1

System for High Speed Measurement of Head-Related Transfer Function

Andrzej B. Dobrucki, Przemysław Plaskota and Piotr Pruchnicki
Wroclaw University of Technology
Poland

1. Introduction

Recently surround-sound systems have become popular. The effect of "surrounding" the listener in sound is achieved by employing acoustic phenomena which influence localizing the source of the sound. Similarly to stereophony system the time, volume and phase interrelations in signals coming from each sound source are taken into account. Additionally the influence of the acoustic system created by the pinna, head and torso on the frequency characteristic of the sound is taken into consideration. This influence is described by the Head-Related Transfer Function (HRTF). The knowledge of the human physical body characteristics' influence on the perception of the sound source location in space is being more and more frequently applied to building sound systems.

So far the best method of including the influence of the human body on the frequency characteristic of the sound is the HRTF measurement for different locations of the sound in relation to the listener. Then the achieved measurement results are used for creating a database meant for the sound reproduction. Creating a proper HRTF database is a difficult problem – every human exhibits individual body characteristics therefore it is not possible to create one universal database for all the listeners. For this reason applying the knowledge of the human body influence on the frequency characteristic of the sound is impeded. In order to include these parameters it is necessary to conduct all these laborious measurements for each individual.

2. Head-Related Transfer Function

The HRTF is a representation of the influence of the acoustic system formed by the pinna, head and human torso on the deformation of the acoustic signal spectrum reaching the listener's ear. The head's shape and tissue structure have a bearing on acoustic signal spectrum distortion (Batteau, 1967; Blauert, 1997; Hartmann, 1999; Moore, 1997). The changes in the spectrum enable the listener is able to more accurately localize the sound source in the space which surrounds her/him. In case of headphone listening the influence of the acoustic system formed by the pinna, head and human torso is eliminated and the acoustic signal received by the listener is unnatural – the listener localizes the sound source inside her/his head. Through the use of HRTF measurement results the signal can be so deformed that the listener subjectively identifies the spatial properties of the sound whereby the location of the sound source in the space surrounding the listener is reproduced (Hartmann & Wittenberg, 1996; Horbach et al., 1999; Hen et al., 2008, Plaskota & Kin, 2002; Plaskota et al. 2003). Since there are many sound source locations in the space surrounding the listener many HRTFs are needed to accurately reproduce the location of the sound source in this space.

The function describing the direction-dependent acoustic filtering of sounds in a free field by the head, torso and pinna is called HRTF. Although it is obvious that the linear dependence between Interaural Time Difference (ITD), Interaural Level Difference (ILD) and the perceived location in space needs to be predicted, it is less obvious how the spectral structure and the location in space can be mathematically interrelated (Cheng & Wakefield, 2001). The first step towards understanding the significance of the signal spectrum in directional hearing was an attempt at physical modeling and empirical measurement followed by computer simulations of the ear's frequency response depending on the direction. The measured frequency response of the ear is subject to further analysis.

Formally a single HRTF function is defined as an individual right and left ear frequency response measured in a given point of the middle ear canal. The measurement is conducted in a far-field of the source placed in a free-field. Typical HRTFs are measured for both ears in a particular distance from the head of the listener for several different points in space. Thus the transmittance function related to the head depends on the azimuth angle, elevation angle and the frequency, and apart from that it has a different value for the left ear (L) and for the right one (R): $HRTF_{L,R}(\theta,\phi,f)$. The HRTF's time-domain equivalent is the Head-Related Impulse Response (HRIR).

In fact a measured transmittance function includes also a certain constant factor. This factor characterizes the measurement conditions – the measurement chamber characteristic and the measurement path. This is a reference characteristic, and the value of this parameter is determined by measuring the impulse response without the presence of the measured subject. Therefore by additionally taking into consideration the reference characteristic the result of the transmittance function can be presented as

$$h_{L,R}(\theta,\phi,t) = s(t) * c(t) * HRIR_{L,R}(\theta,\phi,t), \tag{1}$$

where: $h_{L,R}(\theta,\phi,t)$ – impulse response by the entrance to the ear canal,

$s(t)$ – measurement signal,

$c(t)$ – impulse response of the measurement system,

$HRIR_{L,R}(\theta,\phi,t)$ – impulse response related to the head.

