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Design Criteria for Headphones*

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An alternative procedure is proposed for measuring headphone performance on human ears. Psychoacoustic procedures are replaced with the measurement of sound pressure at the input to the human ear canal. Furthermore, the exposure of each subject to a reference sound field is replaced by prior knowledge of a desired frequency response. Design goals are given for free-field- and diffuse-field-calibrated headphones, and for measurements at the open and blocked ear canal. The new method avoids the uncertainty from a psychometric procedure, and it allows diffuse-field calibration even at pure tones and narrow frequency bands. Also the extra variance from a physical diffuse sound field is avoided.

0 INTRODUCTION

Sound reproduction by means of headphones has a wide range of applications. Among these are the playback of binaural signals. It has previously been shown [1] that headphones for binaural technology should have a flat frequency response when measured at the position in the ear canal where the recording is made. Other applications of headphones are in audiology. For these purposes the requirement is often that the headphone have a flat, or at least well documented, frequency response measured at the eardrum or in a coupler.

The most frequent use of headphones, however, is for the reproduction of standard commercial program material. Such material is originally recorded and mixed for playback by means of a stereo loudspeaker setup. During headphone reproduction the headphone replaces the whole setup, including the loudspeakers and the listening room. If the headphone should provide the listener with the same sound as the loudspeaker setup, the demands to its transfer function would be very complex. Therefore various simplifications are usually made, resulting in demands only to the amplitude response.

Even simple design procedures involve quite extensive measurements for the evaluation of a headphone. Physical or psychoacoustic measurements must be carried out on a number of subjects, not only when they are exposed to sound from the headphone but also during exposure to a certain reference sound field.

In our previous work we obtained insight into the transmission of sound to the ear canal from headphones [2], and from an external sound field [3]. It is the aim of the present investigation to utilize this knowledge to develop simpler design procedures for headphones and to compare the methods with traditional procedures. Only demands for headphones that serve to replace loudspeakers are considered. It is not the intention of the present paper to discuss the suitability of various reference sound fields.

0.1 Headphone Reproduction versus Loudspeaker Reproduction

When the headphone replaces the loudspeaker in the reproduction situation, it replaces not only the electroacoustical conversion carried out by the loudspeaker, but also the complete sound transmission through the listening room to the listener's ears. The sound transmission through the listening room adds two things, which are not offered in the traditional headphone design, namely, crosstalk and reflected sound waves from the surroundings.

Crosstalk denotes the sound from the left loudspeaker that reaches the right ear, and vice versa. The reflected sound waves are filtered delayed versions of the sound signal from the loudspeaker. It is obvious that a headphone produces neither crosstalk nor the proper reflections. Systems have been described which add crosstalk and simulated reflections to the electrical signal [4]–[7], but in the following it is assumed that the headphone is given the same electrical signal as the loudspeaker.

It is evident that the headphone will not be able to show the same temporal reproduction as a loudspeaker setup in a room. The demands for the headphone will therefore be reduced to a demand on its frequency

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weighting, namely, that the headphone should give the same "timbre" of the reproduced sound as a loudspeaker setup would give. An interpretation of this demand is that the amplitude of the frequency response should be the same for sound produced by the headphone as for sound produced by the loudspeaker. This interpretation constitutes the general design criterion for the headphone. The reproduction with loudspeakers is called the reference situation, and a more precise description of this is given in Section 0.3.

0.2 Mathematical Description of Design Criterion

The general design criterion can be expressed as

$$\left|\frac{P_7}{E_{\text{headphone}}}\right| = \left|\frac{P_4}{E_{\text{loudspeaker}}}\right| \tag{1}$$

where P_7 is the sound pressure at the listener's eardrum in the playback situation with a headphone, and P_4 is the sound pressure at the listener's eardrum in the reproduction situation with loudspeakers. $E_{\text{headphone}}$ denotes the voltage applied to the headphone terminals, and $E_{\text{loudspeaker}}$ the voltage applied to the loudspeaker terminals. The signals are given in the frequency domain. The reader is asked to make allowance for the rather odd numbering, which will appear more logical when the remaining numbers between 1 and 7 are introduced in Section 1.

The right-hand side of Eq. (1) can be expressed as a sum of sound pressures originating from different sound waves, each with its transmission path i,

$$\left|\frac{P_4}{E_{\text{loudspeaker}}}\right| = \left|\sum_{\text{path } i}^{N} \frac{P_4}{E_{\text{loudspeaker}}}(i)\right| . \tag{2}$$

The contribution from each signal path is naturally divided into two terms, where one term relates to the sound transmission through the listening room to the listener's position, and the other to the transformation of the sound field carried out by the listener's ear, head, and body. Each part is specific for the transmission path i. This is described by

$$\left|\frac{P_4}{E_{\text{loudspeaker}}}\right| = \left|\sum_{\text{path } i}^{N} \left[\frac{P_4}{P_1}(i) \cdot \frac{P_1}{E_{\text{loudspeaker}}}(i)\right]\right| \tag{3}$$

where P_1 is the sound pressure found at the listener's position in the situation of the listener's absence. When it is assumed that the arriving signals have random phase (which may not always be true for low frequencies), the summation can be made in a power basis, and Eq. (3) can be written as

$$\left|\frac{P_4}{E_{\text{loudspeaker}}}\right| = \sqrt{\sum_{\text{path } i}^{N} \left[\left|\frac{P_4}{P_1}(i)\right|^2 \cdot \left|\frac{P_1}{E_{\text{loudspeaker}}}(i)\right|^2\right]} . \tag{4}$$

A weighting function $w(i)$ is now introduced,

$$w(i) = \frac{\left|\frac{P_1}{E_{\text{loudspeaker}}}(i)\right|^2}{\sum_{\text{path } j}^{N} \left|\frac{P_1}{E_{\text{loudspeaker}}}(j)\right|^2} . \tag{5}$$

The denominator in Eq. (5) is the square of the resulting sound pressure, and the nominator is the square of the sound pressure from each transmission path. Thus $w(i)$ represents each transmission path's share of the resulting sound energy at the listening position. It is obvious that

$$\sum_{\text{path } i}^{N} w(i) = 1 . \tag{6}$$

If Eq. (5) is inserted into Eq. (4), the result is

$$\left|\frac{P_4}{E_{\text{loudspeaker}}}\right| = \sqrt{\sum_{\text{path } i}^{N} \left[\left|\frac{P_4}{P_1}(i)\right|^2 \cdot w(i) \cdot \sum_{\text{path } j}^{N} \left|\frac{P_1}{E_{\text{loudspeaker}}}(j)\right|^2\right]} . \tag{7}$$

The last term in Eq. (7) (the sum over j) is independent of i, and the equation can therefore be rearranged,

$$\left|\frac{P_4}{E_{\text{loudspeaker}}}\right| = \sqrt{\sum_{\text{path } j}^{N} \left|\frac{P_1}{E_{\text{loudspeaker}}}(j)\right|^2} \cdot \sqrt{\sum_{\text{path } i}^{N} \left[\left|\frac{P_4}{P_1}(i)\right|^2 \cdot w(i)\right]} . \tag{8}$$

As a design goal, let the headphone simulate an ideal loudspeaker. This will be interpreted as a loudspeaker with a flat frequency response, measured at the listening position. In this case the first term of the right-hand side of Eq. (8) is a constant. By introducing

$$\text{constant} = \sqrt{\sum_{\text{path } j}^{N} \left|\frac{P_1}{E_{\text{loudspeaker}}}(j)\right|^2} \tag{9}$$

the original design criterion [Eq. (1)] can be written as

$$\left|\frac{P_7}{E_{\text{headphone}}}\right| = \text{constant} \cdot \sqrt{\sum_{\text{path } i}^{N} \left[\left|\frac{P_4}{P_1}(i)\right|^2 \cdot w(i)\right]} . \tag{10}$$

In some cases the number of transmission paths may amount to infinity. A more general description is therefore obtained by substituting summations by integrations. If ϕ is the azimuth angle and θ the elevation angle, then

$$\left|\frac{P_7}{E_{\text{headphone}}}\right| = \text{constant} \cdot \sqrt{\frac{1}{4\pi}\iint \left|\frac{P_4}{P_1}(\phi, \theta)\right|^2 v(\phi, \theta)\, d\phi\, d\theta} \tag{11}$$

where

$$\frac{1}{4\pi}\iint v(\phi, \theta)\, d\phi\, d\theta = 1\,. \tag{12}$$

0.3 Reference Situation

Existing design criteria have their origin in various assumptions as to which ones of the traveling paths are most important for the listening experience with loudspeaker reproduction. The term *reference* situation is used to describe the situation with loudspeaker reproduction when certain assumptions are made about the properties of the listening room.

The limiting case of a completely damped room is similar to that of a single sound source placed in front of the listener in an anechoic chamber. This is the idea behind free-field calibration of headphones [8]–[10]. An azimuth angle different from zero could also be used in free-field calibration, as suggested in Blauert [11, p. 362]. The argument is that the direct sound reaching the listener from a loudspeaker in the standard stereo setup has an angle of incidence typically between 20° and 50°.

