APPLICATION NOTE

About this document

Content

This document is the first of three application notes on spatial hearing and binaural measurement technology. The first chapter explains the different mechanisms used by the human hearing to localize a noise source. The second chapter describes the human head-related transfer function.

Target group

This document is intended for acousticians who want to learn more about binaural signal processing, spatial hearing, and sound source localization with human hearing.

Questions?

Do you have any questions? Your feedback is appreciated!
For questions on the content of this document: Imke.Hauswirth@head-acoustics.com
For technical questions on our products: SVP-Support@head-acoustics.com

Spatial hearing

1. Binaural signal processing

Introduction

The human sense of hearing can identify the origin of a noise source, separate noise sources coming from different directions, and partially suppress disturbing noises. This is primarily possible because humans hear with two ears.

Hearing with two ears is also referred to as binaural hearing (composed of the two Latin words „bi“ for two and „auris“ for ear). In binaural hearing, the human sense of hearing evaluates the two ear signals and forms an auditory event from them. The characteristics of these signals provide the auditory system with both information on the actual sound and information needed to localize the sound source, i.e., to determine its direction and distance.

Interaural differences

Depending on the position of the sound source, the signals reaching the two ears of a person may differ. The differences between the ears are also called interaural differences. They are caused by the following:

ITD

Interaural Time Differences (ITD) resulting from different path lengths the sound needs to propagate if the sound source is not exactly in the median plane (see page 4). The different path lengths cause time delays when the sound arrives at the left or right ear. See example in Figure 1: sound from the right reaches the right ear earlier than the left ear.

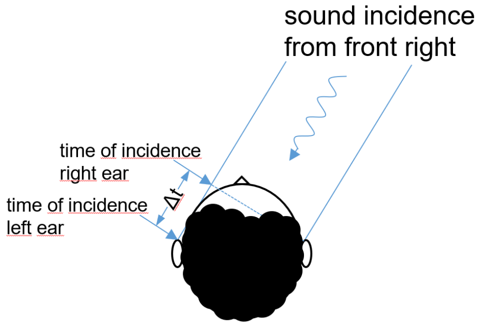

Figure 1: *Interaural Time Differences between the right and the left ear*

ILD

Interaural Level Differences (ILD) resulting from the acoustic shadowing of sound by the head. Due to the acoustic shadowing, the sound level is slightly lower at the ear facing away from the sound source. See example in Figure 2: sound from the right has a higher level at the right ear than at the left ear.

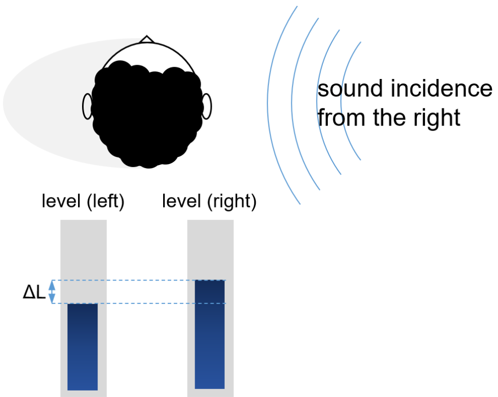

Figure 2: *Level Difference between the right and the left ear*

Sound source localization

The position of a sound source can be determined in all spatial directions. This means that the listener can determine whether the sound source is to his right or left, in front or behind, and also whether the sound source is above or below his head. To determine the lateral direction of incidence (from the left, from the right), the human sense of hearing analyzes both the Interaural Time Differences and the Interaural Level Differences. Even though these differences are not consciously perceived, the brain is able to deduce a direction.

Spectral differences

For certain directions of sound incidence, no interaural differences occur. For example, the sound of a sound source located directly in front of a person arrives at the left and the right ear at the same time. Nevertheless, even in these situations, the direction of sound incidence can be determined. The distinction above/below or front/back is made possible by the direction-dependent spectral filtering of the sound by the outer ear. Depending on the direction of incidence, the incident signal is filtered differently, i.e., the spectrum of the signal is modified by diffraction and reflection of the incident sound waves at the upper body, shoulders, head and auricle (see next chapter). By assigning specific distortions to certain directions, these spectral differences can be interpreted as direction by the brain. Spectral differences are not perceived consciously but are translated subconsciously by the brain into information on the place of origin of the sound source. However, the accuracy of this localization is lower than that based on the evaluation of the interaural differences.

Noise cancellation

However, the binaural signal processes not only enable localization. With the aid of the two ear signals, the human sense of hearing is also able to select individual sounds from a mixture of signals, e.g., to improve speech intelligibility in noise-filled environments. At a party, for example, it is possible to concentrate on a particular conversation partner despite the many different sound sources, and to ignore other sounds (so-called cocktail party effect). Other noises can be suppressed (binaural noise cancellation of up to 15 dB is possible).