In some conditions it can be assumed that $c(t)$ is constant and not influenced by the measurement point's position in space. Then the $c(t)$ value is a mean measurement result for several different azimuth angles and elevation angles. But if the measurement chamber does not fulfill the conditions of the anechoic chamber or in the room are present some elements which cause generating undesirable reflections, the $c(t)$ factor is influenced not only by the time, but also by the position of the measurement point in the space surrounding the listener, and it differs for the left and right ear: $c_{L,R}(\theta,\phi,t)$. In order to increase the accuracy of the measurement the $c_{L,R}(\theta,\phi,t)$ value can be measured for every measurement point and then these values can be applied while processing the results of the measurement.

Formula (1) can be also written in the frequency domain:

$$H_{L,R}(\theta,\phi,f) = S(f)\,C(f)\,HRTF_{L,R}(\theta,\phi,f)\,. \tag{2}$$

Further the HRTF value is calculated according to the following interrelations:

$$\left|HRTF_{L,R}(\theta,\phi,f)\right| = \frac{\left|H_{L,R}(\theta,\phi,f)\right|}{\left|S(f)\right|\left|C(f)\right|}, \tag{3}$$

$$\arg HRTF_{L,R}(\theta,\phi,f) = \arg H_{L,R}(\theta,\phi,f) - \arg S(f) - \arg C(f), \tag{4}$$

$$HRTF_{L,R}(\theta,\phi,f) = \left|HRTF_{L,R}(\theta,\phi,f)\right| \exp\left[j \arg HRTF_{L,R}(\theta,\phi,f)\right], \tag{5}$$

and the HRIR value:

$$HRIR_{L,R}(\theta,\phi,t) = \mathcal{F}^{-1}\left[HRTF_{L,R}(\theta,\phi,t)\right], \tag{6}$$

where: $\mathcal{F}^{-1}$ – inverse Fourier transform.

It has been empirically proven that HRTFs are minimum-phase, therefore minimum-phase FIR filters are used to simplify the HRTF description interrelated (Cheng & Wakefield, 2001). Firstly, minimum-phase requirement allows to explicitly define the phase on the basis of the amplitude response. This is a consequence of the fact that the logarithm of the amplitude response and phase response in a casual system are related by the Hilbert transform. Secondly, the minimum-phase requirement allows to isolate the information about the ITD from the FIR characteristic describing the HRTF. When the minimum-phase filter has the minimum group-delay property and the minimum energy delay, most of the energy is accumulated at the beginning of the impulse response and the appropriate for the left and right ears minimum-phase HRTFs have zero delay.

In order to achieve the characteristic of the hearing impression related to a particular point in space there are three values to be measured: the left ear amplitude response, right ear amplitude response, and ITD. The characteristics of the filter include both the ITD and ILD information: time differences are included in the phase characteristic of the filter, whereas the level differences correspond with the total power of the signal transmitted through the filter interrelated (Cheng & Wakefield, 2001). The interaural time difference can be calculated by many various measurement methods: as a result of measurement with the participation of people, a result of the dummy-head measurement, simulations performed on the spherical and elliptical models, calculation based on Woodsworth-Slosberg formula (Minnaar et al., 2000; Weinrich, 1992).

Conducting the measurements for a big number of people is a complicated issue (Møller et al., 1995; Møller et al., 1992). The head-related transmittance functions show a great individual variability: the discrepancy between the measurement results reaches about 3 dB for the frequency to 1 kHz, 5 dB for the frequency to 8 kHz and about 10 dB for the higher frequencies. The first reason is an obvious dependence on individual physical body differences. Other reason are the measurement errors which are hard to be calculated in the final results – e.g. the error resulting from the differences in positioning the head in relation to the sound source or the differences in placing the measurement microphone in the ear canal. The individual HRTF variable is lower for the measurements conducted with a closed ear canal than for the measurements with an open ear canal.