In contradiction to this it may be argued that even in a moderately damped room, the direct sound contributes only a fraction of the sound reaching the listener, and the sound at the listening position consists mainly of reflected sound waves. This assumption is true if the distance from the loudspeaker to the listening position is somewhat larger than the hall radius. The reference situation is then given as a diffuse sound field, and a headphone fulfilling this design criterion is termed diffuse-field calibrated [12]–[15].

Another argument for the diffuse-field calibration is given by Theile [12], who claims that the free-field calibration involves a head-related transfer function for a specific direction, and the hearing might interpret this as a directional cue. As this cue is inconsistent with other cues present in a standard stereo recording, the hearing is confused, listening becomes unnatural, and internal localization occurs. Diffuse-field calibration will not introduce cues from any specific direction. Theile also performed listening tests in which diffuse-field-calibrated headphones were preferred to those with free-field calibration. As already mentioned, it is not the intention of the present paper to discuss the suitability of various reference situations.

0.4 Traditional Test Procedures

Most procedures for headphone testing depend on psychoacoustic listening tests, such as threshold or loudness comparisons of sound presented to subjects in the reference situation and by the headphone under test [8]–[10]. Such procedures require the physical setup of the reference situation (such as a diffuse or a free field) and time-consuming listening tests. The result will be inaccurate not only due to inaccuracies and statistical variation from the psychoacoustic evaluation, but also to inaccuracies in the sound field provided by the setup for the reference situation. Nevertheless it can be argued that it is the only way to guarantee that the listener obtains the same perceived loudness in the two situations and thus, when the procedure is carried out at many frequencies, the correct timbre.

Listening tests can be avoided if it is assumed that the same perception is obtained if the same physical sound pressures are provided to the ears. Test procedures that depend on this assumption consist of measurements of the sound pressures in the ears of a number of subjects or a manikin in the reference situation and in the listening situation with headphones [12]–[16]. Also these procedures require the physical setup of the reference situation to provide the correct transmission from the reference field to the ear canal. In the headphone situation the only participation of the test subjects is to provide the correct acoustic loading of the headphone.

The physical creation of the reference field is sometimes avoided through the use of a reference headphone, which is determined beforehand to have the desired frequency response [9], [10], [13], [15]. The possible sources of errors are evidently not reduced.

For diffuse-field calibration it is a drawback in all methods that the reference situation cannot be made for narrow bands or pure tones. In practice, a diffuse sound field can only be made in one-third-octave bands or wider, and this frequency resolution may not be sufficient to disclose the peaks and dips in the headphone frequency response.

0.5 Purpose of Investigation

A more convenient test procedure than those presented in Section 0.4 will be to know in advance of the test situation which sound pressures the headphones are required to provide, and then only carry out measurements of the electroacoustical transfer function of the headphone. The idea of such a procedure has previously been presented by Sank [17] and Toole [18]. The method requires the existence of a general design goal, which can be taken from the literature (for example, this paper). In the test situation the method still needs the participation of test subjects to provide loading of the headphone, but the physical setup of the reference situation can be avoided.

It is the purpose of the present investigation to compute design goals for headphone transfer characteristics. For all choices of reference situations, the design goal is described as a weighted sum of head-related transfer functions (as shown in Section 0.2).

1 METHOD

The sound pressure used in the general design criterion [Eq. (1)] is sound pressure at the eardrum. In the following it is shown that the measurement of sound pressure at the eardrum can be replaced by the measurement of sound pressure at the entrance to the ear canal. A model, given by Møller [1] and verified by Hammershøi and Møller [19], is used to describe the sound transmission in the reference situation and the situation with headphone reproduction.

1.1 Free-Field Sound Transmission Model

Fig. 1(a) is a sketch of the physics of the human external ear exposed to a sound field in a real-life listening situation, and Fig. 1(b) a corresponding analog model. The sound pressure at the input to the ear canal is denoted by P_3. The ear canal acts as an acoustical two-port terminated by the eardrum impedance Z_{eardrum}, and the resulting pressure at the eardrum is denoted by P_4 (already used in Section 0.2). Everything outside the ear canal is modeled by a Thevenin equivalent with the generator sound pressure P_2 and the generator impedance $Z_{\text{radiation}}$. P_2 does not exist physically in the listening situation, but for measurement purposes it can be found at the entrance to the ear canal when the ear canal is blocked, for instance with an earplug.

The sound transmission in Fig. 1 is independent of the direction of sound incidence, and it consists of the pressure division at the entrance to the ear canal, given by

$$\frac{P_3}{P_2} = \frac{Z_{\text{ear canal}}}{Z_{\text{ear canal}} + Z_{\text{radiation}}} \tag{13}$$

and the transmission along the ear canal P_4/P_3.

The transmission outside the ear canal is dependent on the direction of sound incidence. It consists of the sound transmission from the free-field sound pressure P_1 with the listener absent to the Thevenin sound pressure P_2 at the entrance to the ear canal. The directional dependent part is described by

$$\frac{P_2}{P_1}(\phi, \theta) = \frac{\text{sound pressure at entrance to blocked ear canal}}{\text{sound pressure at center position of head}} . \tag{14}$$

The complete transmission from the free field to eardrum is thus

$$\frac{P_4}{P_1}(\phi, \theta) = \frac{P_4}{P_3} \cdot \frac{P_3}{P_2} \cdot \frac{P_2}{P_1}(\phi, \theta) . \tag{15}$$

1.2 Headphone Sound Transmission Model

A headphone transmission model very similar to the free-field model is used to describe the transmission from voltage at the headphone terminals to sound pressure in the ear canal. The model is shown in Fig. 2. The sound pressure at the entrance to the ear canal is denoted by P_6, the sound pressure at the eardrum by P_7, and the voltage at the headphone terminals by $E_{\text{headphone}}$ (as already known from Section 0.2). The headphone is modeled by a Thevenin equivalent with the generator P_5 and the source impedance $Z_{\text{headphone}}$.

The pressure division at the input to the ear canal is here given by

$$\frac{P_6}{P_5} = \frac{Z_{\text{ear canal}}}{Z_{\text{ear canal}} + Z_{\text{headphone}}} . \tag{16}$$

The parallels to the free-field model are easily seen, and the total transfer function is given by the equation

$$\frac{P_7}{E_{\text{headphone}}} = \frac{P_7}{P_6} \cdot \frac{P_6}{P_5} \cdot \frac{P_5}{E_{\text{headphone}}} . \tag{17}$$

1.3 Choice of Measuring Point

Some similarities are seen in the sound transmission in the two situations. It is easily verified that the sound transmission from the entrance of the ear canal to the eardrum is equal in the two situations, since the transmission only depends on the ear canal and its termination. Therefore,

$$\frac{P_7}{P_6} = \frac{P_4}{P_3} . \tag{18}$$

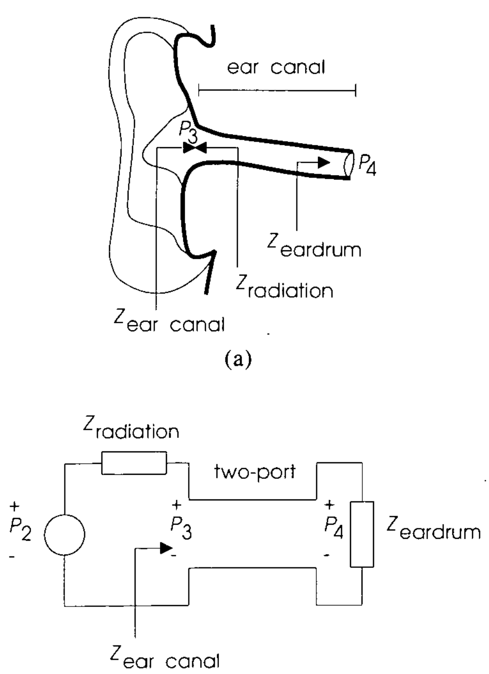


Fig. 1. Free-field sound transmission model. (a) Anatomical sketch. (b) Analog model.