Direct sound and reflected sound

In addition, the relationship between direct sound and reflected sound is evaluated. If a sound signal arrives with time delays from different directions due to reflections, only the direction of the sound signal that arrived first is perceived (law of the first wavefront or precedence effect). This means that even if the sound in a room with a lot of reverberation is reflected by the walls and windows and thus arrives at the listener from all sides (see Figure 4), the listener can determine the location of the original sound source.

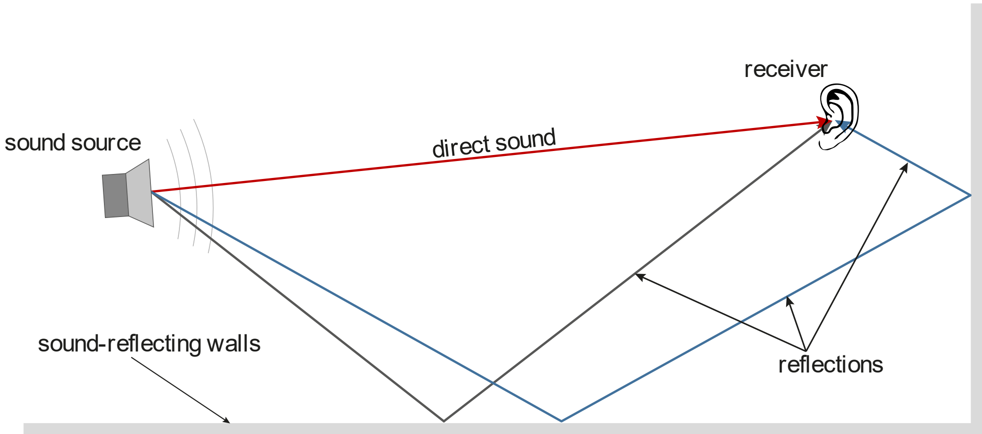

Figure 3: Direct sound and reflections

2. Head-related transfer function

Summary

Before reaching the eardrum, the sound is tonally modified (filtered) by the human body. Acoustically relevant body parts are the upper body, shoulders, head, auricle (also called pinna) and ear canal. The changes depend on the direction from which the sound arrives. They can be measured by microphones within a test person's ear canal and displayed as a head-related transfer function. Each body and ear being individually shaped, the head-related transfer function also differs from one person to another.

Head-related coordinate system

Head-related coordinate system

In the head-related coordinate system, the **median plane** is perpendicular to the ear canal axis, which is the connecting line between the two ears. The **horizontal plane** is on the ear canal axis, parallel to the ground and perpendicular to the median plane. The deflection of a sound source in the horizontal plane is described by the horizontal **horizontal sound incidence angle** φ (also called azimuth angle). The horizontal sound incidence angle is positive for clockwise deflections.

An elevation of the sound source from the horizontal plane is described by the **vertical sound incidence angle** δ (also called elevation angle). The vertical sound incidence angle is positive for upward deflections. The location of a sound source relative to the origin of the head-related coordinate system can be defined by the following information:

- distance r
- horizontal sound incidence angle φ
- vertical sound incidence angle δ

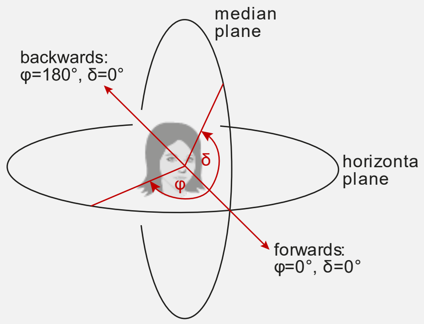

Figure 1: Head-related coordinate system

Direction-dependent filtering

The outer ear[1] imprints a significant pattern on the sound signals depending on the direction of incidence. It is thus a direction-dependent filter that changes the sound pressure level as a function of the sound incidence angle and frequency by +15 dB to –30 dB.

HRTF

The head-related transfer function (HRTF) shows the sound pressure at a reference point in the presence of the outer ear in relation to the sound pressure in the undisturbed sound field. The head-related transfer function is always specified in relation to a specific sound incidence direction (e.g., sound incidence directly from the front at the level of the ear canal). For this reason, there are many different head-related transfer functions for each person. The head-related transfer functions can be measured in an anechoic room using a measurement microphone placed in the ear canal of a test subject. The measurement also requires a sound source located at a defined position (relative to the test subject).

[1] In the following, the term „outer ear" refers to a summary of all acoustically effective parameters consisting of the upper body, shoulders, head, auricle and ear canal.

Example of a head-related transfer function

Figure 5 shows examples of measured head-related transfer functions of an individual person. Frequency is plotted on the x-axis and sound pressure is plotted on the y-axis. The diagram shows four curves representing the frequency-dependent head-related transfer function of the left ear of a test subject for four different sound incidence angles φ in the horizontal plane:

- φ = 0°: sound incidence from the front
- φ = -90°: sound incidence from the left
- φ = 180°: sound incidence from behind
- φ = 90°: sound incidence from the right

The curves shown differ significantly, i.e., the sound is attenuated or amplified to different extents by the outer ear depending on the direction of sound incidence. The higher the frequency, the greater the changes.