3. HRTF measurement requirements

In general, the HRTF parameters are measured in anechoic chamber, e.g. Møller et al., 1995. During measurement it must be possible to place the sound source in a distance of minimum 1 m from the middle of the listener's head in each direction. Especially the direction above the listener's head is important because of chamber size. Taking into account the listener's height and minimal distance between the loudspeaker and the human head it can be assumed that the minimal height of the measurement room is ca. 3 m. The intermediate solution is to place the listener sitting on a chair, although in this case reflections from knees can be observed (Møller et al., 1996). The reflections from measurement device placed into the measurement room have more significant influence on the result of the measurement in comparison with the reflections from body parts (Møller et al., 1995), so these last can be omitted.

The HRTF measurement can be provided in ordinary room, e.g. auditorium (Bovbjerg et al., 2000; Møller et al., 1996). Measurements in non-anechoic chamber are convenient because of availability of this kind of room. Usually, when measurements with people go on a few days, there is a necessity to leave measurement devices in a fixed setup for long time. To make measurements in an ordinary room a noise-gate must be used for eliminating the reverberation signals (Plaskota & Dobrucki, 2004).

In the measurement room it is necessary to place the video devices for controlling and eventually recording the head position and head movements. Head movements are a significant source of errors. Verifying a head position allows to increase the measurement accuracy (Algazi et al., 1999; Gardner & Martin, 1995).

For measurements in many points in space around the listener it is needed to use many sound sources in fixed positions or use movable set of loudspeakers. Generally, it is possible to apply two methods of changing the position of the loudspeaker relatively to the listener's pinna. One of them is a movement of the sound source (one loudspeaker or set of loudspeakers) around the listener's head (Algazi et al, 2001; Bovbjerg et al., 2000; Grassi et al., 2003). The listener can improve measurement's accuracy by a visual control of head position. In the case of changing the listener's position relatively to the loudspeaker set (e.g. by chair rotation) it is needed to use an additional equipment for monitoring the head position (e.g. video camera) (Møller et al., 1995). A convenient situation is when the position of the listener and positions of the loudspeakers are fixed. In this situation very good control of measurement setup is obtained, but the number of measurement points is limited (Møller et al., 1996).

The next important parameter of the measurement system is a placement of measurement microphone in an ear canal. In publications four main positions are considered: a few millimeters over an ear entrance, an ear entrance, a few millimeters under an ear entrance, directly over the tympanic membrane (Pralong & Carlile, 1994). Additionally, the ear entrance closing influence on the measurement result is considered. It was found out that a smaller individual variation is obtained in measurements with closed ear entrance (Møller et al., 1995). It was also determined that the ear canal transfer function is independent of sound source position in the space around the listener (Bovbjerg et al., 2000).

The parameters of electroacoustic transducers have a great influence on the measurement result, especially a frequency response. The frequency responses of microphones are more important than the frequency responses of loudspeakers (Plaskota, 2003). It is suggested to use loudspeakers with a frequency response without large deeps (Møller et al., 1995).

In the studies there are informations available about used signals during the HRTF measurements. One of the applied signals is the Maximum Length Sequence (MLS) (Møller et al., 1995). It is possible to use Golay codes (Algazi et al., 2001), but difficulties in results interpretation are known (Zahorik, 2000). In anechoic chamber, the use of chirp signal is adequate to measurement conditions. It can be supposed that in a non-anechoic chamber the impulse signal is applied. It comes from a necessity of providing good measurement conditions.

4. Measuring system

4.1 Conception of measuring system

The HRTF measuring device is built for a special group of test participants. It is assumed that the measurement will be made for people with severe vision problems (Bujacz & Strumiłło, 2006; Dobrucki et al. 2010). Therefore, the device is designed to reach many demands such as the highest automation of measurements which assures a short measurement time (ca 10 minutes) and offers great ease of manipulation. The participant of the test should feel comfortable during the measurement process and should be given sufficient information on each part of the measurement. To reach these demands, the device is equipped with a bidirectional communication system allowing the participant to report the problem at any time. In addition to voice communication, a visual control of the room is provided. It is possible to monitor the test room using a camera mounted on an arc with loudspeakers.