Both sides of Eq. (18) are independent of the direction of sound incidence, and if this is used in Eq. (11), then

$$\left|\frac{P_6}{E_{\text{headphone}}}\right| = \text{constant} \cdot \sqrt{\frac{1}{4\pi}\iint \left|\frac{P_3}{P_1}(\phi, \theta)\right|^2 v(\phi, \theta)\, d\phi\, d\theta}\,. \tag{19}$$

This means that the measurements at the eardrum can be replaced by measurements at the entrance to the open ear canal. Also the pressure division is independent of direction [Eqs. (13) and (16)], and after insertion of these, Eq. (19) can also be written as

$$\left|\frac{P_5}{E_{\text{headphone}}}\right| = \left|\frac{Z_{\text{ear canal}} + Z_{\text{headphone}}}{Z_{\text{ear canal}} + Z_{\text{radiation}}}\right| \cdot \text{constant} \cdot \sqrt{\frac{1}{4\pi}\iint \left|\frac{P_2}{P_1}(\phi, \theta)\right|^2 v(\phi, \theta)\, d\phi\, d\theta}\,. \tag{20}$$

The first term on the right-hand side of Eq. (20) represents the difference in pressure division at the entrance to the ear canal in the reference and the headphone situations. It reduces to unity if $Z_{\text{headphone}}$ and $Z_{\text{radiation}}$ are equal, or if both are small compared to $Z_{\text{ear canal}}$. A headphone fulfilling this is called an FEC headphone [2] (a headphone with *f*ree-air *e*quivalent *c*oupling to the ear). This term is identical to the term "open" used in [1]. The reason for changing the term is that "open" is used commercially to describe a headphone that does not exclude sound from the outside. Examples of headphones with FEC properties are also shown in [2].

It is seen that the general design criterion [Eq. (1)] can be met using any of the three possible choices of measuring points as long as the same point is used in the reference and the headphone situation.

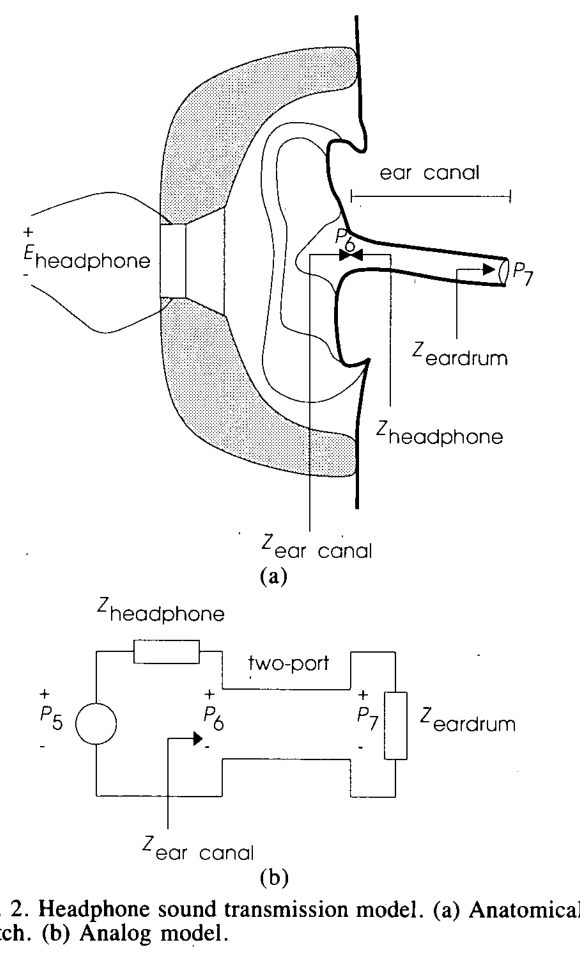


Fig. 2. Headphone sound transmission model. (a) Anatomical sketch. (b) Analog model.

A more convenient notation is to be introduced at this point. The left-hand side of Eqs. (11), (19), and (20) is the electroacoustical transfer function of the headphone from terminal voltage to sound pressure at a specific point. This will be called the head*p*hone *t*ransfer *f*unction (PTF). The measuring point can be specified by a subscript (5, 6, or 7).

The ratio between any of the sound pressures P_2, P_3, or P_4 and P_1 describes the sound transmission from the free field to the point in the ear canal concerned. These ratios are recognized as head-related transfer functions (HRTFs). A subscript may specify the measuring point (2, 3, or 4).

The square root on the right-hand side of Eqs. (11), (19), and (20) describes the magnitude of the "combined" HRTF in the reference sound field and is called RF-HRTF (reference field head-related transfer function). Here also a subscript may specify the measuring point (2, 3, or 4). A specific reference field may be indicated by substituting RF with FF (free field) or DF (diffuse field).

The design criterion can now be written in the following general form:

$$\text{PTF} = \text{constant} \cdot \text{RF-HRTF} \tag{21}$$

where the design goal, that is, the RF-HRTF, is given by

$$\text{RF-HRTF} = \sqrt{\frac{1}{4\pi}\iint |\text{HRTF}(\phi, \theta)|^2\, v(\phi, \theta)\, d\phi\, d\theta}\,. \tag{22}$$

The measuring point should be the same for the reference situation and the headphone situation, and measurements at the blocked ear canal should only be used for FEC headphones. Selection of a certain reference field is just a matter of inserting the corresponding weighting function $v(\phi, \theta)$.

In many cases measurements and calculations are carried out using logarithmic scales, and square brackets will be used to indicate values in decibels (relative to 1 Pa/V for PTF and for the constant). In logarithmic form Eq. (21) becomes

$$[\text{PTF}] = [\text{RF-HRTF}] + [\text{constant}]\,. \tag{23}$$

1.4 Design Procedure

The design criterion of Eqs. (21) or (23) and Eq. (22) should ideally be fulfilled for each individual listener. However, it is hardly possible to design a headphone that fits each individual listener, and it is only expected that the equations can be fulfilled for mean values.

It is the idea of the present design procedure that a mean value of the RF-HRTFs is used as the design goal. During tests of a headphone only the measurements of the PTFs on a number of subjects are needed. The deviation of the measurements from the design goal can be used as data for an electronic equalization or as a starting point for a redesign. And of course, it can simply be taken as a measure of the quality of the headphone.

If the subscript "goal" is used to denote the mean value for the group used to determine the design goal, and the subscript "measure" denotes the mean value obtained during the measurement, then the design procedure will correspond to the following form of Eq. (23):

$$[\mathrm{PTF}]_{\mathrm{measure}} = [\mathrm{RF\text{-}HRTF}]_{\mathrm{goal}} + [\mathrm{constant}]\,. \qquad (24)$$

The significance of statistical variations, group size, and so on, is discussed in Section 3.6.

1.5 Computation of Design Goal

The design goal is computed from the data obtained in a previous study with a completely different objective [3]. HRTFs were collected for 40 human subjects with the purpose of evaluating the binaural recording and reproduction technique.

The measurements were carried out on subjects standing in an anechoic chamber. Eight loudspeakers were placed in an arc with a radius of 2 m (6.6 ft), and the subjects were rotated to yield measurements from 97 directions covering the whole sphere. 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_1, P_2, or P_3. The impulse responses were measured with the maximum-length-sequence (MLS) technique, and HRTFs were obtained through Fourier transformations followed by appropriate divisions.

The FF-HRTF is calculated from Eq. (22) in the following way. The free sound field is by definition a sound field with only one traveling path, in this case with sound incidence from the front of the subject. As the incoming sound energy is concentrated in this direction, $\nu(\phi, \theta)$ is given by a two-dimensional Dirac impulse,

$$\frac{1}{4\pi}\,\nu(\phi, \theta) = \delta(0°, 0°)\,. \qquad (25)$$

By substitution the following is found:

$$\mathrm{FF\text{-}HRTF} = \sqrt{\frac{1}{4\pi}\iint |\mathrm{HRTF}(\phi, \theta)|^2\, \nu(\phi, \theta)\, d\phi\, d\theta}$$

$$= |\mathrm{HRTF}(0°, 0°)|\,. \qquad (26)$$

The measurements included exactly this direction, so these data are used directly in the calculation of the design goal.

The DF-HRTF is also found by substitution into Eq. (22). The diffuse sound field is by definition a sound field where the angles of sound incidence are equally distributed over the sphere. Thus

$$\nu(\phi, \theta) = 1 \qquad (27)$$

for all angles. Substituting, the following is found:

$$\mathrm{DF\text{-}HRTF} = \sqrt{\frac{1}{4\pi}\iint |\mathrm{HRTF}(\phi, \theta)|^2\, d\phi\, d\theta}\,. \qquad (28)$$

From the measurements the HRTFs are known only at 97 discrete directions and not as continuous functions of ϕ and θ. The integral is therefore approximated by a sum, where each HRTF represents a space angle sa,

$$\mathrm{DF\text{-}HRTF} \approx \sqrt{\frac{1}{4\pi}\sum_{k=1}^{97} |\mathrm{HRTF}(k)|^2\, \mathrm{sa}(k)}\,. \qquad (29)$$

The space angle represented by a single one of the 97 measured HRTFs is between 0.1083 and 0.1532 steradian.

1.6 Prior Measurements of Headphone Transfer Functions

In a prior experiment some characteristics of 14 headphones were investigated with the aim of selecting headphones for the binaural technique [2]. The electroacoustical transfer functions (PTFs) were measured at the open and the blocked ear canal of 40 subjects. Data from these measurements are used in Section 3.6 to illustrate the variations between subjects and in Section 3.7 to illustrate the frequency responses of some commercial headphones in comparison with the design goals.

