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Published in:
Journal of the Audio Engineering Society

Publication date:
1995

Transfer Characteristics of Headphones Measured on Human Ears*

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For 14 headphones and 40 human subjects, transfer functions were measured from the voltage at the headphone terminals to the sound pressure at the entrance to the blocked ear canal. For all headphones the frequency responses were characterized by smooth fluctuations at low frequencies and rather individual high-Q resonances at high frequencies. Data were also obtained on the headphones' acoustical loading of the ear canal. The main objective of the investigation was an evaluation of the headphones as a means for the reproduction of binaural signals, but the transfer functions were also compared with design goals adequate for the reproduction of normal stereo recordings.

0 INTRODUCTION

The use of binaural technology has increased rapidly in recent years. Since headphones offer a separation of the two channels, they are normally used for reproduction. The purpose of the present investigation is to collect data for headphone performance on human subjects. Although the investigation is focused on the use of headphones in the binaural technique, the methods and data obtained are also relevant for other situations where sound is reproduced through headphones. The investigation was reported at the 92nd Convention of the Audio Engineering Society in Vienna in 1992 [1].

0.1 Binaural Technique

The idea behind the binaural technique is the following. The input to the hearing consists of two signals—the sound pressures at each of the eardrums. If these are recorded in the ears of a listener and reproduced exactly as they were, then the complete auditory experience is assumed to be replicated, including timbre and spatial aspects.

A system that implements the binaural technique is called a binaural system. In most systems the listener is replaced by an artificial head during recording. The artificial head has the same shape and acoustical properties as an average human head. For playback of the recorded signals headphones are normally used since they offer almost total channel separation.

0.2 Model of Sound Transmission

For a binaural system it is crucial to have the correct total transmission from the recording situation to the playback situation. Previous work by Møller [2] describes the transmission in a binaural system. The playback part of the transmission is represented by the model given in Fig. 1.

The voltage at the headphone terminals is denoted by $E_{\text{headphone}}$. The acoustical excitation from the headphone is modeled by a Thevenin equivalent at the entrance to the ear canal. The source impedance is denoted by $Z_{\text{headphone}}$ and the Thevenin pressure by P_5. This pressure does not normally exist physically, but if the ear canal is blocked as, for example, with an earplug, the Thevenin pressure is found at the outer side of the earplug.

To yield the sound pressure at the entrance to the open ear canal, denoted by P_6, the Thevenin pressure is divided between the source impedance and the input impedance to the ear canal, denoted by $Z_{\text{ear canal}}$,

$$\frac{P_6}{P_5} = \frac{Z_{\text{ear canal}}}{Z_{\text{ear canal}} + Z_{\text{headphone}}} . \qquad (1)$$

The ear canal acts as an acoustical two-port terminated by the eardrum impedance Z_{eardrum}, and the pressure at the eardrum is denoted by P_7. Subscripts 5, 6, and 7

* Manuscript received 1994 July 11; revised 1995 January 9.

have been chosen in order to prevent conflicts with the description in [2], where subscripts 1 to 4 were used to describe sound pressures during free-field sound exposure.

Binaural recordings may be made at any point in the ear canal, since the transmission along the ear canal is independent of direction. The recording point is often referred to as the reference point. It has been shown that recording of the Thevenin pressure at the entrance to the blocked ear canal should be preferred since this pressure includes the directional information, and it is the pressure that is least affected by variations between listeners [3].

When the recording is made outside a blocked ear canal, it can be shown that the correct eardrum signals are obtained during playback if the electrical gain of the transmission is given by the expression [2]

$$G = \frac{1}{M \cdot P_5/E_{\text{headphone}}} \cdot \frac{Z_{\text{ear canal}} + Z_{\text{headphone}}}{Z_{\text{ear canal}} + Z_{\text{radiation}}} \qquad (2)$$

where M is the transfer function from pressure to voltage of the recording microphone and $Z_{\text{radiation}}$ is the free-air radiation impedance seen from the ear canal. The term $P_5/E_{\text{headphone}}$ is the electroacoustical transfer function of the headphone, measured at the entrance to the blocked ear canal. It is called head*p*hone *t*ransfer *f*unction (PTF).

The last term of G—the term involving the four impedances—is the ratio between the pressure divisions of the Thevenin pressure in the two situations, 1) when the ear is in free air and 2) when the headphone is placed over the ear. It is called *p*ressure *d*ivision *r*atio (PDR). The term is easily verified since in the free-air situation $Z_{\text{headphone}}$ in Eq. (1) is replaced by $Z_{\text{radiation}}$.

With these definitions, Eq. (2) can also be written as

$$G = \frac{1}{M \cdot \text{PTF}} \cdot \text{PDR}\,. \qquad (3)$$

If the two pressure divisions are equal, the PDR reduces to unity. A headphone for which this is the case is defined as an FEC headphone, that is, a headphone with *f*ree-air *e*quivalent *c*oupling to the ear. (This term is identical to the term "open" used in [1], [2]. The reason for changing the term is that "open" is used commercially to describe a headphone that does not exclude sound from the outside.) For FEC headphones G should only equalize for the combined transfer function of the recording microphone and the headphone. Furthermore, the microphone will often have a flat frequency response, and thus G should only equalize for the PTF.

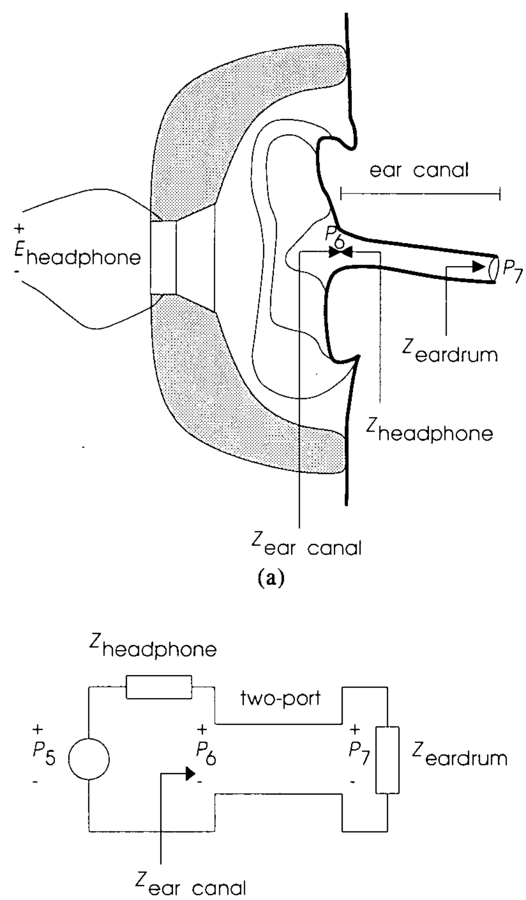

Fig. 1. Sound transmission through external ear when exposed to sound from a headphone. (a) Anatomy. (b) Analog model as described in [2].

0.3 Previous Measurements of Headphone Transfer Characteristics

Transfer functions of headphones are seldom measured on human subjects. One reason is the practical difficulties associated with measurements in the ear canal. Another reason is the fact that for the reproduction of traditional recordings, the headphone is supposed to simulate the entire transmission in a traditional setup, including the loudspeaker response and the transmission through the room to the listener's ear canal. This transmission is rather complex, and headphones are normally evaluated through loudness comparisons between sound emitted by the headphone under test and sound emitted by a loudspeaker in specified surroundings [4], [5]. The sound field created by the combination of loudspeaker and room is called the reference field. The comparison may also be made between a reference headphone and the headphone under test [6].

Even when measurements are made in the ear canal, results are normally given as the deviation between the sound obtained from the headphone and that from the reference sound field [7]–[9]. Measurements in the ear canals of human subjects and aiming at a predetermined design goal—corresponding to the transmission from the reference sound field—have been suggested by a few authors [10]–[12].

Although a few measurements on human ears are reported in the literature (for example, [10], [11], [13], [14]), a comparison is not possible. Not only have different methods been used, but the headphones are often unidentified, or they differ from the ones used in the present investigation.

0.4 Goal of Present Investigation

It is the purpose of the present investigation to determine PTFs and PDRs for a number of commercially available headphones, measured on a large number of subjects, and to use these data to evaluate existing headphones as means of reproduction for binaural recordings.