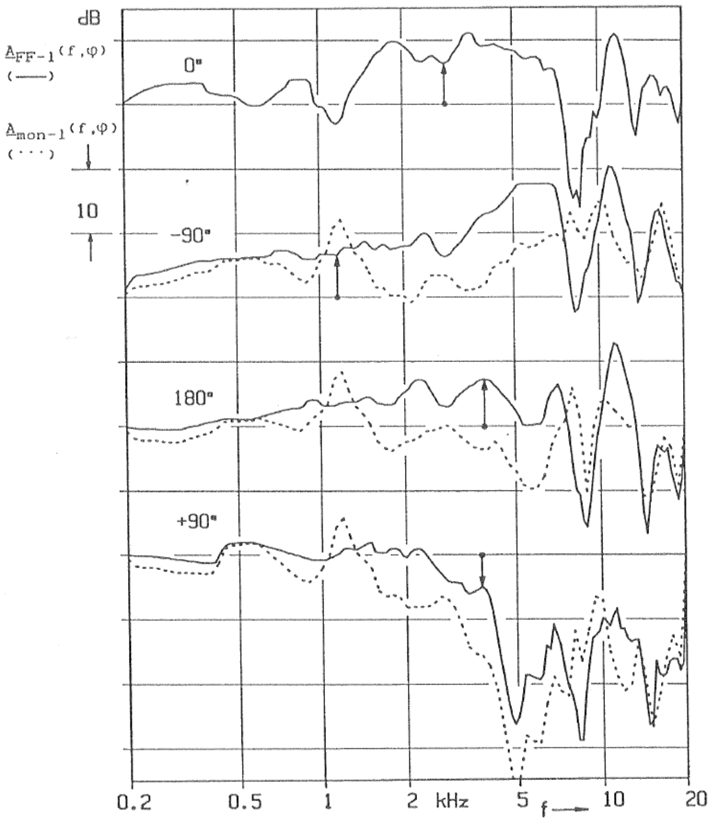

Figure 2: Measured head-related transfer function (solid line: free field, dashed line: monaural transfer function) of a test subject's left ear for the four major directions of incidence in the horizonal plane (Genuit: "Ein Modell zur Beschreibung von Außenohrübertragungseigenschaften" ["A model for describing head-related transfer properties"], dissertation, 1984)

Influence of the human geometry

The transfer function of the human outer ear is functionally related to the outer geometry of human beings. It is determined by reflections and diffractions at the upper body, the shoulders, the head, and the auricle as well as by resonances in the lower cavum conchae (see Figure 6) and in the ear canal.

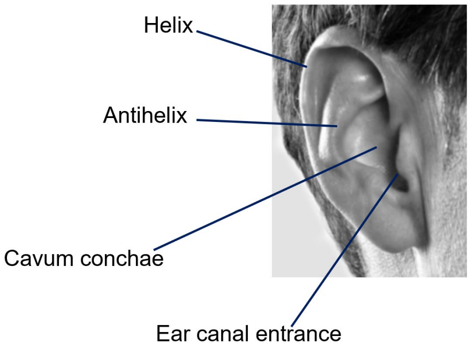

Figure 3: Structure of the auricle

Every ear and body being individually shaped, the course of the head-related transfer function varies from one person to another. For this reason, there may even be differences in the head-related transfer functions of a person's left and right ear.

Acoustically relevant parts of the body

The following is a list of qualitative changes caused by the various acoustically relevant parts of the body:

- The combination of **upper body and shoulders** influences the directional and distance hearing, especially in the median plane. The influence arises from the superposition of the directly incident sound wave in the ear canal entrance by a sound wave reflected from the upper body or shoulders and is particularly clear in the low-frequency range.
- The **head** and, above all, the **position of the ear canal entrance** on the head significantly determine the directional characteristic when sound is incident from the horizontal plane. This is caused by reflections as well as diffraction and shadowing properties. In the case of sound incidence from the median plane, however, the head exerts a negligible influence on the head-related transfer function.
- The **helix** determines the directional characteristic for higher frequencies (>3 kHz) in the horizontal plane.
- The reflection at the **antihelix** influences the directional characteristic in the spectral range above 6 kHz in the median plane.
- The spectrum of the incident sound is also influenced by anatomical factors that are identical for all directions of sound incidence and thus are independent of direction. These factors include the **ear canal** and the **cavum conchae**. The resonance properties of both the ear canal and the cavum conchae influence the structure of the head-related transfer function at higher frequencies.

➞ *Proceed to the second application note on binaural recording technology*