2 RESULTS

In this section individual design goals are presented as data for the left ear of each subject. Before calculation of the mean design goals and standard deviations, each subject's left- and right-ear [RF-HRTF]s were averaged. Thus all averages are on a logarithmic scale.

2.1 Design Goals for Free-Field Calibration

Design goals for free-field-calibrated headphones are given in Fig. 3. The goals are shown for measurements at the entrance to the open ear canal as well as to the blocked ear canal. Fig. 3(a) shows the individual design goals. For both methods the variations between subjects are low up to approximately 700 Hz. Between 700 Hz and 2 kHz the variations are slightly higher, but still about the same for the two methods. Between 2 and 6 kHz the variations between subjects are clearly larger for the open ear canal than for the blocked ear canal. Above 6 kHz there are very large variations between subjects for both methods.

In the following comments it should be remembered that the free-field design goal is identical to the HRTF for frontal sound incidence. Most of the variations are due to differences in the shape of the subjects' bodies, heads, and pinnae. At low frequencies the sound field is almost undisturbed, and this results in a design goal close to 0 dB and with little interindividual variation. At increasing frequencies the disturbance of the sound field becomes more significant, the design goal deviates from 0 dB, and the effect of the subject's individual geometry becomes more predominant. The same structures are present in most of the curves, but as the peaks and dips appear at different frequencies, a very scattered pattern is seen, especially above 6 kHz.

The extra variations seen between 2 and 6 kHz for the open ear canal method are due to individual variations in the pressure division at the input to the ear canal [Eq. (13)]. Above 2 kHz this pressure division is known to be highly individual [3], [19].

The mean design goals are shown in Fig. 3(b). Despite the individual variations mentioned, both methods offer a fairly well-defined design goal. Note that the grey zones indicate the mean ±1 standard deviation. Due to the large number of subjects involved, the standard error of the mean is much smaller than the standard deviation. Up to 5 kHz for the blocked ear canal and up 2 kHz for the open ear canal the standard error of the mean is below 0.6 dB. Above these frequencies values of 1–1.5 dB are typical. The effect of statistical variations is discussed in Section 3.6.

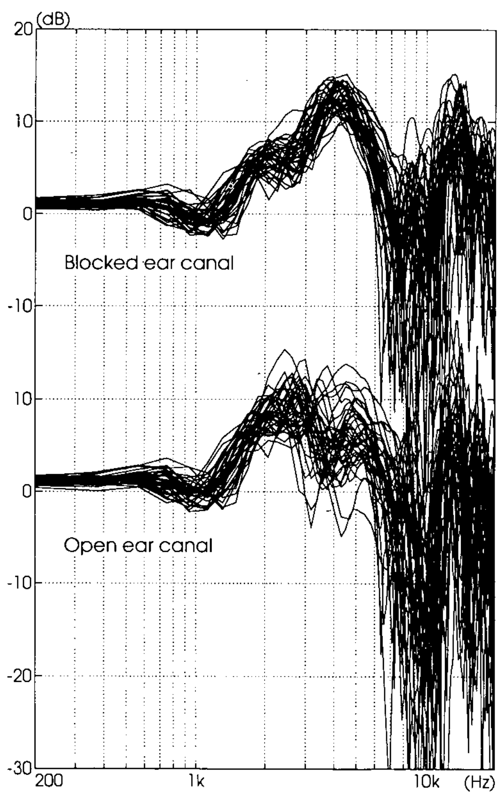
The blocked ear canal design goal is characterized by peaks of approximately 13 dB slightly above 4 kHz and approximately 8 dB at 13–14 kHz, separated by a plateau just below 0 dB in the range of 7–11 kHz. The lower end of the 4-kHz peak is "disturbed" by some extra fluctuations due to interference with a reflected sound wave from the shoulder. It is not within the scope of the present paper to discuss the anatomical origin of the various structures of the design goal.

Because of the pressure division, the structure of the open ear canal design goal is slightly different, especially in the 2–10-kHz frequency range. The 4-kHz peak has turned into a dip, and the plateau at 7–11 kHz has turned into a sharp dip at 10 kHz.

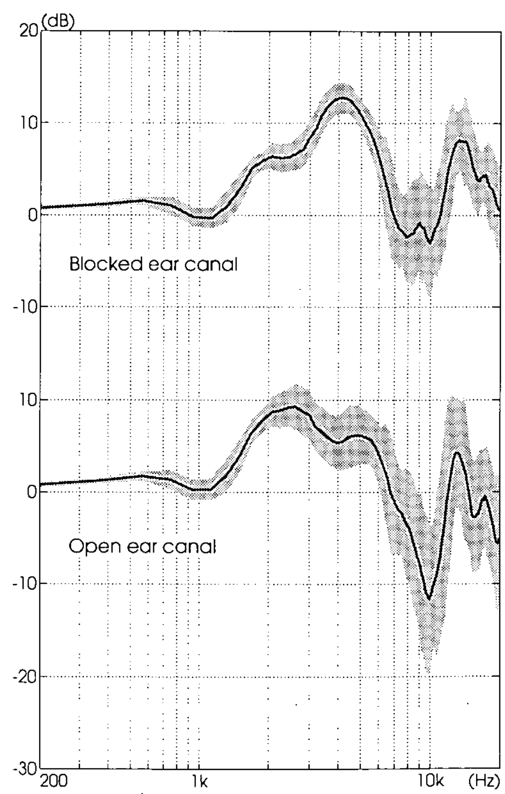
As mentioned in Section 0.3, other angles than direct frontal sound incidence might be appropriate for free-field calibration. The design goals for an azimuth angle of 22.5° are shown in Fig. 4. The mean values are a few decibels higher at most frequencies. The fluctuations in the mean design goal at 1–4 kHz have moved slightly up in frequency.

2.2 Design Goals for Diffuse-Field Calibration

Design goals for diffuse-field-calibrated headphones are shown in Fig. 5 for the blocked and open ear canals. The individual design goals for the blocked ear canal are almost identical up to 2 kHz. Above this frequency some variations are seen, but they are much smaller than for the corresponding free-field design goals. Evidently anatomical differences may have a large effect on the HRTF for a single direction, but when these are averaged over



(a)



(b)

Fig. 3. Design goals for free-field-calibrated headphones. (a) Individual design goals for 40 human subjects. (b) Means. Grey zones indicate mean ±1 standard deviation.

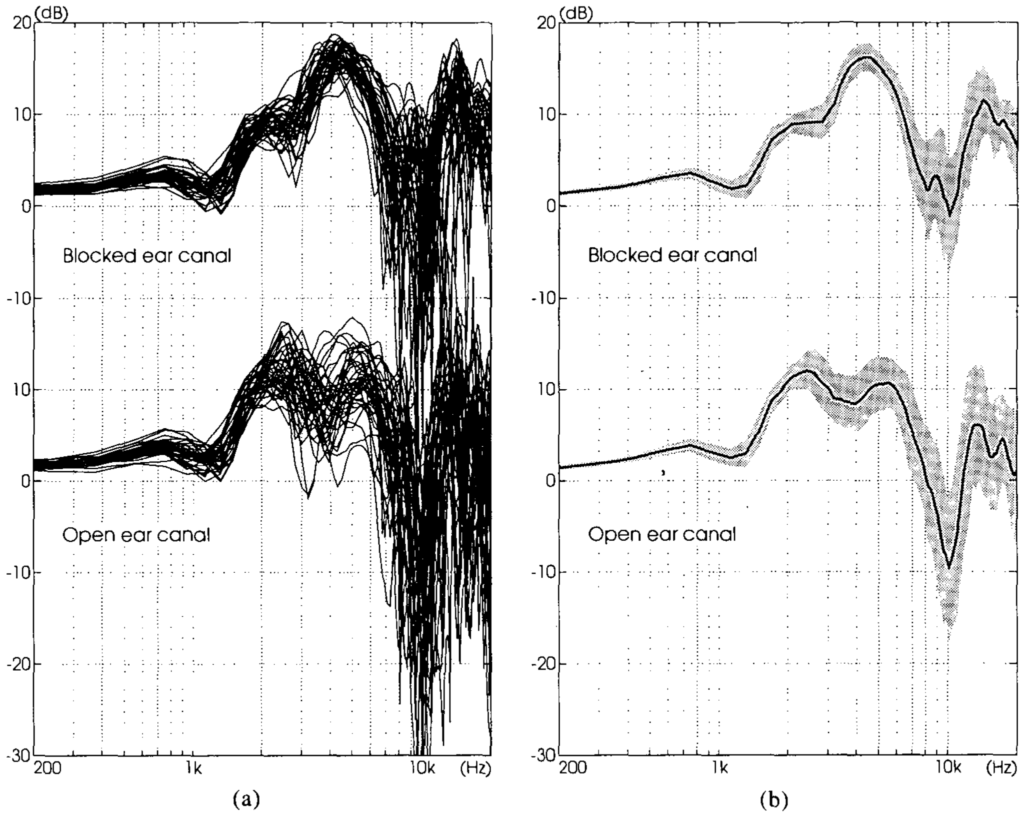


Fig. 4. Design goals for free-field-calibrated headphones when alternative azimuth angle of 22.5° is used. (a) Individual design goals. (b) Means for 40 humans subjects. Grey zones indicate mean ±1 standard deviation.