1 METHOD

Measurements were carried out with 14 headphones placed on the ears of 40 subjects. Impulse responses were measured for the transmission from voltage at the input of the power amplifier to the output of the measuring microphone placed to measure P_5 or P_6. The impulse responses were measured using the maximum-length-sequence (MLS) technique simultaneously at both ears. PTFs and pressure divisions P_6/P_5 were obtained through Fourier transformation of the measured impulse responses, followed by appropriate divisions. PDRs were determined using pressure divisions for the free-field situation found for the same subjects in a parallel investigation at our laboratory [15].

For each subject and each headphone, three types of measurements were made. P_5 was measured with a miniature electret microphone, and both P_5 and P_6 were measured with a probe microphone.

1.1 Subjects

40 subjects participated, 22 males and 18 females; 31 were randomly chosen students and 9 were staff members. The age range was from 21 to 40 years. All subjects had normal hearing, and none had reported ear abnormalities that might affect the middle-ear function. The same subjects participated in a parallel investigation of head-related transfer functions [15].

1.2 Microphones

The choice of microphone for measurements in the human external ear is a compromise between acceptable dimensions and satisfying sensitivity and frequency response. For measurement of the Thevenin pressure P_5 a Sennheiser KE 4-211-2 miniature microphone was used. This is an electret microphone, cylindrical in shape, 4.75 mm (0.19 in) in diameter by 4.20 mm (0.17 in) long. Two selected microphones were used throughout the experiment, one for each ear.

The microphones were mounted in EAR earplugs placed in the ear canals. The microphone was inserted in a hole in the earplug, and then the soft material of the earplug was compressed during insertion in the ear canal. As the earplug expanded, the outer end of the ear canal was completely filled out. The end of the earplug and the microphone were mounted flush with the ear canal entrance. The placement of the microphone is shown in Fig. 2.

For the measurement of P_6 it was reckoned that the miniature microphone was so big that it might disturb the sound field, and a probe microphone was therefore used. This type of microphone would not disturb the sound field in the ear canal since the interference of the probe tip is minimal, but it has the disadvantage of a low sensitivity and a nonflat frequency response. The probe microphone was a Brüel & Kjær 4182 with a 45-mm (1.77-in) metal tube extended by 5 mm (0.2 in) of a flexible plastic tube [outer diameter 1.65 mm (0.06 in)]. The acoustic impedance of the probe was approximately 10^9 N·s/m^5, which at 500 Hz corresponds to the impedance of a 0.05-cm^3 (0.003-in^3) volume. At higher frequencies the corresponding volume decreases, and the loading by the tube was therefore considered negligible in the frequency range of interest.

During measurements the probe microphone was attached to the external ear by a metal strap. The strap and the tube were adjusted individually to fit the shape of the ear. To avoid displacement of the probe microphone during the experiment, it was fixed along the subject's neck with surgical tape, and the position of the tip was controlled before and after each single measurement. Fig. 3 shows the probe microphone attached to a subject's ear and neck.

Even though efforts were undertaken to keep the metal tube of the probe microphone close to the subject's head surface, a small leak could arise between the headphone cushion and the head surface for some headphones. The presence of the probe tube could also cause minor changes in the position and orientation of the headphone capsule. Therefore P_5 measurements were also carried out with the probe microphone for all headphones. In this way the capsule displacement and the leak would have the same influence on P_5 and P_6, and the influence on the pressure division was eliminated. Due to the disturbance from the metal tube, the measurements with the probe microphones were considered less suitable for the determination of PTFs than the measurements with the miniature microphones.

In order to minimize the error due to the displacement of the probe tip between measurements of P_5 and P_6, the probe measurements were carried out in the following way. P_5 was measured first with a whole earplug blocking the ear canal. Then the earplug was carefully removed with as little disturbance of the probe microphone as possible.

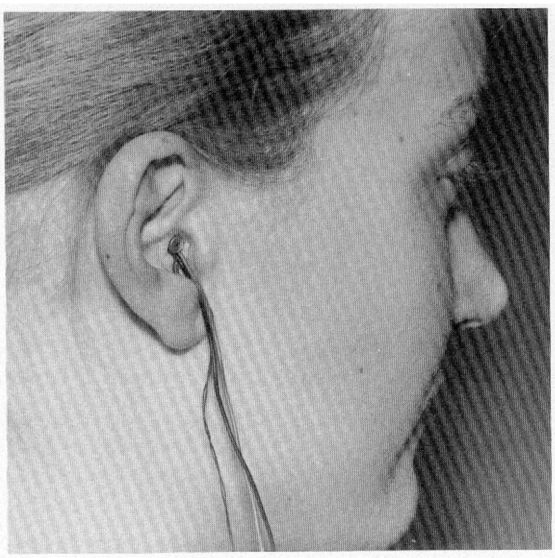

Fig. 2. Miniature microphone mounted in subject's ear to measure blocked ear canal pressure P_5.

Immediately afterward P_6 was measured.

Pressure frequency responses for the miniature and probe microphones are given in Fig. 4. The sensitivities of all microphones at 1 kHz were measured every working day during the 2-month measurement period. Although deviations from the nominal values were small (below ±0.3 dB), appropriate corrections were made in the final data processing.

1.3 Headphones under Test

A total of 14 headphones were tested, as listed in Table 1 together with information about the capsule types. The manufacturers' specifications of the frequency range are also given. The headphones were chosen as a wide selection of commercial headphones available when the investigation was started.

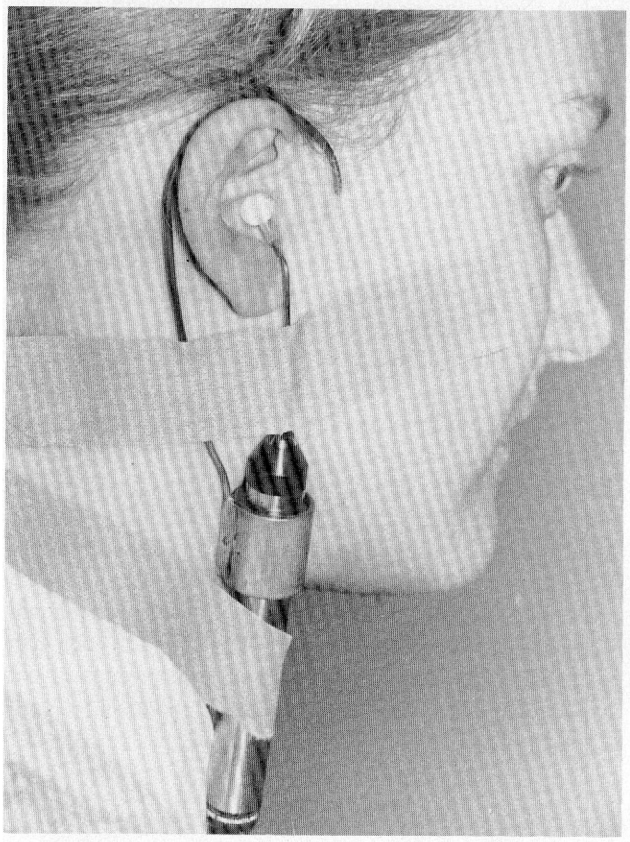

Fig. 3. Probe microphone mounted on subject to measure blocked ear canal pressure P_5.

The BALL is not an ordinary headphone, but two small loudspeakers placed 250 mm (10 in) from the subject's head center position in azimuths of ±110° relative to a frontal direction. The loudspeakers were 70-mm (2.76-in)-diameter midrange units (Vifa M10MD-39) mounted in 155-mm (6.1-in)-diameter hard plastic balls.

The FLOAT is rather large, covering areas of 120 by 170 mm (4.7 by 6.7-in) parallel to the side of the head. It touches the rear rim of the pinna but is otherwise free from the ear.

The LAMBDA is electrostatic whereas the others are electrodynamic. The measurements on the LAMBDA include a driver unit (SRM-1/MK-2). The driver unit's volume control was arbitrary but fixed.