To provide a short measurement time the HRTFs are measured for both ears simultaneously. The way sound sources are configured significantly shortens this time too. The loudspeakers are mounted on vertically positioned arc (see Fig. 1). It allows to measure the range of vertical angles from -45° to +90° in one chair position. In certain points in the space of the room the measurement is made by switching the measurement signals to subsequent loudspeakers by an electronic switch.

The number of measurement points for elevation angles is adjusted by changing the number and position of the loudspeakers. On the other hand, the number of measurement points for horizontal angles depends on the size of the rotation step of the chair. The rotation of the chair is controlled by a stepper motor which assures high horizontal resolution. Default vertical resolution is 9° in regular sound source positions. Assuming the same horizontal resolution the number of measurement points is 640. The measurement in 16 points for one horizontal angle and simultaneous measurements for both ears allows to conduct the whole measurement in less than 10 minutes. Obviously, the number of measurement points can be modified. Changing the resolution in a vertical plane means changing the position of the loudspeakers. In a horizontal plane, changing the resolution means changing the rotation step of the chair.

Fig. 1. Overview of the HRTF measurement equipment.

The HRTF measurement can be done within the range of frequencies from 200 Hz to 8 kHz. The lowest frequency depends on the test room parameters. The device works in an anechoic chamber, therefore the cut-off frequency of the chamber limits the operational range of the device. The high cut-off frequency of the device is on the one hand confined by the set of loudspeakers, and on the other – by the set of microphones. Miniature microphones used in hearing aids, but with an untypical flat frequency response, are used in the device (Fig. 2). Another factor limiting the high cut-off frequency are the dimensions of microphone fixing elements. For 5-mm tubes the wave phenomena are significant for the frequencies above 10 kHz.

