MEASUREMENTS OF HEAD-RELATED TRANSFER FUNCTIONS (HTFs)
ON 40 HUMAN SUBJECTS

Kim Alan Larsen, Jørn Vagn Hundeøj
Perceptive Acoustics A/S
Fredrik Bajersvej 7
DK-9220 Aalborg Ø
Denmark

Dorte Hammershøi, Henrik Møller
Institute for Electronic Systems, Aalborg University
Fredrik Bajersvej 7
DK-9220 Aalborg Ø
Denmark

Introduction

A Head-related Transfer Function (HTF) is a transfer function that - for a certain angle of incidence - describes the sound transmission from a sound source in a free field to a point in the ear canal of a human subject. Knowledge of HTFs from a large population is essential for 1) design and evaluation of artificial heads for binaural recordings, 2) computer synthesis of binaural signals (virtual environment applications and auralization in room modelling systems), and 3) determining diffuse field to free field corrections of hearing thresholds and equal loudness contours.

The major interest in this investigation is the use in binaural recording technique. This technique is based on the following idea. The input to the hearing consists of two signals: sound pressures at each of the eardrums. If these are recorded in the ears of a listener and reproduced exactly as they were (usually through headphones), then the complete auditive experience is assumed to be reproduced, including timbre and spatial aspects. During recording the listener is normally replaced by an artificial head that replicates the acoustical properties of an average human head.

A thorough description of the HTF measurements is given in Hammershøi et al. [1] whereas this paper only describes the most important aspects. Among these is the choice of the point in the ear canal where the recording is made - the reference point. In this investigation the choice of reference point is based on a model described by Møller [2] and verified by Hammershøi & Møller [3]. The model is seen in Figure 1.
The sound transmission is divided into a part that creates all directional cues, and a part that is independent of direction. The directional dependent part consists of the transformation from the free field to the Thevenin sound pressure $p_2$. $p_2$ does not exist in the listening situation but if an earplug is placed with its outer end flush with the ear canal entrance $p_2$ can be found outside the earplug.

In the non-directional part $p_2$ is the sound source, and the source impedance is the radiation impedance seen from the ear canal, $Z_{\text{radiation}}$. The sound pressure at the entrance to the open ear canal is denoted $p_3$. The ear canal acts like an acoustical transmission line terminated by the eardrum impedance, $Z_{\text{eardrum}}$, and the sound pressure at the eardrum is denoted $p_4$.

$p_2$, $p_3$ and $p_4$ can all be used for binaural recordings. However, $p_2$ is the most convenient to use, as it does not require insertion of microphones deeply in the ear canals. Furthermore, $p_2$ includes the directional information and in addition avoids individual differences caused by the ear canal. With a reference sound pressure $p_1$ defined as the sound pressure at the position in the middle of the subject’s head but with the subject absent, the choice of HTF is therefore:

$$HTF = \frac{P_2}{P_1} = \frac{\text{sound pressure at entrance to the blocked ear canal}}{\text{sound pressure in the middle of the head, without the listener}}$$

Møller showed elsewhere [2] how the correct total sound transmission in a binaural system is especially simple to achieve, if the reproduction involves a pressure division similar to the one seen between $Z_{\text{ear canal}}$ and $Z_{\text{radiation}}$ during recording. To evaluate this the pressure division $[P_3/P_2]$, is measured, yet only for a few source directions assuming directional independence. In Møller et al. [4] these data are used for comparison with measurements of the pressure division in the playback situation.

**Method**

The microphone techniques used for measuring $p_2$ and $p_3$ are sketched in Figure 2.
The left sketch shows measurement of $p_2$ using a miniature microphone placed in a hole in an earplug. The end of the earplug and the microphone were mounted flush with the ear canal entrance.

A probe microphone was used for $p_3$ measurements. The right sketch above shows the metal probe tip extended by a small, individually fitted, piece of flexible plastic tube. The microphone was attached to the subject's pinna with a metal strap and fixed along the subject's neck with tape to avoid displacements.