Two of the headphones were actually the same unit measured under two conditions. The K1000 was measured with two different positions of the headphone capsule. Measurements were made with a distance of 20 mm (0.8 in) between the fixed part of the headphone

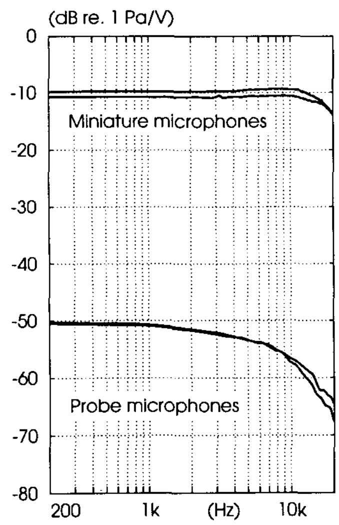

Fig. 4. Pressure frequency responses of two miniature microphones (Sennheiser KE 4-211-2), including 20-dB front-end amplifiers, and two probe microphones (Brüel & Kjær 4182), including 45-mm (1.77-in) metal tube and 5-mm (0.2-in) plastic tube.

Table 1. Headphones under test. Frequency range as specified by manufacturer.

Abbreviation	Headphone	Capsule Type	Frequency Range (Hz)
BALL	Close-mounted ball loudspeakers	—	—
MDR102	Sony MRD-102	Supraaural	—
FLOAT	Jecklin float model two	Free from ear	30–20 000
DT770	Beyerdynamic DT 770 professional	Circumaural	5–35 000
DT990	Beyerdynamic DT 990 professional	Circumaural	5–35 000
LAMBDA	Stax SR lambda professional	Circumaural	8–35 000
HD250	Sennheiser HD 250 linear	Circumaural	10–25 000
HD420	Sennheiser HD 420 SL	Supraaural	18–20 000
HD540	Sennheiser HD 540 reference	Circumaural	16–25 000
HD560	Sennheiser HD 560 ovation	Circumaural	16–30 000
K240	AKG Acoustics K 240 DF	Circumaural	20–20 000
K500	AKG Acoustics K 500	Circumaural	15–25 000
K1000,2	AKG Acoustics K 1000	Free from ear	30–25 000
K1000,M	AKG Acoustics K 1000	Free from ear	30–25 000

and the adjustable part (K1000,2) and with the maximum angle obtainable (K1000,M). For a few subjects the headphone touched the pinna without deforming it in the first position, whereas it was always free from the pinna in the second position.

The headphones were placed on the subjects by the experimenter.

1.4 Measuring Setup

The general-purpose measuring system known as MLSSA (DRA Laboratories) was used. The MLS method offers a number of advantages compared to traditional frequency- and time-domain techniques. It is basically noise immune, and combined with averaging, the achieved signal-to-noise ratio is high. A thorough review of the MLS method is given by Rife and Vanderkooy [16].

For the purpose of measuring at both ears simultaneously, two MLSSA systems were used, coupled in a master–slave configuration by a custom-made synchronization unit allowing sample synchronous measurements. The sampling frequency of 48 kHz was provided by an external clock.

The stimulus amplitudes (between ± 0.06 and ± 0.68 V for the different headphones) were selected to cause a sound level of 80–90 dB(A) at the microphone position in a head and torso simulator (Brüel & Kjær 4128). This corresponds to free-field sound pressure levels of approximately 67–77 dB(A), levels where the stapedius is assumed to be relaxed. The headphones were driven by the loudspeaker output of a power amplifier (Pioneer A-616, modified to have a calibrated gain of 0.0 dB). No series resistance was present, as in many headphone outputs.

From the microphone (miniature as well as probe) the signal was sent through a measuring amplifier (Brüel & Kjær 2607). To avoid 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. Also the 22.5-Hz high-pass filter on the measuring amplifier was active.

It is a prerequisite that the MLS used in a measurement be longer than the impulse response of the system under test. In the present setup for headphone measurements this is satisfied with the minimum length offered in MLSSA, which is 4095 points. In order to achieve a high signal-to-noise ratio, the recording was averaged 16 times, called preaveraging in the MLSSA system. Even with this averaging the total time for a measurement was as short as 1.45 s.

1.5 Data Processing

Results of the measurements were impulse responses for transmission from the input to the power amplifier to the output of the measuring amplifier. In order to obtain the wanted information, some postprocessing was needed. This was carried out using the program MATLAB (The MathWorks, Inc.). The first 256 samples were used in the postprocessing, giving a frequency resolution of 187.5 Hz.

For determining the pressure division P_6/P_5, the impulse responses to P_5 and P_6 were Fourier transformed, and a complex division was carried out in the frequency domain. As exactly the same equipment (including the probe microphone) was involved during the measurements of P_5 and P_6, the influence of this cancels out. Pressure divisions for the same subjects, but with the ear in free air, were transferred from a parallel work in our laboratory [15]. PDRs were calculated as a complex division in the frequency domain between the free-field pressure division and the P_6/P_5 found for each headphone.

The calculation of $P_5/E_{\text{headphone}}$ was slightly more complicated. The impulse response to the output of the miniature microphone placed to measure P_5 was Fourier transformed, and a directly measured "version" of $P_5/E_{\text{headphone}}$ was thus obtained. This included the transfer functions of the miniature microphone and of the electric system (power amplifier, measuring amplifier, filters). Following a measurement of the transfer function of the electric system, the effect of this was removed through a complex division in the frequency domain. The effect of the miniature microphone was removed by dividing by the ratio of the transfer function of the miniature microphone to that of a reference microphone (the ratio found by measuring the same sound field with the two microphones). Finally only the transfer function of the reference microphone remained. As the chosen reference microphone (Brüel & Kjær 4136) has a flat pressure response in the audio frequency range, the correct $P_5/E_{\text{headphone}}$ was found after a division by the nominal sensitivity of this microphone.

1.6 Signal-to-Noise Ratio

The signal-to-noise ratio cannot be expressed as a single figure since it depends on the response being measured. For illustration, the total noise level was found by repeating a measurement, but with the headphone electrically replaced by a resistor. All gain settings were as in the original measurement. Examples with the two types of microphones are given in Fig. 5. The signal-to-noise ratios for the miniature microphones are typically around 70 dB and only below 50 dB at frequencies where a transfer function exhibits very low values. For the probe microphones the corresponding figures are approximately 15 dB lower.

2 RESULTS

PTFs and PDRs are given in Sections 2.1 and 2.2, respectively. Based on three independent measurement series on the same subject, an assessment of the validity of the results is given in Section 2.3. In general the results for the left and right sides are almost identical. Differences reflect differences in the ears as well as in the headphone capsules. These differences are small, an observation made previously by Burkhard and Corliss [13]. In the following sections data are presented for the left side only. The data for the right side have been analyzed in parallel, and the results support all observations and conclusions.

It is stressed that the data are assessed with the purpose of the reproduction of binaural recordings in mind, and the desired response is thus an FEC headphone with a flat—or at least correctable—frequency response.

2.1 Headphone Transfer Functions (PTFs)

The PTFs for all headphones, measured on all subjects, are shown in Fig. 6. The overall gains of the various headphones are, not unexpectedly, very different. Note that the solid horizontal lines represent a gain of 1 Pa/V. The MDR102 has the highest gain, whereas the K1000,M has the lowest. In general the responses are far from being flat. All headphones show large fluctuations with frequency. At frequencies up to a few kilohertz, the curves are relatively smooth, and the resonances are of a low-Q nature. Above 8 kHz all responses are dominated by narrow peaks and dips.

For all headphones the responses show considerable variations between subjects. At low frequencies this variation can be regarded as a variation in the sensitivity of the headphone, since for most headphones the curves for different subjects are similar but displaced vertically. The lowest variation in sensitivity is seen for the LAMBDA (below 2 dB), but also the BALL and the HD540 have low variations (below 3 dB). High variations are seen for the MDR102, the FLOAT, and the K1000,2 (7 dB or more).

At high frequencies the variations between subjects become larger. The variations are mainly reflected in the exact frequencies at which the peaks and especially the dips are located. For some headphones, though, it is difficult to find a common structure at all. At certain frequencies, variations between subjects may be as large as 20 dB or even more. Fig. 7 shows PTF means and standard deviations for all headphones, calculated on a decibel basis. Also the mean curves show large variations with frequency, although some of the resonances, especially at high frequencies, have been "flattened" by the averaging.

The low intersubject variations in the sensitivities of several headphones (BALL, LAMBDA, HD420, HD540, and K500) are reflected in low standard deviations of these at low frequencies. Similarly, the high variations in sensitivity of the MDR102, the FLOAT, and the K1000,2 are reflected in the high standard deviations of these at low frequencies.