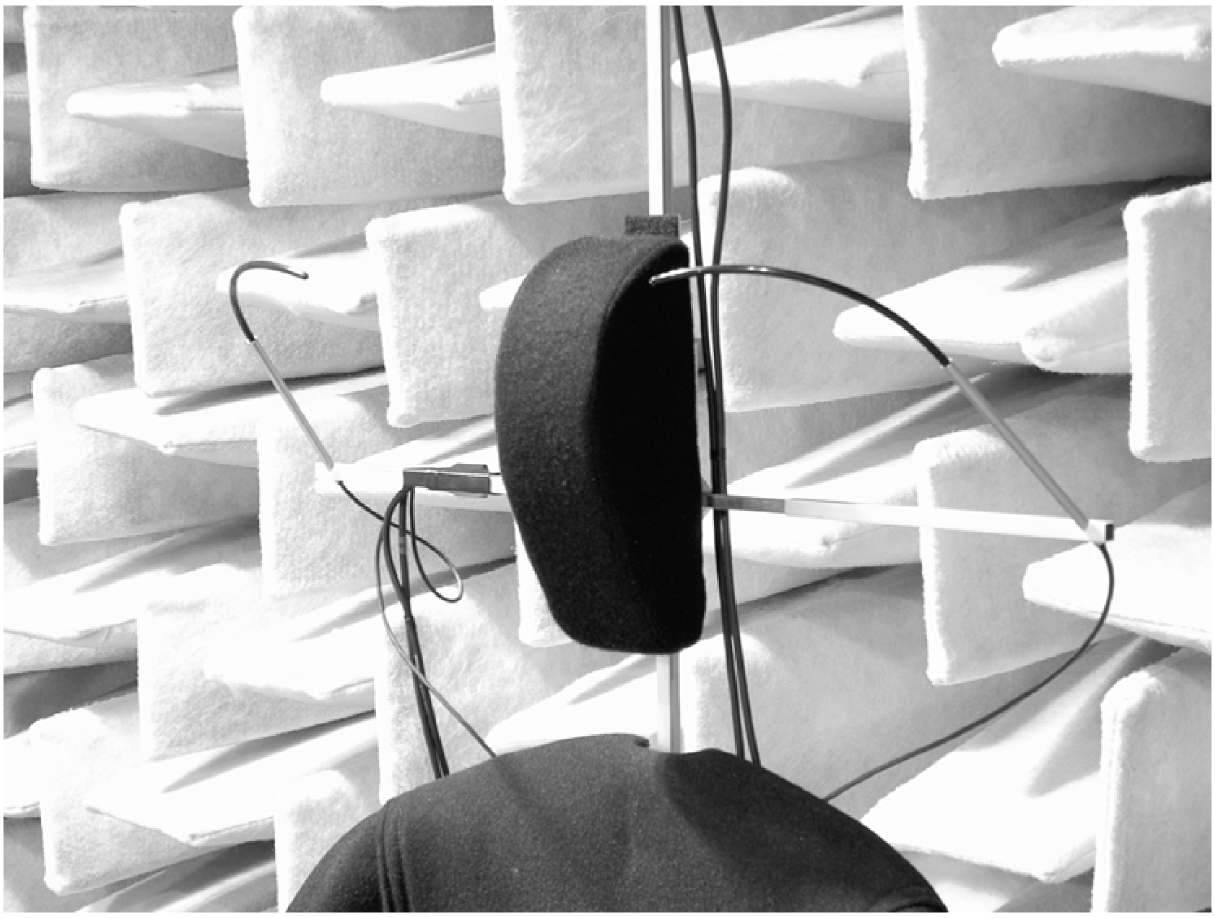


Fig. 2. The scheme of setting the measurement microphones.

The system is operated via portable IBM PC computer to control measurements and data acquisition (Pruchnicki & Plaskota, 2008). The device communicates with the computer through a USB interface. At the same time signals operating the device, measurements signals and camera pictures are transmitted via interface. A special feature of the device is its compact construction and modularity which makes it very easy to assemble or disassemble and convenient to transport.

4.2 Measurement algorithm

The measurement of a single HRTF is accomplished using a transfer method, which is popular in digital measurements systems. A wide spectrum measurement signal is used for stimulation. The system uses the following signals: chirp, MLS, white noise, pink noise, Golay codes. The length of a generated signal can be changed within the range from 128 up to 8192 samples. Sampling frequency is 48 kHz but it is possible to decrease it. The stimulating signal is repeated several times in order to average the answer of the system in the time domain. This operation allows improving the S/N ratio of received responses. There is no need to apply longer measurement signals because, according to other researches, HRTFs may be presented even with such resolution as 100 Hz. On the other hand, responses determined in the system will be used for convolution with real signals and therefore they cannot be too long. Moreover, long measurement signals make the assessment time longer.

The whole measurement procedure is comprised of two parts: the measurement of reference responses and the measurement of regular HRTFs. The measurement of reference responses is made for all measurement spots determined by the system operator. During this procedure microphones, loudspeakers and the whole system work exactly like during any regular measurement. The only difference is that there are no test participants. The HRTF measurement results obtained in the second part are related to reference responses obtained before.

Using a reference response for each measurement point in the space allows limiting many inconvenient effects which decline measurement accuracy (Plaskota & Pruchnicki, 2006). Especially the influence of frequency responses and directivity responses of loudspeakers and microphones is eliminated. The influence of a test room and the reflection from the device elements on measurement results is partly reduced.

The final result of the measurement process are HRIRs (Head Related Impulse Response, that is HRTF's reverse Fourier transform) produced to allow their direct use in convolution with real signals.

4.3 Measurement procedure

The measurement procedure comprises several phases. The first is the system activation and configuration. It involves determining the horizontal and vertical resolutions of measurements. The next step is the selection and fixing of active test loudspeakers position. At this stage the kind of measurement signal and the number of averages should be chosen as well as the calibration of sound level should be carried out.

In the second phase, participant of the test should be properly positioned in the chair, so that the 0° loudspeaker is placed on the ear canal entrance level and the microphones are located at ear canals entrance. The setup of the loudspeakers' arc in relation to the microphones can be monitored using the camera view.

After the test participant measurement is completed, the reference responses are measured. Once the preparation is finished, regular HRTF measurements are carried out according to earlier parameter setups.

In the last phase of the procedure, measurement results are saved in plain text files in the form of the HRIR. Such storing allows access to the test results from any other application at the same time, and is clear to the user.