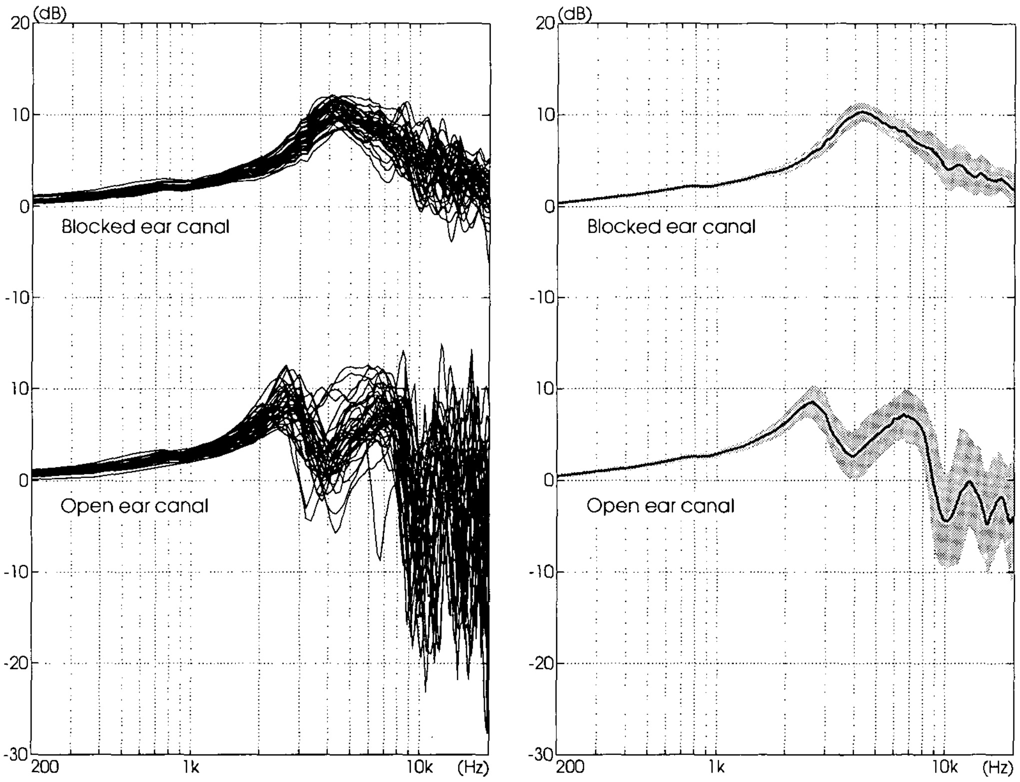


Fig. 5. Design goals for diffuse-field-calibrated headphones. (a) Individual design goals for 40 human subjects. (b) Means. Grey zones indicate mean ±1 standard deviation.

the sphere, the effects of interindividual differences are reduced drastically.

The individual design goals for the open ear canal look almost identical up to 2 kHz. Above this frequency significantly larger variations between subjects are seen. This is due to the interindividual variation in the pressure division at the input to the ear canal.

The mean design goals are seen in Fig. 5(b). In accordance with the observations of the individual design goals, the standard deviations are smaller, and the mean design goals are determined with even better accuracy than for the free field.

In contrast to the free-field design goal, the blocked ear canal design goal is here a very smooth curve with a wide peak of approximately 10 dB slightly above 4 kHz. The open ear canal design goal has two characteristic peaks of approximately 8 dB between 2 and 3 kHz and approximately 7 dB around 7 kHz.

3 DISCUSSION

In this section various aspects of the proposed calibration procedure and design goals are discussed, and comparisons are made with earlier design goals and traditional methods.

3.1 Comparison of Design Goals for Different Reference Fields

The free-field and diffuse-field design goals have their origin in different assumptions about the sound field to which the listener is exposed in the reference situation. Consequently two very different design goals are found. A real-life loudspeaker setup in a listening room would probably give a sound field somewhere between the two extremes, the free and diffuse sound fields. Fig. 6 illustrates the transition from a free-field design goal to a diffuse-field design goal when more and more directions of sound incidence are included. As more directions are included, peaks become lower and dips are "filled up." This is a natural consequence of the fact that the HRTFs from various directions have peaks and dips at different frequencies. The fluctuations from the shoulder reflections are only seen in the pure free-field design goal. The most significant change is seen already in the first step from the free-field toward the diffuse-field design goal.

A realistic compromise between the free-field and diffuse-field design goals would be to weight directions within ±45° azimuth and ±45° elevation equally and with a total weight of 50%, while distributing the remaining 50% equally over the rest of the sphere. An alternative design goal based on this assumption is shown in Fig. 7. Compared with the diffuse-field design goal, the 4-kHz peak is higher, and at this point the influence from the free-field design goal is seen. The very low values at 7–11 kHz of the free-field design goal have, however, been avoided.

It is remarkable how close this alternative design goal is to curve c of Fig. 6, which represents averaging over the frontal hemisphere. The similarity suggests that an exact description of the sound field in the listening room is not important. Various sound fields characterized by waves from many directions and with special emphasis on the frontal region will lead to almost identical curves.

A psychoacoustic investigation is needed to disclose whether a free-field response, a diffuse-field response, or maybe the compromise in Fig. 7 is preferable.

3.2 Comparison with Previous Design Goals

As mentioned in Section 0.5, Sank [17] and Toole [18] have previously suggested a design procedure very similar to that of the present investigation. They also presented some preliminary design goals. Sank called his design goal HEAT (headphone electroacoustic transfer) curves.

Sank's reference field was created by a studio monitor in a small studio with a highly damped rear wall, and with a reverberation time of 0.3 s. He measured open ear canal HRTFs in the reference field for nine subjects and used the envelope of these curves as a design range (but omitting two response peaks that did not fit the trend).

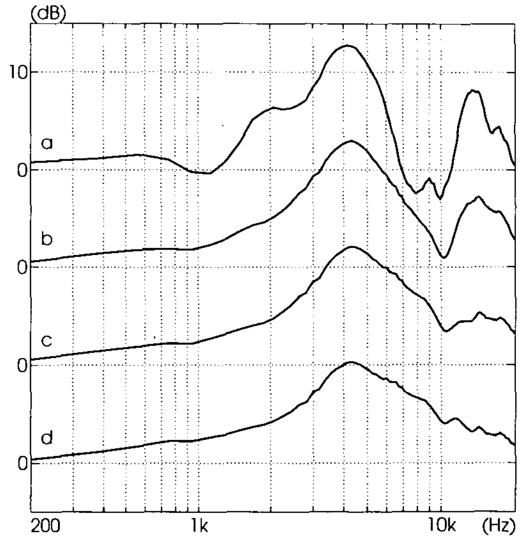


Fig. 6. Gradual transition from free-field to diffuse-field design goal. a—free-field design goal; b—modified diffuse-field design goal, where sound only arrives within ±45° azimuth and elevation angles; c—sound within ±90° azimuth and elevation angles (frontal hemisphere); d—normal diffuse-field design goal. Only curves for blocked ear canal are shown.

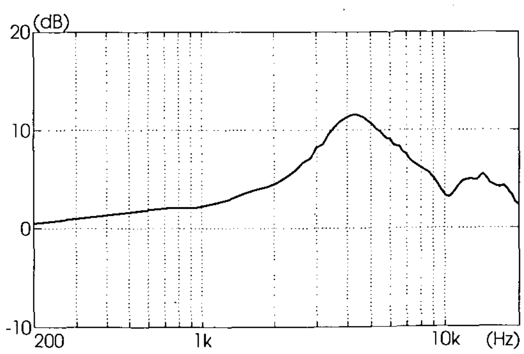


Fig. 7. "Combined field" compromise with 50% weight equally distributed to directions within ±45° azimuth and elevation angles and 50% to all other directions.

Toole's design goal is based on blocked ear canal pinna responses from Shaw [20] ("HRTF"s for the pinna alone). The envelope of the pinna responses for some more or less elevated frontal directions is used as a design "range." Two design ranges are presented, which differ only in the number of directions included.

Fig. 8 shows the design ranges of Sank and Toole together with our free-field design goals for the appropriate ear canal condition (solid lines). Although our free-field design goal is within Sank's design range for most frequencies, the two goals do not show the same fluctuations with frequency. The difference may be partly explained by Sank's sound field, which is not a free field but includes some reflections. Our design goal for a combined field from Fig. 7 fits slightly better (dashed line). Sank used a 6.4-mm (1/4-in) microphone projecting into the concha through the intertragal incisure. Disturbance from his microphone and the slightly different measuring point may also explain discrepancies.