The measurements were made in an anechoic chamber, where 8 loudspeakers were fixed on an arc of a circle in 22.5° steps beginning from directly above the subject. The subject stood in a natural upright position on a rotatable platform with a backrest. The platform was individually adjusted in height and it could be fixed at the desired azimuth in steps of 22.5° (for elevation ±67.5° the stepsize was 45°). In this way the imaginary point right between the subject's ears was in the center of a sphere with radius 2 m. HTFs were determined for 97 source directions, and the pressure division was determined for 5 directions: front, back, left, right and above. Figure 3 shows the setup.

To control the horizontal position and orientation, the subject had a paper marker on top of her/his head. This marker was observed through a camera placed right above the subject and shown on a moveable monitor as seen in Figure 3. The operators had a similar monitoring. If movements were observed during a single measurement, it was discarded and redone.

Sample synchronous measurements of both ears was enabled using two synchronized MLSSA measuring systems which are based on Maximum Length Sequence (MLS) technique. This method is basically noise immune, and combined with averaging the resulting signal to noise ratio is typically 70 dB for measurements with the miniature microphone and 60 dB with the probe microphone. The MLS length used was 4095 points and with 16 pre-averagings at 48 kHz sampling frequency the total time for each single measurement was 1.45 s. During this period the subjects were normally able to stand still.
Figure 3. Free field setup in the anechoic chamber. Note that for phototechnic reasons the monitor is slightly closer to the subject than during measurements.

HTFs and pressure division were determined by Fourier transformation of the impulse responses measured, followed by complex division in the frequency domain. By this division the measuring equipment cancels out. The Head-related Impulse Responses (HIRs $[p_1-p_2]$), often required for computer synthesis of binaural signals, are obtained by inverse Fourier Transformation of the lowpass filtered HTFs.

Results

Measurements were carried out on 40 human subjects, 18 females and 22 males, all with controlled normal hearing.

An example of HTF and HIR for one subject with sound incidence from left is shown in Figure 4. As expected, the signal at the right ear (dashed line) is attenuated compared to the right ear, especially at high frequencies. This is also seen from the HIRs shown to the right. The left HIR is non-causal, because this ear is closer to the source than the measuring point of $p_1$. 
The pressure division is shown in Figure 5. The upper set of curves shows the left ear of one subject with sound from the 5 directions measured. As it is seen the pressure division is similar for all directions and thus direction independent as assumed. The lower set of curves shows the pressure division for 12 subjects with sound from above. A large inter-individual variation is seen from about 8 kHz. $p_3$ will reflect the individual variation in HTF as well as the individual variation in the pressure division. This means that $[P_3/P_1]$ is expected to show larger variation than $[P_2/P_1]$. 

Figure 5. Illustration of the pressure division. Upper set: left ear of one subject, 5 directions. Lower set: left ear of 12 subjects, sound from above.
This is exactly seen from Figure 6, where both $[P_2/P_1]$ and $[P_3/P_1]$ are shown for the left ear of the same 12 subjects. Variations for $[P_2/P_1]$ are seen but they are smaller and they appear at higher frequencies than for $[P_3/P_1]$.

![Figure 6](image.png)

Figure 6. Upper curves: HTFs for the left ear of 12 subjects, sound from above. Lower curves: $[P_3/P_1]$ for the left ear of the same subjects and same sound incidence direction.

**Conclusion**

A suitable technique for HTF measurements is developed. HTF data are obtained, sample synchronously measured on both ears of 40 human subjects, for 97 source directions covering a whole sphere. The reference point for the measurements is at the entrance to the blocked ear canal. Data indicate that this is a suitable point for binaural recordings as inter-individual variation caused by differences in the ear canal is avoided. This means that it is unnecessary to design artificial heads with ear canals.

**References**