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Psychoacoustic Evaluation of the Basis for Binaural Technique

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DESIGN CRITERIA FOR HEADPHONES

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ABSTRACT

An alternative procedure for measuring headphone performance on human ears is proposed. The traditional psychoacoustic procedures are replaced with 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 at pure tones and narrow frequency bands. Also the extra variance from a physical diffuse sound field is avoided. Here, the investigation is only introduced, a more detailed description is given in [1].

INTRODUCTION

Sound reproduction by means of headphones has a wide range of applications. Among these are playback of binaural signals, where the headphones is required to have a flat frequency response when measured at the same position in the ear canal, as the recording is made [2]. Other applications are within audiology, where the requirement often is that the headphone has 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 reproduction of normal, commercial program material. Such material is originally recorded and mixed for playback by means of a standard stereo loudspeaker set-up. During headphone reproduction the headphone replaces the whole set-up, including the loudspeakers and the listening room. If the headphone should provide the listener with the same sound as the loudspeaker set-up, the demands to its transfer function would be very complex and hardly realizable. Therefore, various simpler demands are used for the transfer function.

Even the simple design procedures involve quite extensive measurements for 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 got insight into the transmission of sound to the ear canal from headphones, as well as from an external sound field. In this context this knowledge is utilized to develop simpler design procedures for headphones and to compare the methods with traditional procedures.

HEADPHONE REPRODUCTION VERSUS LOUDSPEAKER REPRODUCTION

When the headphone replaces the loudspeaker in the reproduction situation, it replaces not only the electro-acoustical 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, which 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. There are systems - more or less experimental - which add crosstalk and simulated reflections to the electrical signal, 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 set-up in a room. The demands for the headphones will therefore be reduced to a demand on its frequency weighting, namely that the headphone should give the same "timbre" of the reproduced sound, as a loudspeaker set-up 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 after a more detailed description of the design criterion.

MATHEMATICAL DESCRIPTION OF DESIGN CRITERION

The general design criterion can be expressed as

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

where P_7 is the sound pressure at the listener's eardrum in the playback situation with headphone, and P_4 is the sound pressure at the listener's eardrum in the reproduction situation with loudspeakers. $E_{headphone}$ denotes the voltage applied to the headphone terminals, and $E_{loudspeaker}$ denotes 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 is upheld because it has been used in our earlier investigations with similar considerations.

The right side of Equation (1) can be expressed as a sum of sound pressures originating from different sound waves with each their transmission path i

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

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 term relates 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 (next page)

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

where P_1 is the sound pressure found at the listener's position, in the situation of his 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 on power basis, and Equation (3) is written as

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

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

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

The denominator in Equation (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

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

If (5) is inserted in (4), the result is

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

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

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

As a design goal it will be sensible to 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 side of Equation (8) is a constant. By introduction of

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

the original design criterion (Equation (1)) can be written as

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

REFERENCE SITUATION

Existing design methods have their origin from various assumptions of which of the travelling paths that are the most important for the listening experience in the situation 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.

If it is assumed that the normal listening room is fairly damped, and that the most frequent listening orientation is facing the loudspeaker(s), the reference situation 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 [3], [4], [5]. An azimuth angle different from zero could also be used in free field calibration as suggested by Blauert (p. 362 in [6]). The argument is that the direct sound reaching the listener from a loudspeaker in the normal stereo set-up, has an angle of incidence typically between 20° and 50°.

In contradiction to this, it may be argued that even in a fairly damped room, the direct sound constitutes 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 denoted *diffuse field* calibrated [7], [8], [9], [10].

Another argument for the diffuse field calibration is given by Theile [7], 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 normal 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.

TRADITIONAL TEST PROCEDURES

Most procedures for test of headphones use psychoacoustic listening tests, for instance threshold or loudness comparisons of sound presented to subjects in the reference situation and presented by the headphone under test [3], [4], [5]. The procedures require the physical set-up of the reference situation and time consuming listening tests. The result will be inaccurate not only due to inaccuracies and statistical variation from the psychoacoustic evaluation but also due to inaccuracies in the sound field provided by the set-up 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.

The accomplishment of 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 utilize this, consist of measurements of the sound pressures in the ears of a number of subjects or a mannikin in the reference situation and in the listening situation with headphones [11], [7], [8], [9], [10]. The method requires the physical set-up 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 acoustical loading of the headphone.

The physical creation of the reference field is sometimes avoided through use of a reference headphone, which is beforehand determined to have the desired frequency response [4], [5], [8], [10]. The possible sources of errors are evidently not reduced.

For diffuse 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 third octave bands or wider, and this frequency resolution may not be sufficient to disclose the peaks and dips in the headphone frequency response.

PROPOSED TEST PROCEDURE

A more convenient test procedure than the ones just mentioned is 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 a such procedure has previously been presented by Sank [12] and Toole [13]. The method requires the existence of a general design goal, which can be taken from the literature. In the test situation the method still needs the participation of test subjects to provide loading of the headphone, but the physical set-up of the reference situation can be avoided.