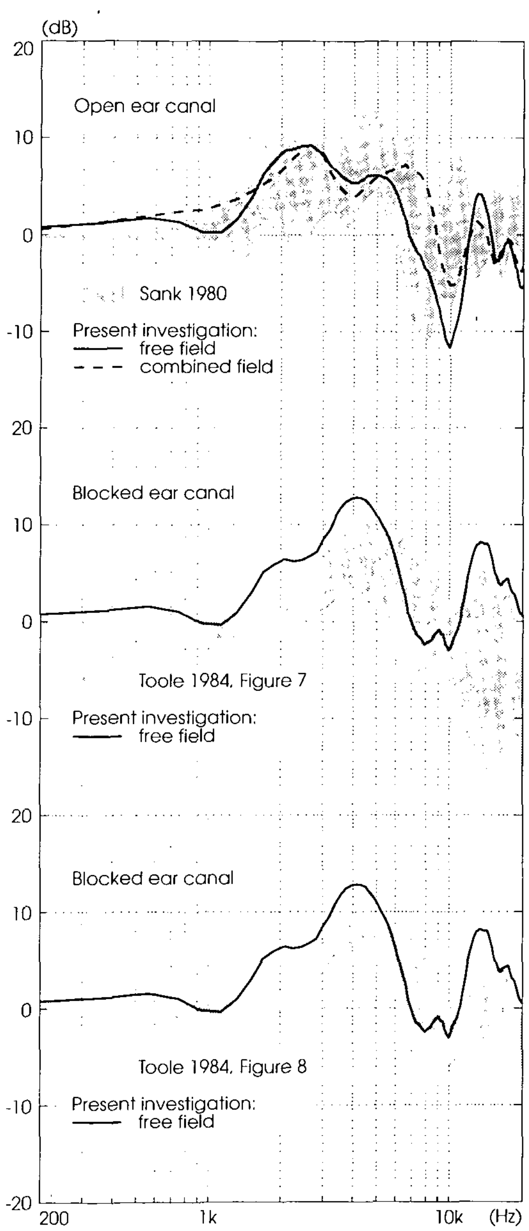


Fig. 8. Design goal "ranges" as presented by Sank [17] and Toole [18] (two ranges proposed, Toole's Figs. 7 and 8) shown together with free-field and combined design goals from the present investigation for the appropriate ear canal condition.

Toole's design ranges are clearly too low and lack resonances at 1–6 kHz compared to our design goal. This is easily explained from his use of pinna responses rather than real HRTFs.

The meaning of the design "range" is slightly different in the two earlier proposals. Sank has shown a range that accommodates interindividual variations in HRTFs for the reference field. However, interindividual variations will also be present during headphone measurements and influence the obtained PTFs. We believe that the total uncertainty is reduced by using a more precise design goal (calculated as a mean), and aim at that for the mean of headphone measurements. The effect of interindividual variations is discussed in Section 3.6.

Toole has shown a range that accommodates various directions of sound incidence in the reference field. We assume that he expects listening tests to disclose which curve within the range should be aimed at for the mean of headphone measurements.

3.3 Approximation of Diffuse Field

As measurements were only available for discrete directions, an integral was approximated by a sum [Eq. (29)]. An evaluation of the acceptability of this approximation can be found if the spatial sampling is reduced, for instance, by a factor of 2 in angle. The result of a calculation based on only 25 directions is shown in Fig. 9 together with the original result based on 97 directions. It is quite obvious that the two curves are very similar and the approximation is acceptable.

3.4 Frequency Resolution

The design procedure suggested in this paper permits measurements to be carried out at pure tones and for narrow bands of noise. For the diffuse field this is not possible in traditional methods, where the reference field must be created physically. In practice, a frequency resolution of one-third octave is used, a resolution that might not be sufficient.

Fig. 10 compares a typical individual diffuse-field design goal for the open ear canal as a continuous curve

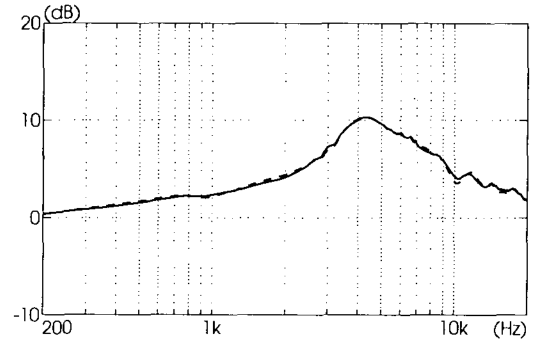


Fig. 9. Comparison between diffuse-field design goal calculated from 97 discrete directions and calculated with reduced spatial sampling from 25 discrete directions. Only design goal for blocked ear canal entrance is shown.

and calculated for one-third octaves. It is easily seen that information is lost with one-third-octave resolution. Peaks and dips appear at slightly incorrect frequencies, and their amplitudes are wrong. Structures may even be hidden as, for example, the double peak between 2 and 3 kHz. The picture may look even worse when the transfer function of a headphone is considered, since this can often have more severe peaks and dips.

The traditional free-field calibration procedures can in principle be carried out at pure tones, but in order to reduce the number of loudness comparisons, one-third-octave noise bands are often used. With the before mentioned observations in mind this cannot be recommended, and a better frequency resolution should be used.

3.5 Creation of a Physical Diffuse Sound Field

The traditional diffuse-field calibration procedures require a physical diffuse field. This will also contribute inaccuracy. Fig. 11 shows the DF-HRTF of a sample artificial head when measured at various positions in a reverberant room. Differences on the order of 2 dB are seen up to 5 kHz, increasing to 3–4 dB at higher frequencies.

3.6 Statistical Variations

In this section the effect of individual variations between subjects is evaluated. A design procedure is assumed in which the deviation of a particular headphone from the design goal is determined. The deviation is used to design an electronic equalizer.

The first step in the design procedure is to select from the literature a design goal, specified as the mean HRTF for a specific sound field. Following the previous notation, the design goal is denoted by $[\text{RF-HRTF}]_{\text{goal}}$. The subscript "goal" indicates that the value is a mean for the group of subjects that participated when the design goal was determined.

The next step is to measure the particular headphone on a number of subjects and at the measuring point for which the design goal is given. The mean of these measurements is called $[\text{PTF}]_{\text{measure}}$. The subscript "measure" indicates that the value is a mean for the group participating in the measurements.

On the basis of these two amplitude responses, an equalization $[G]$ in decibels is determined so that Eq. (24) is fulfilled when $[\text{PTF}]_{\text{measure}} + [G]$ is inserted for [PTF]. Then

$$[G] = [\text{RF-HRTF}]_{\text{goal}} - [\text{PTF}]_{\text{measure}} + [\text{constant}] . \tag{30}$$

When a listener uses a headphone that is designed in this way, there may be an error in the transmission despite all possible care. This is due to the facts that the design goal is encumbered with some uncertainty, that a single listener deviates from the average listener, and that the performance of the headphone on a single listener deviates from the performance on the average listener.

The total error Δ in decibels can be found as the difference between the actual and the desired transmission to the eardrum,

$$\Delta = ([\text{PTF}_7] + [G]) - ([\text{constant}] + [\text{RF-HRTF}_4]) . \tag{31}$$

If it is recalled that the transmission along the ear canal for a given listener is the same in the reference situation and when listening with headphones [see Eq. (18)], this can be subtracted in the two terms of Eq. (31) and

$$\Delta = ([\text{PTF}_6] + [G]) - ([\text{constant}] + [\text{RF-HRTF}_3]) . \tag{32}$$

It is possible to derive various statistics for Δ. Each of the following has a physical meaning and gives useful information about the design procedure.

The mean μ of Δ is the mean when averaged over the whole "population of headphone users." Of course, it is reasonable to want μ to equal 0 dB.

The standard error of the mean (s.e.m.) indicates the spread in the mean that will be seen if the design proce-

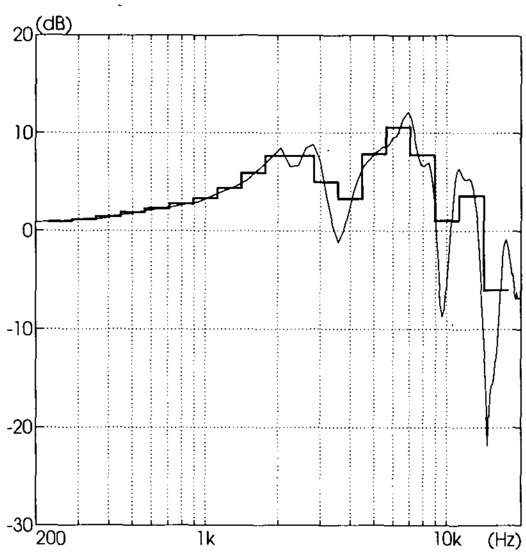


Fig. 10. Typical individual diffuse-field design goal calculated for pure tones and one-third-octave bands. Values are for open ear canal.

