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Hammershøi, Dorte; Møller, Henrik

Published in:
93rd Audio Engineering Society Convention (AES), San Francisco, Oct. 1-4, 1992

Publication date:
1992

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Dorte Hammershøi and Henrik Møller
Aalborg University
Institute of Electronic Systems
Aalborg, Denmark

Presented at the 93rd Convention 1992 October 1–4 San Francisco

AES

AN AUDIO ENGINEERING SOCIETY PREPRINT

BINAURAL AURALIZATION: HEAD-RELATED TRANSFER FUNCTIONS MEASURED ON HUMAN SUBJECTS

Dorte Hammershøi, Henrik Møller
Institute of Electronic Systems, Aalborg University
Aalborg, Denmark

Summary

The result of a room analysis program can be made audible by computer generation of binaural signals. This auralization technique is based on knowledge of the Head-related Transfer Functions (HTFs). Data has been collected for 40 human subjects, measured with 97 directions of sound incidence covering the whole sphere.

1. Introduction

Binaural auralization is based on the fact that the human hearing creates the three-dimensional sound image on basis of only two signals: sound pressure at each of the eardrums. On its way to the two ears, a sound wave undergoes a filtering caused by diffractions around the head and body of the listener. The filtering is dependent on direction to the sound source, and may include a delay between the two ears. The hearing is able to "recognize" which filtering a sound wave has been exposed to, and thus determine the direction of sound incidence.

In binaural auralization, the filtering which in the free field is carried out by the head and body, is done electronically. For each sound wave being simulated, the sound should be sent through two filters, corresponding to the transmission to each of the two ears. This filtering can be described by the *Head-related Impulse Responses* (HIRs) $h_{left}(t)$ and $h_{right}(t)$. Head-related impulse responses are time domain representations of Head-related Transfer Functions (HTFs) - and are of course dependent on the direction of sound incidence. If the incident sound signal is given in time as y(t), then the signals $z_{left}(t)$ and $z_{right}(t)$, which should be found in the two ears can be found by convolution:

$$\begin{aligned} z_{left}(t) &= h_{left}(t) * y(t) \\ z_{right}(t) &= h_{right}(t) * y(t) \end{aligned} \qquad (1)$$

A detailed description of the binaural auralization process is given in [1].

Binaural auralization systems are attractive, because the reproduction is carried out by means of headphones. Sound examples can be recorded on traditional recorders, and they can be brought anywhere for demonstration.

The technique requires a detailed knowledge of HTFs and HIRs. Such data have been collected in our laboratory for 40 human subjects [2] for several purposes. Apart from our interest in binaural auralization, we have interest in design and evaluation of artificial heads for the binaural recording technique. For the same reason, data for a number of artificial heads were collected [3], which are also applicable for auralization. Since the characteristics of the headphone used is crucial for the correct reproduction, data for several commercial headphones were collected in a previous study [4].

2. Methods

The methods and definitions used are thoroughly described in [2], and they will only be summarized in this presentation.

Crucial for the character and quality of HTFs and HIRs are the choice of reference point (microphone placement). It was the purpose of a previous study to divide the free field sound transmission into two parts, a directional dependent part that creates all directional cues, and a part that is independent of direction. A model of the sound transmission from a source in the free field to the ear canal was derived [1], and verified [5].

The directional dependent part of the model consists of the sound transmission from the free field to the Thevenin sound pressure at the entrance to the ear canal. This pressure does not normally exist physically, but if the ear canal is blocked, for example with an earplug placed with its outer end flush with the ear canal entrance, the Thevenin pressure is found outside the earplug.

It was chosen to use the entrance to the blocked ear canal as reference point, because the Thevenin sound pressure contains all the directional dependent information, and it is not influenced by inter-individual differences in the subject's ear canal.