In general the intersubject variations of the exact frequencies of the resonances have contributed to large standard deviations at high frequencies (on the order of 3–5 dB; even higher for some headphones). As an example, the K500 has a dip slightly below 10 kHz, but the exact frequency varies between subjects in the range of 7.5–10 kHz. An atypical example is seen for the same headphone, where a dip between 4 and 5 kHz occurs at the same frequency for all subjects, and no increase in standard deviation is seen at this point.

As mentioned earlier, a headphone for the binaural technique should have a linear, or at least correctable, PTF. The HD420 has a relatively flat response up to approximately 7 kHz. The FLOAT and the K500 have complicated structures that are difficult to correct. In general, none of these headphones seem suitable in a binaural reproduction system without equalization of the responses. The question of equalization is further discussed in Section 3.2.

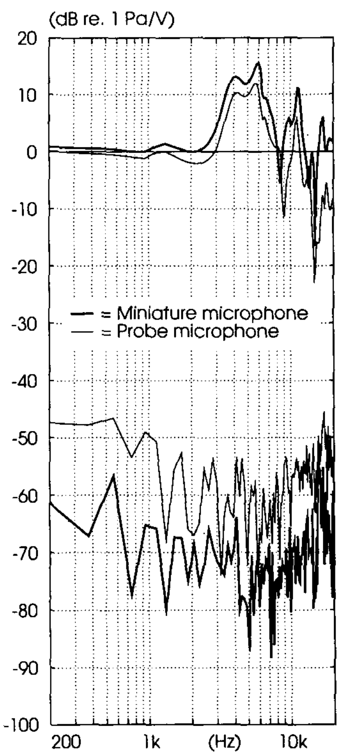

Fig. 5. Illustration of signal-to-noise ratio. Upper curves—typical measurements; lower curves—corresponding measurements with all settings unchanged, but with headphone replaced by a 100-Ω resistor. Note that data are original measurements and not computed PTFs.

2.2 Pressure Division Ratios (PDRs)

Examples of pressure divisions are presented in Fig. 8(a). Pressure divisions are shown for four subjects measured for coupling to the free air and for coupling to a sample headphone. It is seen that the pressure divisions are close to 0 dB up to approximately 1 kHz. The patterns for frequencies higher than 1 kHz look different from subject to subject, with broad dips as large as 15 dB or more.

The pressure divisions for the two situations are seen to deviate slightly. The deviation is expressed by the PDR and shown in Fig. 8(b). It is seen that PDRs are close to 0 dB up to 2 kHz. Above this frequency, PDRs are characterized by several crossings of the 0-dB line. The maximum deviations from 0 dB are approximately 3.5 dB up to 8 kHz and more than 15 dB at higher frequencies, where very narrow spikes occur.

With regard to the repetition measurements in Section 2.3 it is argued that the spikes at high frequencies are most likely caused by small changes in microphone and headphone positions between measurements with open and blocked ear canals and between free-air and headphone measurements. This makes PDRs unreliable above approximately 7 kHz, and thus they are not reported above that frequency.

Fig. 9 shows PDRs for all subjects and all headphones. For each headphone, individual curves as well as the mean and the standard deviation are given. It is seen that the PDRs are approximately flat at frequencies below 2 kHz, although varying in level around 0 dB. Small level variations are also seen in the repetition measurements (Section 2.3), and the deviations from 0 dB are considered coincidental. Above 2 kHz the PDRs show fluctuations, to some extent individual in the exact response, but with a common structure for each headphone.

As mentioned in Section 0.2, a headphone is said to have FEC properties if the PDR is unity. As seen from the mean values, all headphones fulfill this requirement on an average level for frequencies below 2 kHz. Above 2 kHz only the BALL has FEC properties if a strict criterion is used. This is not unexpected, since the BALL is distant from the ear and thus gives the smallest disturbance of $Z_{radiation}$. If a few deviations up to 2 dB are accepted, the K1000,M, K1000,2, DT990, and LAMBDA can be considered FEC headphones. The rest

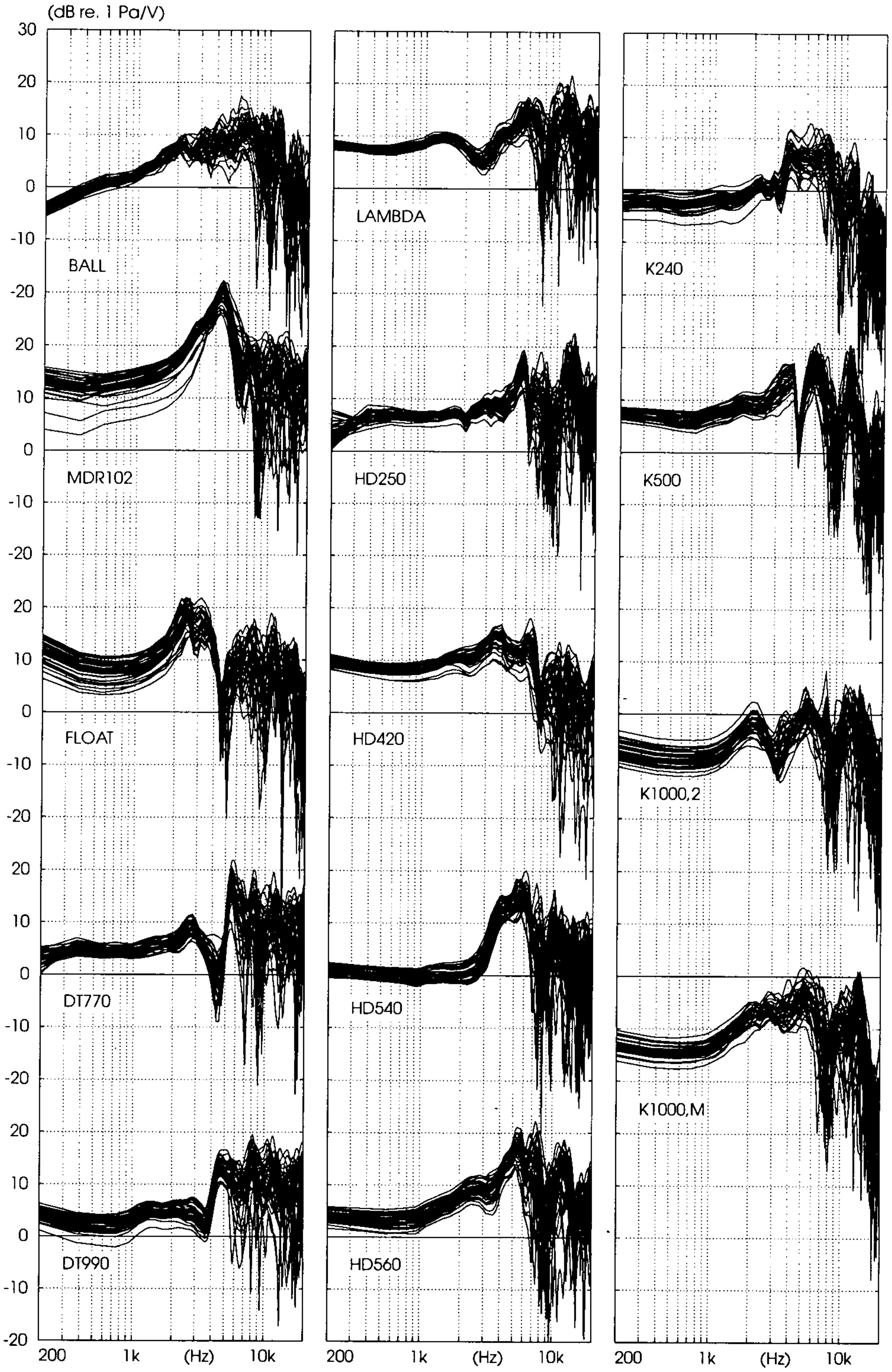

Fig. 6. PTFs for 14 headphones measured at the blocked ear canal of 40 human subjects.

of the headphones have deviations of 2–4 dB, whereas the MDR102 and the FLOAT have the largest deviations. The data do not allow conclusions for frequencies above 7 kHz.

Whether or not deviations of 2–4 dB can be accepted depends on the application. If the deviation for a particular headphone is too large, the possibility of including the PDR in the equalization exists [Eq. (3)]. In any case, the equalization needed to compensate for the PDR is much smaller than the one needed to compensate for the PTF itself.