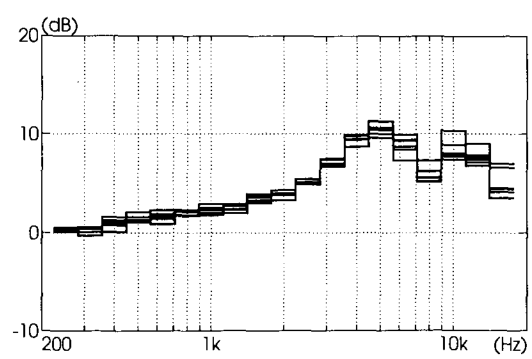


Fig. 11. Measurements of diffuse-field HRTF at input to blocked ear canal (DF-HRTF_2) for sample artificial head (Brüel & Kjær 4128). Measurements are shown for six different positions in a reverberant room [room fulfilling standardized requirements for measurement of sound absorption (ISO 354) and sound power (ISO 3741)].

dure is accomplished repeatedly. Thus the standard error of the mean can be interpreted as the statistical uncertainty in the design procedure.

The standard deviation σ of Δ is an indicator of the spread between subjects.

In the following subsections the standard error of the mean is calculated for the different procedures, and some examples are shown. All the following statistical calculations are made on only one ear for each subject (left ear). The design goals given in Section 2 are based on two ears from each subject, and the statistical accuracy of the design goals may therefore be better than in the following examples.

3.6.1 Design with Measurements at Open Ear Canal

In this case Eq. (30) will have the following form:

$$[G] = [\text{RF-HRTF}_3]_{\text{goal}} - [\text{PTF}_6]_{\text{measure}} + [\text{constant}] . \quad (33)$$

Substituting into Eq. (32),

$$\Delta = ([\text{PTF}_6] - [\text{PTF}_6]_{\text{measure}}) + ([\text{RF-HRTF}_3]_{\text{goal}} - [\text{RF-HRTF}_3]) . \quad (34)$$

μ can be found through averaging across all subjects,

$$\mu = ([\text{PTF}_6]_{\text{population}} - [\text{PTF}_6]_{\text{measure}}) + ([\text{RF-HRTF}_3]_{\text{goal}} - [\text{RF-HRTF}_3]_{\text{population}}) . \quad (35)$$

The subscript "population" indicates the mean for the whole population. It is evident that if $[\text{RF-HRTF}_3]_{\text{goal}}$ and $[\text{PTF}_6]_{\text{measure}}$ reflect the population correctly, then μ will be zero. In other cases a nonzero value will result (unless two opposite deviations cancel out).

Since there is no variance from the two population terms, the standard error of the mean can now be found,

$$\text{s.e.m.} = \sqrt{\text{var}([\text{RF-HRTF}_3]_{\text{goal}} - [\text{PTF}_6]_{\text{measure}})} . \quad (36)$$

Usually the design goal will be taken from the literature, whereas the measurements will be carried out on a group of subjects present at the construction stage. Therefore the *goal* and the *measure* groups are statistically independent, and

$$\text{s.e.m.} = \sqrt{\text{var}([\text{RF-HRTF}_3]_{\text{goal}}) + \text{var}([\text{PTF}_6]_{\text{measure}})} = \sqrt{\frac{\text{var}([\text{RF-HRTF}_3])}{n_{\text{goal}}} + \frac{\text{var}([\text{PTF}_6])}{n_{\text{measure}}}} \quad (37)$$

where n_{goal} and n_{measure} indicate the number of subjects that are used in the determination of the design goal and for the measurement, respectively.

3.6.2 Design with Measurements at Blocked Ear Canal

Here Eq. (30) has the form

$$[G] = [\text{RF-HRTF}_2]_{\text{goal}} - [\text{PTF}_5]_{\text{measure}} + [\text{constant}] . \quad (38)$$

Substituting into Eq. (32),

$$\Delta = ([\text{PTF}_6] - [\text{PTF}_5]_{\text{measure}}) + ([\text{RF-HRTF}_2]_{\text{goal}} - [\text{RF-HRTF}_3]) . \quad (39)$$

After introducing the pressure division for the subject in the reference field $[P_3/P_2]$ and during headphone listening $[P_6/P_5]$, both given in decibels, it is found that

$$\Delta = ([\text{PTF}_5] - [\text{PTF}_5]_{\text{measure}}) + ([\text{RF-HRTF}_2]_{\text{goal}} - [\text{RF-HRTF}_2]) + \left(\left[\frac{P_6}{P_5}\right] - \left[\frac{P_3}{P_2}\right]\right) . \quad (40)$$

Here μ is also found through averaging across all listeners,

$$\mu = ([\text{PTF}_5]_{\text{population}} - [\text{PTF}_5]_{\text{measure}}) + ([\text{RF-HRTF}_2]_{\text{goal}} - [\text{RF-HRTF}_2]_{\text{population}}) + \left(\left[\frac{P_6}{P_5}\right]_{\text{population}} - \left[\frac{P_3}{P_2}\right]_{\text{population}}\right) . \quad (41)$$

The equation has a form similar to that of Eq. (35), except that an extra term now appears. This is due to the difference in pressure division in the two situations. The precondition for using measurements outside the blocked ear canal is that an FEC headphone be used. Then the extra term is zero. (If the precondition is violated, the extra term will tell the error that results.)

The standard error of the mean can be found in a procedure similar to that in the previous section,

$$\text{s.e.m.} = \sqrt{\frac{\text{var}([\text{RF-HRTF}_2])}{n_{\text{goal}}} + \frac{\text{var}([\text{PTF}_5])}{n_{\text{measure}}}} . \quad (42)$$

3.6.3 Traditional Methods

Characteristic for the traditional methods is that the same subjects are used for exposure in the reference field and for determination of the PTF. For the psychoacoustic procedures the reference point is at the eardrum since the ear itself is used as the detector ("microphone"). For the physical methods, measurements at the input to the open ear canal are normally used.

For both the physical and the psychoacoustic procedures, $[G]$ is calculated from an equation similar to Eq.

(30), except that the *goal* and *measure* groups are the same, here denoted by *measure*:

$$[G] = [\text{RF-HRTF}]_{\text{measure}} - [\text{PTF}]_{\text{measure}} + [\text{constant}] . \quad (43)$$

Eq. (43) is now inserted into Eq. (32) for the physical methods and into Eq. (31) for the psychoacoustic methods. In both cases the equation can be reduced to the following form:

$$\Delta = ([\text{PTF}_6] - [\text{PTF}_6]_{\text{measure}}) + ([\text{RF-HRTF}_3]_{\text{measure}} - [\text{RF-HRTF}_3]) . \quad (44)$$

By averaging across a population it is found that

$$\mu = ([\text{PTF}_6]_{\text{population}} - [\text{PTF}_6]_{\text{measure}}) + ([\text{RF-HRTF}_3]_{\text{measure}} - [\text{RF-HRTF}_3]_{\text{population}}) . \quad (45)$$

Since the same group is used in the two exposure situations, the [RF-HRTF]s and the [PTF]s are not statistically independent, so the standard error of the mean must be calculated in the following way:

$$\text{s.e.m.} = \sqrt{\text{var}([\text{RF-HRTF}_3]_{\text{measure}} - [\text{PTF}_6]_{\text{measure}})} = \sqrt{\frac{\text{var}([\text{RF-HRTF}_3] - [\text{PTF}_6])}{n_{\text{measure}}}} . \quad (46)$$

3.6.4 Examples of Standard Error of the Mean

Fig. 12 shows some examples of the standard error of the mean when different methods are used for the calibration of 14 sample headphones. In general the error is low up to approximately 7 kHz. Above this frequency the error increases to an almost constant level for the rest of the audio frequency range. There are only small differences between headphones, and the errors are in general very small for all methods. (Be aware that the vertical scale is different from that of the other figures.)

The blocked ear canal method provides the smallest standard error of the mean. The reason is that the method totally ignores the effect of the ear canal in the reference as well as the headphone situation—and therefore any statistical variation from this. The method can only be used with FEC headphones. The deviation of some practical headphones from a strict FEC criterion is reported in [2].

The method with measurements at the open ear canal and the traditional methods show errors of almost the same size. The traditional methods are slightly better in the frequency range of 2–7 kHz, whereas the proposed open ear canal method is slightly better at high frequencies when only few subjects are used.

In general the differences between methods are small. It should, however, be noted that the psychoacoustical methods may introduce an extra uncertainty from the threshold determination, loudness balance, or whatever procedure is used. In the foregoing calculations this extra variance is not included. Also the implementation of the reference sound field may introduce an extra error, which may be significant for the diffuse field, as mentioned in Section 3.5.

