earphone and ear canal is complex. Since the mean PDs for all earphones agree well, then the ratios of the earphones' impedances and the impedance of the average human ear canal are very similar for all investigated earphones. In that way, these earphones could be considered to behave very similarly in respect to the mentioned ratio of impedances. However, the individual variations cause shifts of the peaks and dips along the frequency axis in the PD for particular earphone, but also a change of their widths (Q-factors) and amplitudes. Thus, an individual PD can differ considerably from the mean PD, e.g. the difference can be even in the order of 15 or 20 dB. Because of that, the relation between the earphone impedance and the impedance of the individual ear canal becomes even more complex. On the other hand, the similarity of the PDs for a given subject with different earphones is greater than the one among PTF_{OE}s and among PTF_{BE}s on both mean and individual basis. The pattern of the PD found for audiometric earphones here is similar to the patterns for other commercially available headphones [21].

Comparison of the PDs in human ears to the PDs in the coupler reveals that there is almost no similarity between them. The prominent features present in the PDs for human ears cannot be found in the PDs for any of the measurement depths in the coupler. Even at low frequencies, the PD in the coupler is close to 0 dB only for bigger blocking tips, while there is a small deviation of few dB for smaller ones. The only exception is the PD for the circum-aural earphone, which is almost equal to 0 dB up to 5 kHz. The first peak present in the PDs in human ears (between 2 and 3 kHz) does not exist in the PDs in the coupler. Also, for all supra-aural earphones, it is difficult to make a comparison between the low amplitude in PDs in the coupler and the first dip in the PDs in human ears appearing around 4 kHz. Nevertheless, the PDs in the coupler for different supra-aural earphones are again fairly similar, but they are not as similar as the PDs in human ears. At the same time, it is difficult to see that the PDs for supra-aural earphones are similar to the PD for circum-aural earphone.

5. CONCLUSIONS

Consideration of the PD as a relevant quantity for comparison of sound transmission in human ears and the standardized coupler further emphasizes the differences between them. Thus, even some similarity that exists in earphone transfer functions measured in ears and the coupler disappears in the PDs. This indicates that some important effects of coupling of the audiometric earphones to human ears, and the sound transmission in ears do not exist in the coupling of the earphones to the coupler and the sound transmission in it. The influences of the mentioned differences as well as their consequences on the results of audiometric tests are investigated in continuation of the research.

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