The free field sound pressure at the head center position - but with the listener absent - is used for reference. The HTF and HIR are thus defined as:

$$\text{HTF} = \frac{\textit{sound pressure at the entrance to the blocked ear canal}}{\textit{sound pressure at center position of head}} \qquad (2)$$

$$\text{HIR} = \textit{Fourier}^{-1}\{\ \text{HTF}\ \} \qquad (3)$$

The HIR is the impulse response for the sound transmission from the reference point to the measuring point, and is therefore non-causal for directions where the ear is closer to the sound source than the middle of the head.

A microphone technique, with a miniature microphone mounted in an earplug, was developed for the purpose of recording the sound pressure at the entrance to the blocked ear canal.

Measurements were carried out on subjects standing in an anechoic chamber. 8 loudspeakers placed in an arc with a radius of 2 meter and an angular distance of 22½° were used. Subjects were rotated in steps of 22½°, to yield measurements from 97 different directions of sound incidence, covering the whole sphere.

Impulse responses were measured using Maximum Length Sequences. Two general purpose measuring systems, known as MLSSA, were coupled in a master-slave configuration with a custom designed synchronization unit, allowing sample synchronous measurements for both ears.

3. Results

A few examples of the extensive data material is given in the following.

Figure 1 is an example of HTF and HIR shown for one subject with soun coming from the left side. As expected, the signal at the right ear is attenuated compared to the left ear, especially at high frequencies. It is also seen that the impulse response is non-causal for the left ear, because this ear is closer to the sound source than the middle of the head. The interaural time difference is approximately 600 µs.

The inter-individual variation in the HTFs and HIRs is seen in Figure 2 and Figure 3. In Figure 2 the HTFs for both ears of the 40 subjects are shown for sound incidence in the horizontal plane, 22½° left of frontal incidence. In Figure 3 the corresponding HIRs are shown, given a time offset so that they all start at the same time, and the time axis is thus relative. Although the HTFs and HIRs vary from subject to subject, there is a common general structure in both frequency and time domain.

For most auralization systems, it is desirable to minimize the length of the HIRs. It is difficult to set an objective criteria to determine the length of the responses. A subjective judgement of our data gives a maximum length of 1,5 ms, measured from the beginning of the responses.

4. Summary

Presently, we have determined HTFs and HIRs for 40 human subjects and several artificial heads. Our work will proceed with psychoacoustic experiments, for evaluation of the influence of the inter-individual variations. Measurements will be carried out to develop and verify interpolation procedures, and implementation of a binaural auralization system. Effort has been taken to design a standard information interface, between sound transmission programs and auralization systems [6], so that the auralization system can be used with a variety of sound transmission programs.

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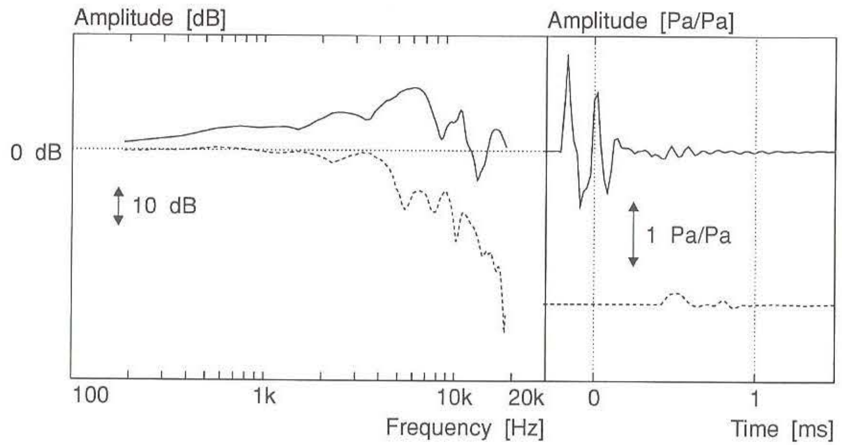

Figure 1. Examples of HTF and HIR shown for one subject for sound coming from the left side. Both ears are shown, dashed line is right ear.