Various design goals for headphone transfer characteristics can be computed, utilizing that for all choices of reference situations, a design goal can be composed as a weighted sum of head-related transfer functions. Measurements at the listeners eardrum can be replaced by measurements at another point in the ear canal, as long as the design goal is based on computations using head-related transfer functions measured at the same point.

If the measurements are carried out at the entrance to the blocked ear canal, it is a requirement that the headphone under test is acoustically "open" (that the acoustical load of ear with the headphone is similar to the load in the free air). The disadvantage of the additional requirement is compensated by the fact that the measurements at the entrance to the blocked ear canal has a very small spread for a population. A design procedure based on measurements at the entrance to the blocked ear canal will therefore in most cases be superior to a design procedure based on measurements, for instance, at the entrance to the open ear canal. The statistical evidence can be found in [1]. An impression of the spread of the population for two different measuring points can be obtained from Figure 1, where the diffuse field design goal for measurements made at the entrance to the open ear canal and measurements made at the entrance to the blocked ear canal are shown.

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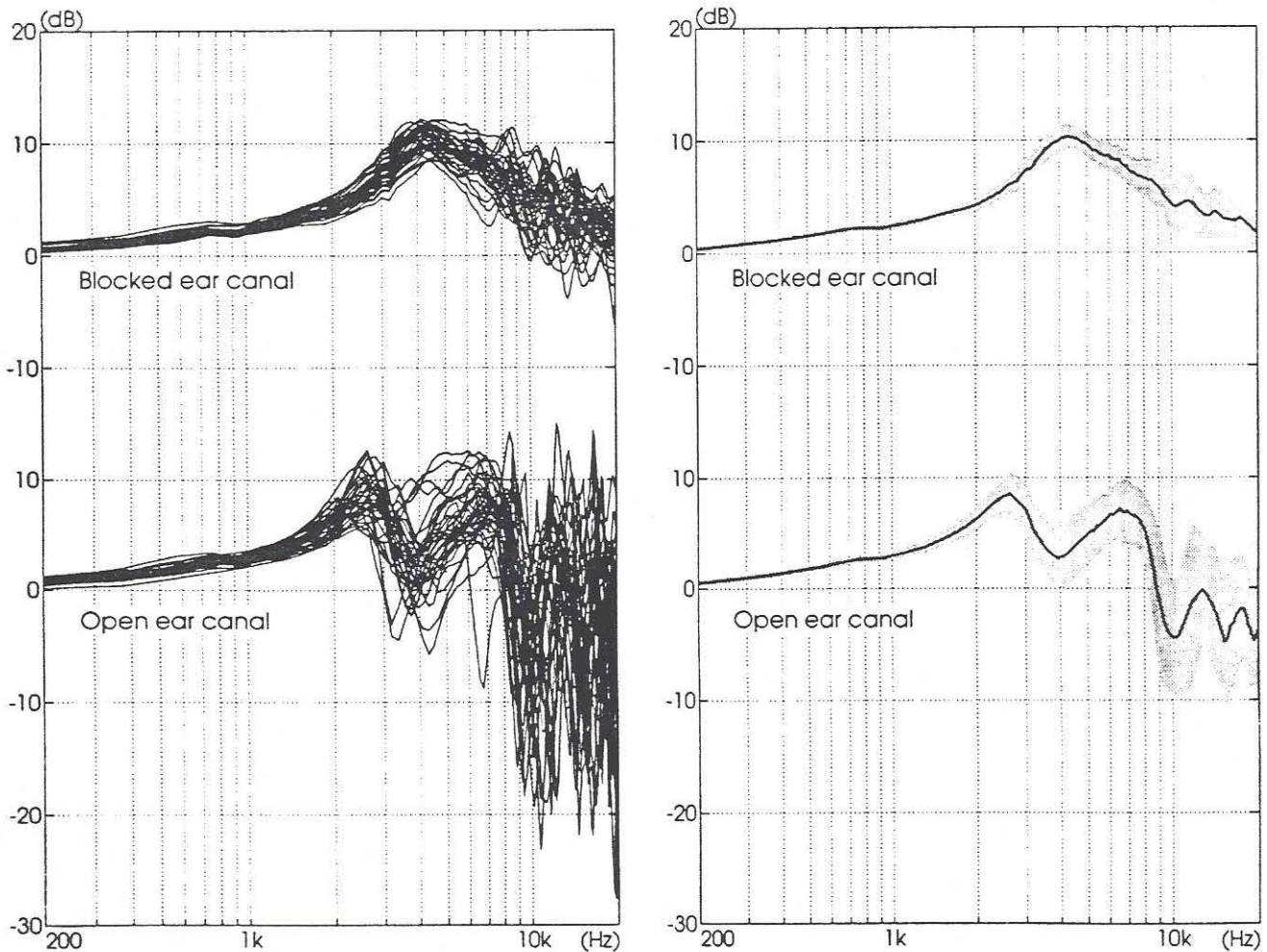
Figure 1

Design goals for diffuse field calibrated headphones. Left side shows individual design goals for 40 human subjects. The curves at the right side show the mean. The grey zones indicate the mean ± one standard deviation.