Our observations are in contrast to a single observation by Sank [10]. For one subject he found a large difference between the blocked and the unblocked ear canal in free air, but almost no difference with an electrodynamic headphone. Using our terminology, this means that the PDR was different from unity, and the headphone does not have FEC properties. Sank did not report which headphone he used, but as his headphones in general were comparable to our headphones, similar results would be expected. Sank did use a slightly different measurement point (in the concha and not at the entrance to the ear canal), but we do not believe that this fully explains the discrepancy.

2.3 Repetition Measurements

To evaluate the validity of the results, three complete measuring series were performed on three different days (within two weeks) for one subject. It is stressed that no special effort was made to make these measurements better than others.

Examples of PTFs computed on the basis of the repeated measurements are given in Fig. 10. Fig. 10(a) shows results obtained with the miniature microphone, and a very good agreement is seen in most of the frequency range. Differences are seen, however, especially at high frequencies and mainly in narrow frequency bands due to different positions of the characteristic dips. Fig. 10(b) shows results from the probe microphone measurements, and a similar agreement is seen.

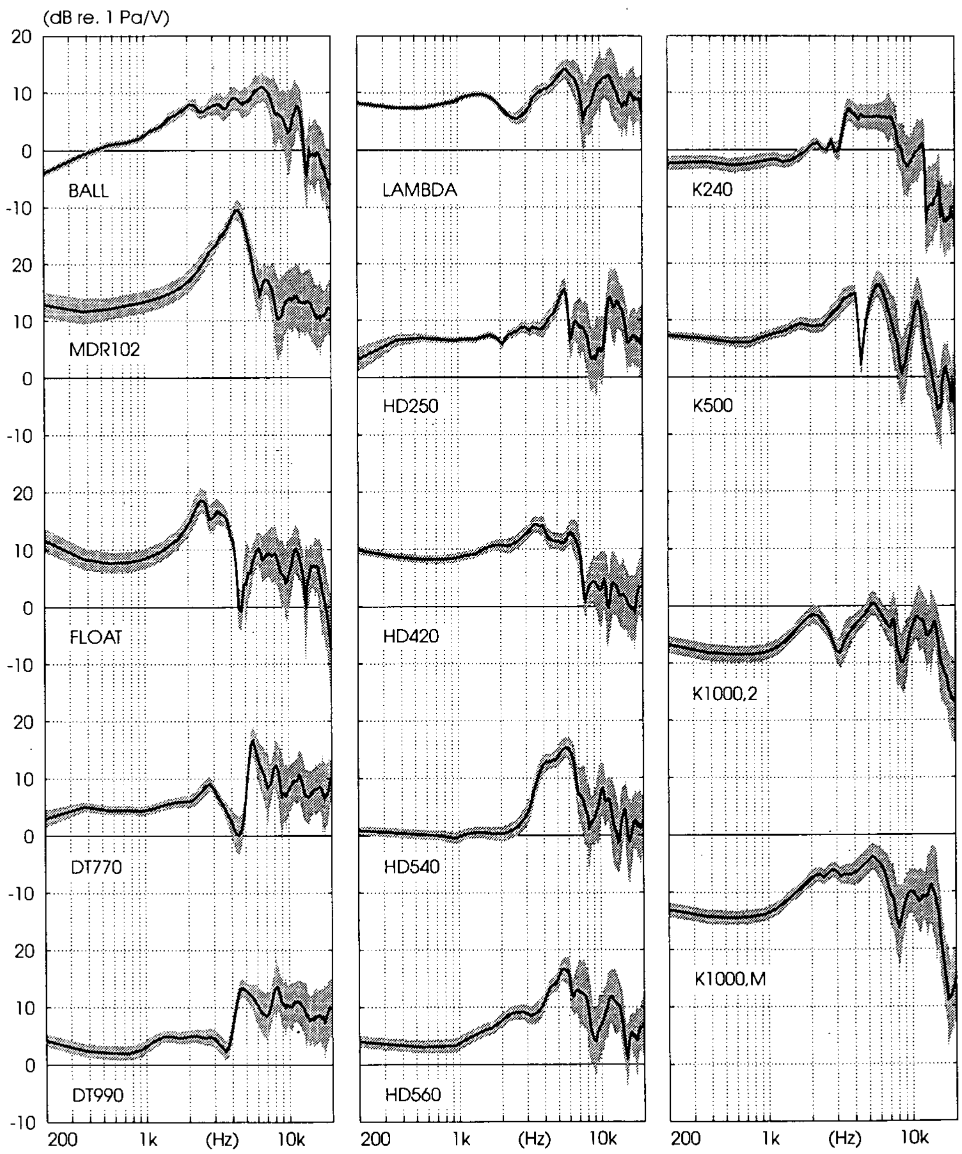

Fig. 7. Means and standard deviations of 14 headphones computed on a decibel basis from 40 PTFs measured at blocked ear canal. Shaded areas—mean ±1 standard deviation.

The validity of the results can be further evaluated by comparing the two sides of Fig. 10. It is seen that the PTFs obtained with the different microphones have the same general shape. Minor differences exist in level and also in the depth, frequency, and bandwidth of the characteristic dips. Both the level and the dip differences may be explained by the fact that the headphone capsules rested on the metal tube of the probe microphone when that was used. The capsule was thus tilted to a slightly different angle relative to the ear, an increase of the enclosed volume occurred, and an unavoidable leakage around the metal tube of the probe microphone was introduced. These sources of error support the use of miniature microphones rather than probe microphones for PTF measurements.

In a later experiment [17] it was seen that even better reproduceability could be obtained if the subjects placed the headphones themselves. This procedure can only be used with the miniature microphones since the probe microphones may easily be displaced by the subject.

Despite the fine repeatability seen in the PTFs, the small uncertainty that does exist becomes serious for the PDRs. PDRs are computed on the basis of four single measurements with the probe microphone, two for each pressure division. As we observed with the PTFs, small displacements of the probe tip and the headphone capsule may slightly change the frequency and the depth of a resonance. Similar problems exist in the free-field measurements. It is very unlikely that these errors can be avoided in the four measurements, and because of the high Qs of the resonances, random spikes should be expected in the PDRs at high frequencies. This was confirmed by PDRs derived from the repeated measurements.

Unfortunately we must conclude that the accuracy in the measurements has only been sufficient to ensure a good validity of the PDRs at frequencies below approximately 7 kHz. Data for the PDRs above this frequency must therefore be disregarded, and thus they were not reported in Section 2.2

3 DISCUSSION

The discussion deals with three subjects: 1) assessment of the measurement technique, 2) the possibility of choosing a proper way of equalizing the headphones

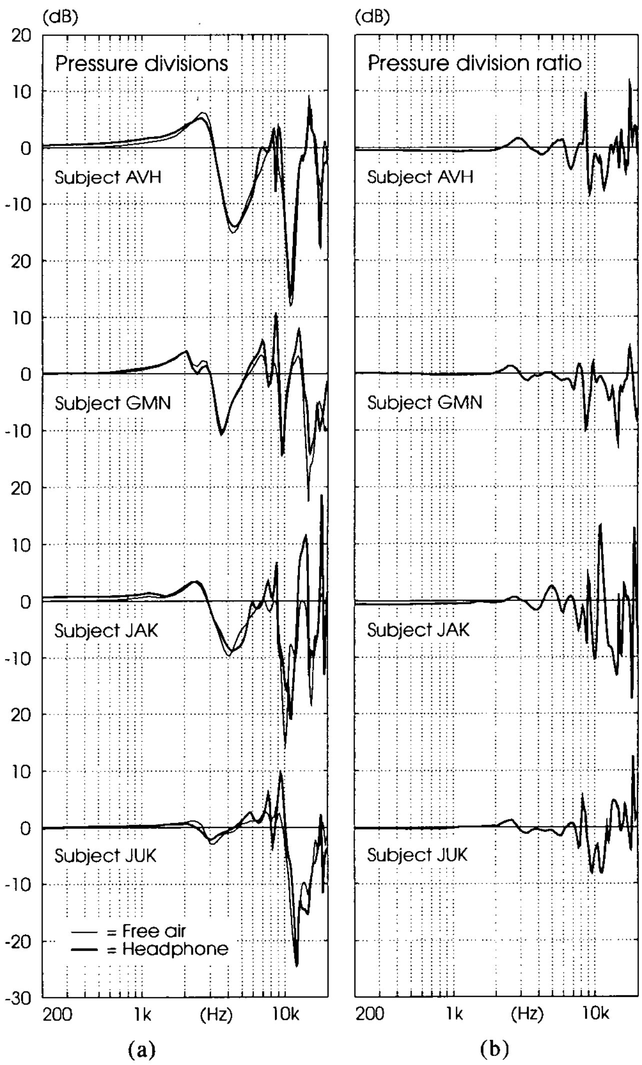

Fig. 8. (a) Pressure divisions for four human subjects in free air and with sample headphone (HD560). (b) Pressure division ratios (PDRs)—difference between the two pressure divisions.

for binaural technique, and 3) use of the headphones for the reproduction of traditional recordings.