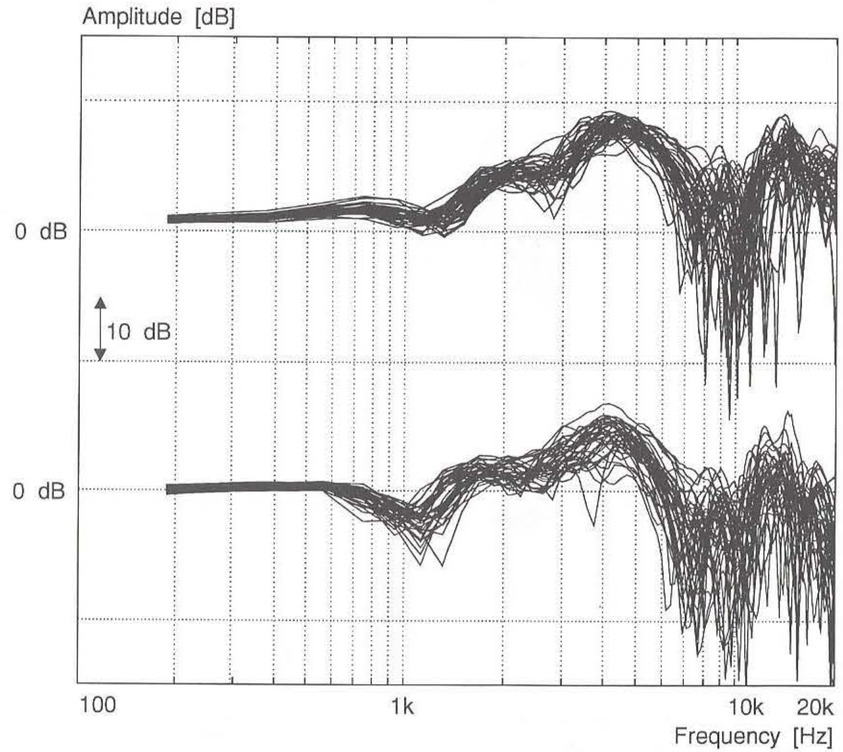

Figure 2. HTFs for 40 human subjects, upper curves left ear and lower curves right ear. Sound incidence in the horizontal plane, 22½° left of frontal incidence.

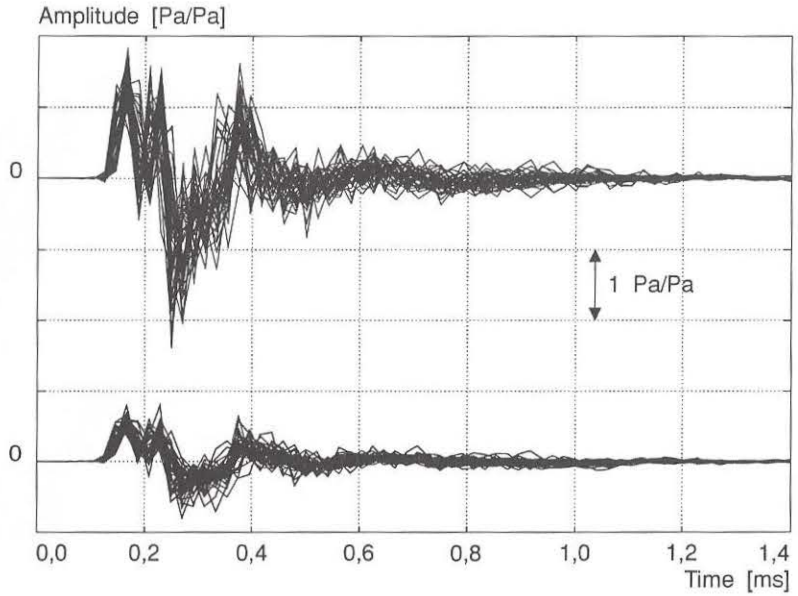

Figure 3. HIRs overlayed for 40 human subjects, upper curves left ear and lower curves right ear. Sound incidence in the horizontal plane, 22½° left of frontal incidence. Note a time offset has been applied so that they all start at the same time, and the time axis is thus relative.