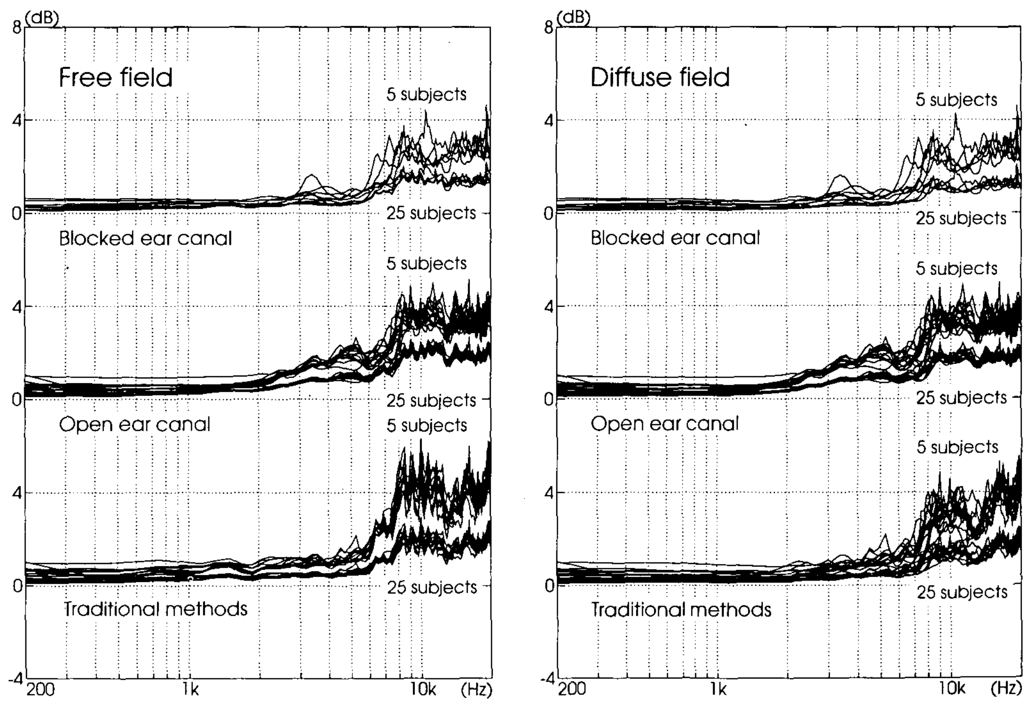


Fig. 12. Examples of standard error of mean for various methods: Blocked ear canal measurement [first row, Eq. (42)]; open ear canal measurements [second row, Eq. (37)]; traditional methods [third row, Eq. (46)]. In each case values are shown for 14 headphones, except for blocked ear canal method, where only five FEC headphones are included. Number of subjects for measurements n_{measure} is indicated as parameter, and for the two first rows it is assumed that the design goal is taken from this article (40 subjects, $n_{\text{goal}} = 40$).

3.6.5 Variation between Listeners

As mentioned, σ expresses the spread of Δ between subjects. It can be determined without knowing which procedure is used for the calculation of $[G]$ since in Eq. (32) $[G]$ appears as a constant, which does not affect the calculation of the standard deviation. Then

$$\sigma = \sqrt{\mathrm{var}(\Delta)} = \sqrt{\mathrm{var}([\mathrm{PTF}_6] - [\mathrm{RF\text{-}HRTF}_3])} \,. \tag{47}$$

It cannot be expected that $[\mathrm{PTF}_6]$ and $[\mathrm{HRTF}_3]$ are statistically independent. Therefore it is not possible to base the calculation on the variance of each of them (at least not without knowing the covariance). Thus σ must be calculated directly by the insertion of both terms for each subject. In Fig. 13 examples are given for 14 headphones.

Up to 6–7 kHz the variation between subjects, expressed by the standard deviation, is reasonably low, say, 1–3 dB. Above 8 kHz quite large variations are seen—5–10 dB for the diffuse-field calibration and slightly higher for the free-field calibration. The variances are almost the same for all headphones. This is a little surprising since headphones of very different construction were included in the investigation. Only headphones that are more or less directly inserted into the ear canal were not represented.

The reason for the large variations at the highest frequencies is that all PTFs show large and narrow peaks and dips at these frequencies. The peaks and dips occur at different frequencies for different subjects, thus contributing to a large standard deviation at a specific frequency. It is unknown how much these fluctuations affect the perceived sound quality when they appear at such high frequencies.

The variations dealt with in this section are due to the fact that the same equalization is used for all listeners. No matter how sophisticated the procedure used to determine a common equalization, it will not affect the size of these variations. It should be noted that all calibration methods lead to standard errors of the mean less than the standard deviation between subjects when only five subjects are used—and significantly less when 25 subjects are involved.

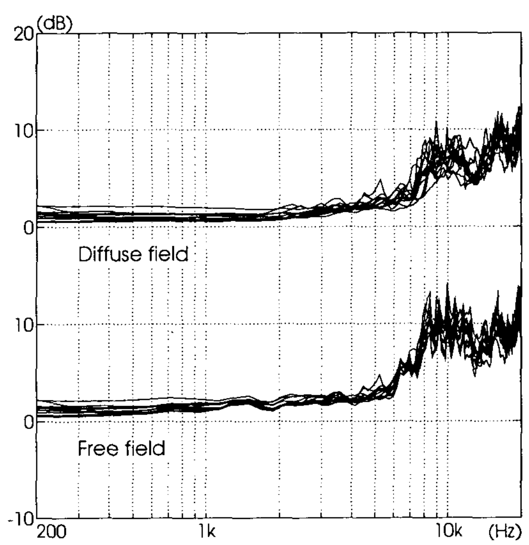


Fig. 13. Examples of σ estimated from data for 40 subjects. Each curve for one headphone (14 in each row).

3.7 Examples of Commercial Headphones

Figure 14 shows some examples of measurements on headphones which the manufacturers claim are diffuse-field calibrated. It is seen that the headphones are very different, and none of them follows very well the design goal developed in this study.

4 CONCLUSION

It has been shown that psychoacoustic measurement procedures for headphones can be replaced by physical sound pressure measurements at the input to the human ear canal. Furthermore, measurements in the reference field can be replaced by prior knowledge about the desired frequency response from voltage at the headphone terminals to pressure at the input to the ear canal.

For all headphones the sound pressure measurements may be made at the open ear canal. For FEC headphones (headphones with a coupling to the ear canal similar to the coupling to free air) measurements may alternatively be made at the blocked ear canal, thus allowing a miniature microphone to be inserted in the blocking device, such as an earplug.

Design goals for the PTF are given for free-field- and diffuse-field-calibrated headphones and for measurement at the open and the blocked ear canal. An alternative design goal is also given as a compromise between free-field and diffuse-field calibration.

As the proposed procedure allows diffuse-field calibration without physical creation of the sound field, even diffuse-field calibration is now possible for pure tones or narrow bands. A frequency resolution between than

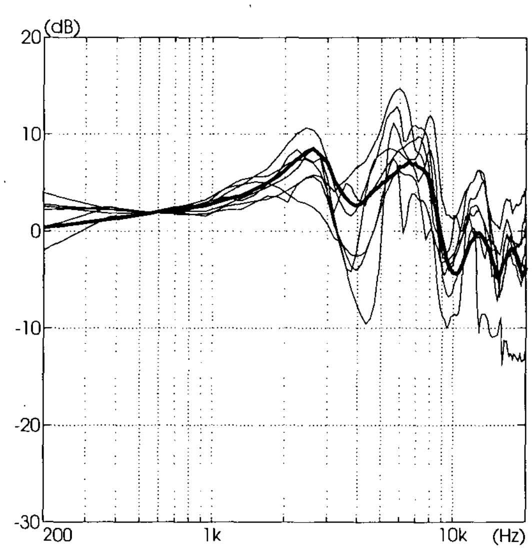


Fig. 14. Diffuse-field design goal (heavy line) and mean frequency response of seven commercial headphones claimed to be diffuse-field calibrated (thin lines). Measurements at entrance to open ear canal were used. Headphone frequency responses were displaced vertically to fit around 600 Hz.

one-third octave is recommended since the design goals—and also the PTFs—have narrow peaks and dips.

It is shown that the statistical uncertainty due to differences between subjects is almost the same for the traditional methods and the new method. If 25 subjects are used, the standard error of the mean will be below 1 dB up to 7 kHz and around 2 dB above this frequency. If only five subjects are used, the standard error of the mean is approximately doubled.

The proposed method avoids extra variance from the psychometric procedure used in loudness or threshold determination. The extra variance from a physical diffuse sound field is also avoided.

From a comparison between the design goal and the measurements on claimed diffuse-field-calibrated headphones it is concluded that seven commercial headphones used in the study fulfill the design goal rather badly. Users are advised not to rely on a manufacturer's specifications without verifying them in a well-controlled measurement procedure. The use of a reference headphone for the calibration of new constructions seems problematic (and unnecessary with the proposed new method).

5 ACKNOWLEDGMENT

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Biographies of the authors are printed on page 217 of this issue.