3.1 Assessment of Measurement Technique

The measurement point for the PTFs—outside a blocked ear canal—was selected as a consequence of the choice of this point for the recording side of the binaural system. In the recording situation the point was chosen because of the small variations between subjects of the sound pressure at this point.

With the data obtained in the present study it is possible to make a comparison of the intersubject variations of the headphone transfer functions measured at the entrance to the blocked and the open ear canal. Fig. 11 shows PTFs for the two measurement points for a sample headphone. The PTFs for measurements at the blocked ear canal have a very clear common structure up to at least 7 kHz. In the range between 7 and 12 kHz it is still possible to observe a common structure, whereas at frequencies above 12 kHz the variations between subjects make this impossible.

A similar agreement between subjects cannot be found for the PTFs measured at the open ear canal. A common structure is seen only up to 2 kHz. At 2–7 kHz variations as large as 20 dB are seen between subjects, and above 7 kHz no common structure can be found. The difference between the two measuring methods is, of course, the pressure division, which adds intersubject variation.

The conclusion is that the entrance to the blocked ear canal is a suitable reference point for measurements of PTFs when a low interindividual variation is desired. It should, however, be noted that the simple use of PTFs measured this way is limited to FEC headphones. Although most of the headphones in this study were shown to have FEC properties within a reasonable tolerance, the same may not be true with other headphones, especially not for those mounted within or more close to the ear canal.

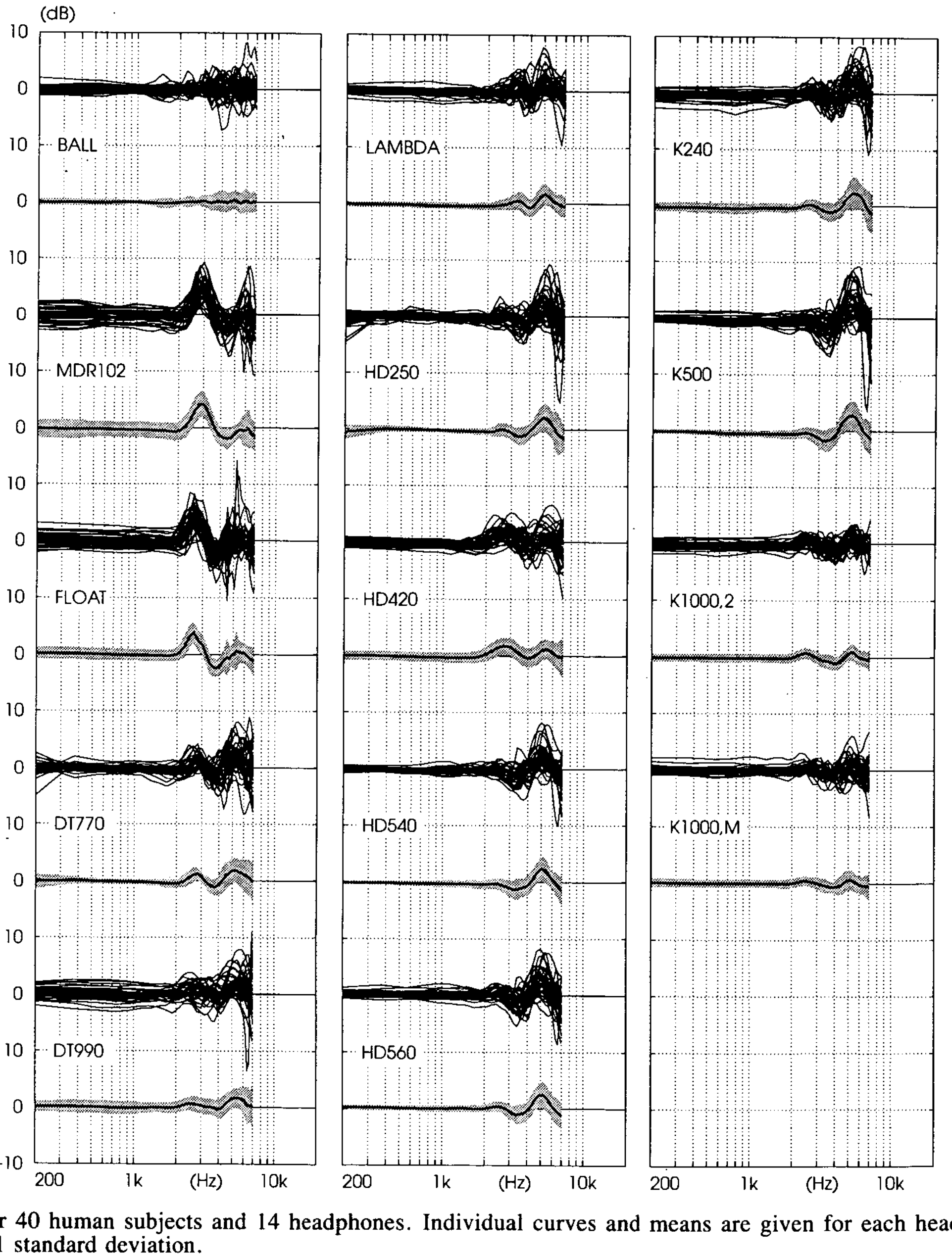

Fig. 9. PDRs for 40 human subjects and 14 headphones. Individual curves and means are given for each headphone. Shaded areas—mean ±1 standard deviation.

For the design of binaural systems it is important to have precise knowledge of the amplitude response of the headphone so that the recorded signals can be reproduced accurately without adding or removing spatial cues and timbre. The present investigation made use of the MLS technique to measure transfer functions. With the chosen record length, a frequency resolution of 187.5 Hz was obtained. This proved sufficient to disclose the fine structures of the PTFs, such as narrow peaks and dips throughout the frequency range of interest. It is evident that the low-frequency response is badly represented with the frequency resolution used in the present investigation. An improvement at this point is a matter of increasing the record length of the MLS calculations.

In many investigations results are presented as one-third-octave amplitude values. To illustrate the lack of information in a one-third-octave representation, an example is shown in Fig. 12. The PTF for a sample headphone measured on one subject is presented as one-third-octave values and with a frequency resolution of 187.5 Hz. It is obvious that information about the peak at 6 kHz and the narrow dips at 4.5 and 8 kHz are completely lost if the PTF is presented as one-third-octave values.

3.2 Equalization for Binaural Technique

As stated in Section 0.2, the headphone should have a flat frequency response PTF, either directly or in combination with an equalizer. A precondition for this is

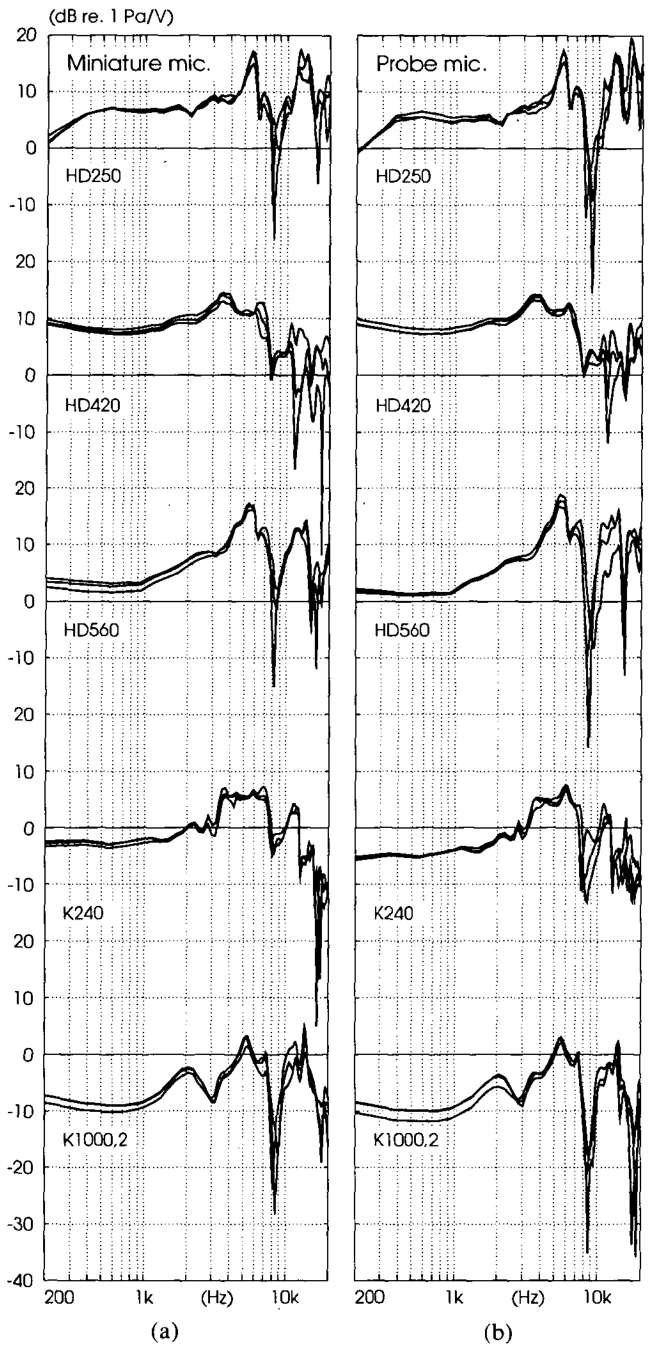

Fig. 10. PTFs for five headphones and the same subject, computed on basis of repeated measurements. (a) Measurements with miniature microphone. (b) Measurements with probe microphone.

that the recording microphone have a flat frequency response, and that the headphone have FEC properties. This condition is assumed for the calculations in this section.

None of the headphones has a flat frequency response, as seen in Section 2.1. Thus they must be corrected with an electronic equalizer. Since the curves are very individual, each listener should in principle have his or her own equalizer setting. Although there are a lot of practical complications, it can be done, and in a recent experiment we have used this technique successfully [17].

In most cases, though, the same equalizer has to be used for all listeners. A logical choice will be to let the equalizer transfer function be the reciprocal of the mean PTF. This makes it relevant to discuss how the mean should be calculated. In Section 2.1 mean values were shown based on averaging across subjects of *sound levels*. This gives the same "weight" to dips and peaks. However, the hearing is more sensitive to peaks than to dips, and it might be argued that more weight should be given to the peaks, and that the averaging should be made on a *sound pressure* basis. Even more weight could be given to the peaks by averaging on a *sound power* basis. Fig. 13 shows for a sample headphone the error that will occur for each individual if a perfect average equalization is made, based on three averaging methods: 1) on a sound level (decibel) basis, 2) on a sound pressure basis, and 3) on a sound power basis.

Quite large errors are seen due to the large intersubject variations in PTFs. Fortunately in all three cases, errors in the form of narrow dips are more common than in the form of peaks. With the sound level averaging many peaks are around 7 dB, and a few around 10 dB. With the power averaging most of the peaks have been reduced to around 4 dB. Of course, the dips have become deeper at the same time, and the overall level has been reduced at high frequencies. Nothing has happened at frequencies below 6–7 kHz. Results from the sound pressure averaging lie between those from the two other averagings. Since peaks are more audible than dips, the power averaging might be preferable. Listening tests are needed to select the best method. However, the differences between methods are not very large.

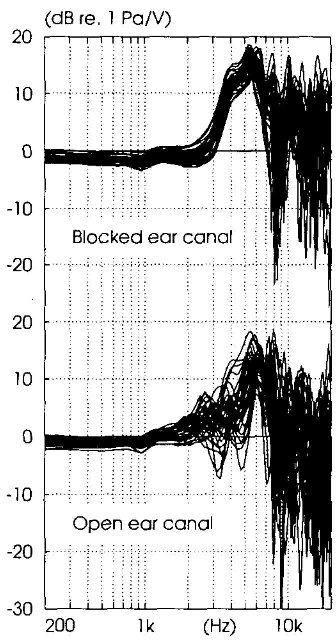

Fig. 11. PTFs measured for 40 subjects at blocked and open ear canal using probe microphone (headphone HD540).

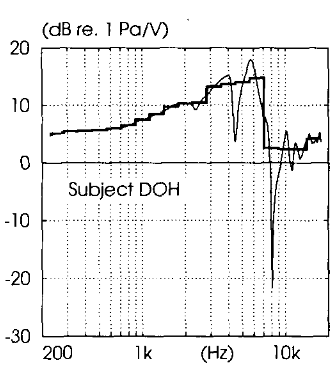

Fig. 12. PTF for K500 presented with frequency resolution of 187.5 Hz and in one-third-octave bands (one subject).

3.3 Use of Headphones for Traditional Recordings

The most common use of headphones is for the reproduction of traditional recordings. It would be interesting to see how well suited the headphones are for this. In another investigation we have developed design goals

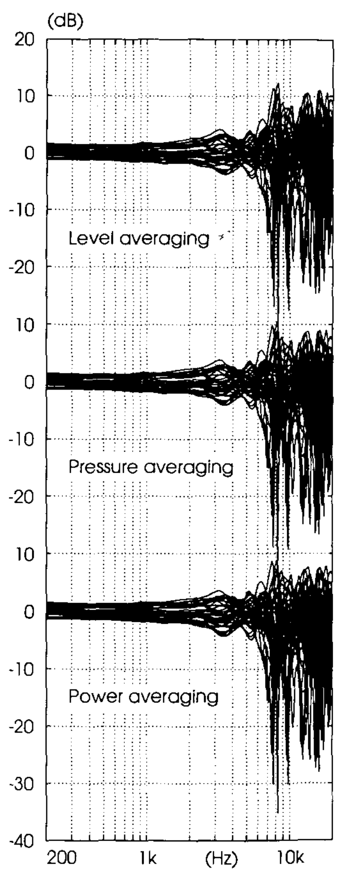

Fig. 13. Calculated individual errors when perfect average equalization is made for sample headphone (HD540). Averages calculated by three different methods.

for diffuse- and free-field-calibrated heaphones [12]. The design goals were given for PTF measurements at the entrance to the open or the blocked ear canal. As the headphones in this study have FEC properties, provided minor deviations from 0 dB are accepted in the PDR, comparisons are made with the blocked ear canal design goal.

Fig. 14 shows the mean PTFs from Fig. 7 on a background of the design goals, either free field or diffuse field, depending on the specification given by the manufacturer. For the headphones where the manufacturers have not specified a particular design goal, the mean PTF is shown on the background of the best fitting design goal. The PTF and the design goal are adjusted to fit in level at 750 Hz.

In general the PTFs deviate from the design goals, with the worst deviations for frequencies above 2 kHz. The K240 provides the best fit, although the slopes at 2–3 kHz and 7–9 kHz are rather steep. The BALL fits surprisingly well, although no effort has been made to obtain a specified response. The FLOAT is hardly comparable to any of the design goals.

The best fits have been chosen intuitively, and the reader is free to question the choice and compare as he or she pleases. It should also be kept in mind that some manufacturers may have followed another design philosophy.

In connection with these comparisons, the question of the different averaging processes should also be raised. However, it would be reasonable to believe that the same type of averaging should be used in the calculation of the design goal and of the mean PTFs. As sound level averaging was used for the design goal, this was also used for the PTFs. A recalculation of the design goals with the two other averaging procedures, and subsequent comparisons with similarly averaged PTDs, show that the deviation from the design goal is almost unaffected by the averaging process.

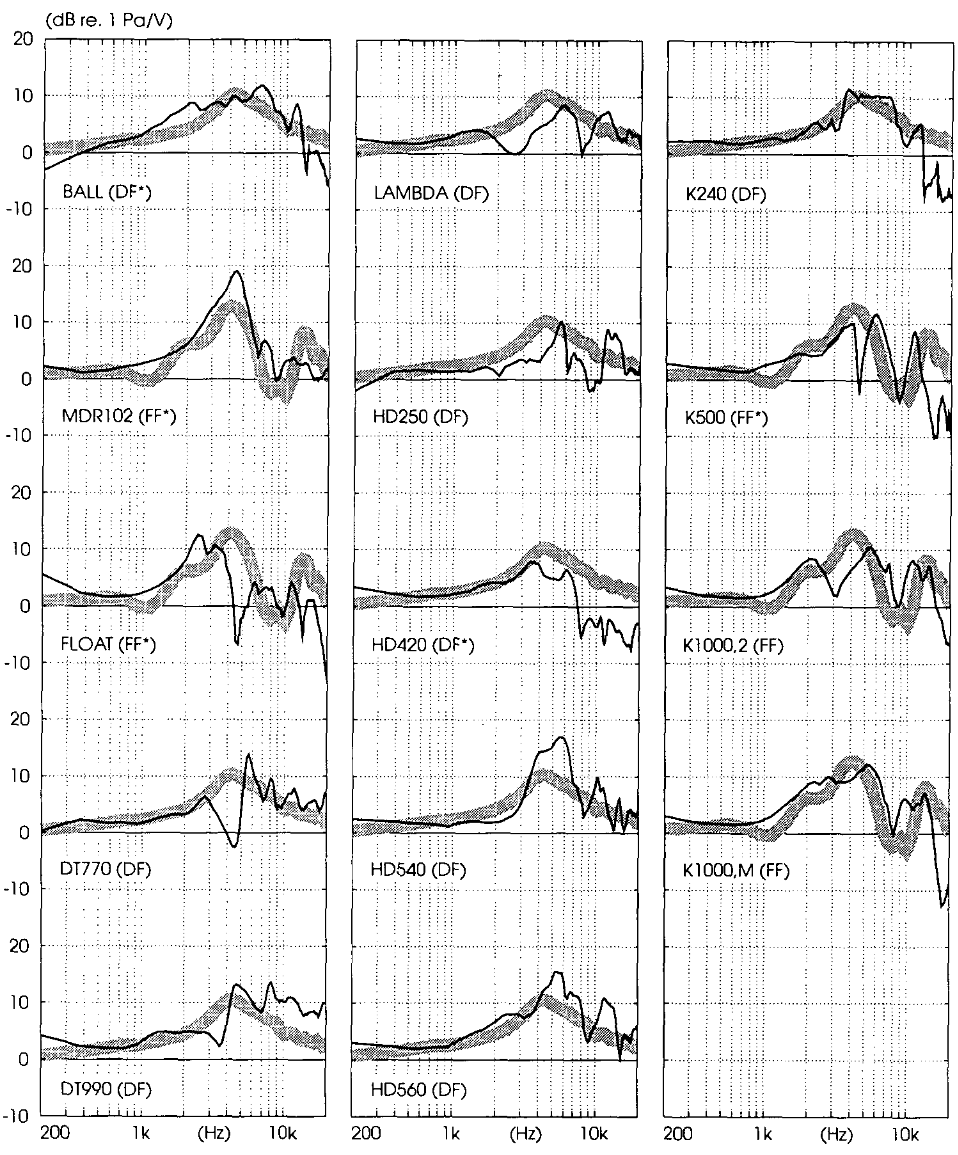

Fig. 14. Measured mean PTFs at blocked ear canal compared to design goals (from [12]): FF—free-field design goal; DF—diffuse field design goal, selected according to manufacturer's specification. If not specified, best fitting goal is selected (indicated by FF* or DF*).

4 CONCLUSION

Measurements of headphone characteristics on human ears have been successful. For measurements at the blocked ear canal, the miniature microphones are preferred to the probe microphones since they can be mounted without disturbing the headphone. The measurements of PDRs are reliable only up to approximately 7 kHz. The MLS measurement technique has proven useful, and the chosen frequency resolution of 187.5 Hz has revealed resonances that would have been lost in a one-third-octave representation. Information on the low-frequency responses of the headphones can be obtained with a longer MLS record length.

For all headphones the frequency responses are characterized by smooth fluctuations at low frequencies and rather individual high-Q resonances at high frequencies. None of the headphones seem adequate in a binaural reproduction system without equalization. Because of the large differences between subjects, individual equalization seems preferable. Equalization with an average curve may be acceptable though, since the errors that occur for each individual are characterized by dips rather than peaks.

The use of a blocked ear canal in measurements of headphone transfer functions reduces the individual variations considerably. The sound pressure outside the blocked ear canal is sufficient to describe the transfer characteristics of FEC headphones (headphones that have a coupling to the ear similar to the coupling to free air).

Only the "headphone" consisting of small loudspeakers mounted away from the ears proved to have FEC properties if a strict criterion is used. If allowance is made for mean deviations up to 2 dB, some real headphones can be considered as FEC headphones, and if mean deviations up to 4 dB are accepted, all the measured headphones have FEC properties.

A comparison with design goals for free-field- and diffuse-field-calibrated headphones showed that only one headphone follows the predefined design goal from [12], whereas the remaining headphones do not.

5 ACKNOWLEDGMENT

Economic support from Brüel & Kjær A/S, Perceptive Acoustics A/S, the National Agency of Industry and Trade, Denmark, Aalborg University, and the Danish Technical Research Council is greatly acknowledged. The authors would like to thank their former colleagues Jørn Vagn Hundebøll and Kim Alan Larsen for their participation when the experiments were planned and carried out. Jørn Vagn Hundebøll also was a co-author when the investigation was preliminarily reported [1]. We would also like to thank Anne Kirstine Andersen, our coordinator, for her handling of all appointments with the test subjects. Claus Vestergaard Skipper, the technical employee at our laboratory, deserves appreciation for his invaluable help with the practical work. At last we would like to thank all our patient subjects for "listening" to headphone after headphone with earplugs and microphones in their ears.

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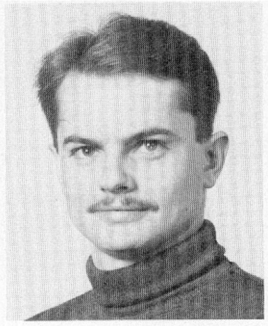

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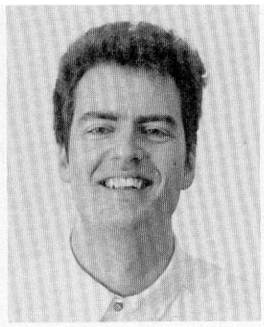

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Henrik Møller was born in Århus in 1951. He studied electrical engineering (Danish Engineering Academy) and received a B.Sc. degree in 1974. He worked as a development engineer for Brüel & Kjær from 1974 to 1976. Since then he has been at Aalborg University. He became associate professor in 1980, received a Ph.D. degree in 1984, and was appointed professor in 1988. During the period 1991–94 he was partly on leave from the university to work as a director of Perceptive Acoustics A/S, a research subsidiary company of Brüel & Kjær.

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When new high-quality acoustical laboratories were built at Aalborg University in 1987, Dr. Møller was responsible for the design as well as control of the work. As head of the Acoustics Laboratory, he is now the manager of research and education in a wide range of areas such as human sound perception, audiology, psychometry, electroacoustics, recording and playback techniques, auralization in acoustic room modeling and virtual reality, acoustical measurement techniques, electronics, and signal processing.

Dr. Møller has organized conferences on Low Frequency Noise and Hearing (Aalborg 1980) and general acoustics (Nordic Acoustical Meeting, Aalborg 1986). He is convener of ISO Technical Committee 43: "Acoustics," Working Group 1: "Thresholds of Hearing," a member of the Nordic Research Group on Noise Effects, and of the editorial board of *Journal of Low Frequency Noise & Vibration*. He holds membership in the Danish Engineering Society, Audio Engineering Society, IEEE, Danish Acoustical Society, Danish Technical-Audiological Society, Danish Biomedical Society, and Danish Standardisation Organisation (Board of Acoustics and Working Group of Audiometry and Hearing).

Dr. Møller spends hours off work (too few) by playing big band music on his baritone saxophone or by keeping his classic British cars in good shape. Now and then, he also drives them.

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