4.4 System control software

In order to apply the measurement procedure, dedicated software was designed. The modularity of this software, which consists of two basic elements, is its special feature. Figure 3 presents the main window used to control measurements. Via this interface the operator can influence the measurement course and conditions as well as all configuration parameters. Additionally, there is also a test participant communication part.

A separate element of the software is an OCX control which exchanges data between the device and the user interface. Calling certain functions of the control it is possible to steer such parameters as the armchair rotation, the loudspeakers movement or switching.

Applying this solution allows to use the device for purposes not provided by the user interface of the system.

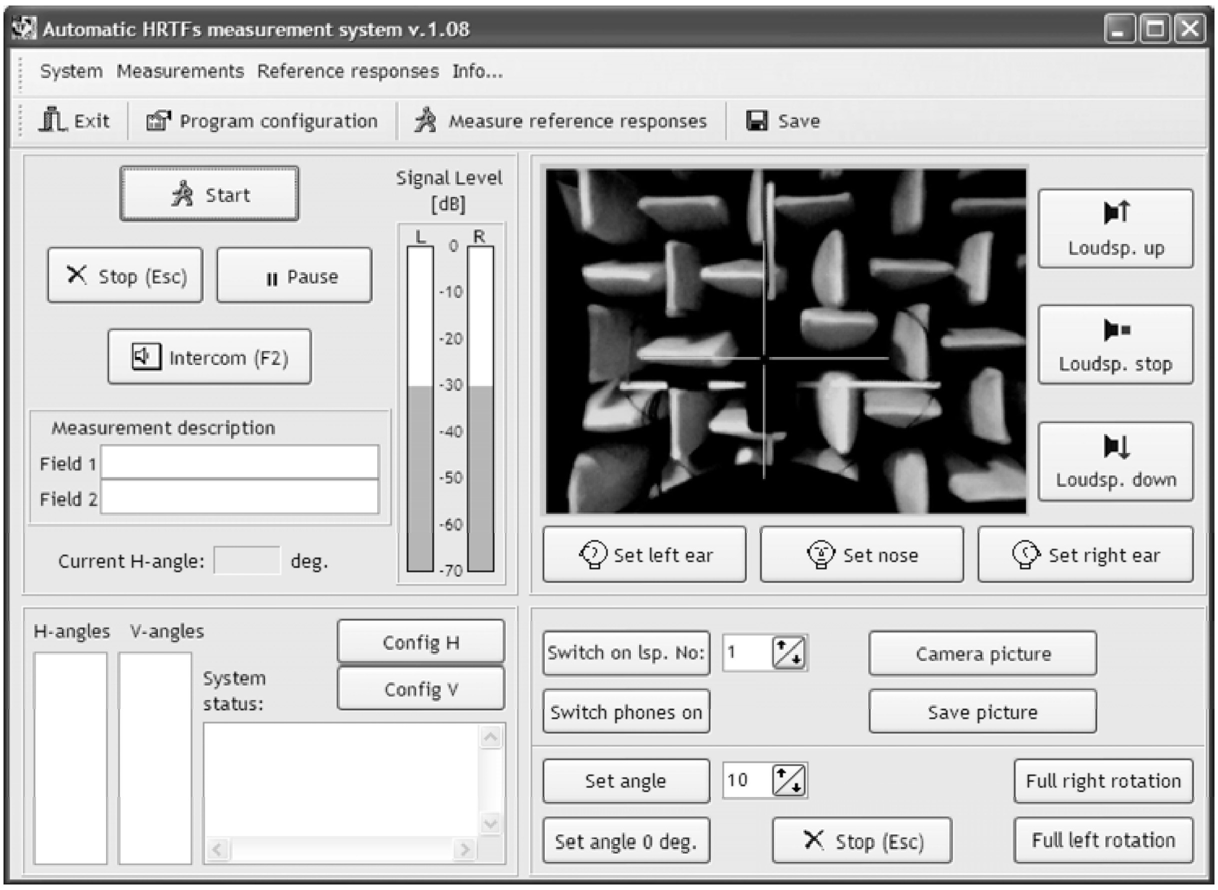


Fig. 3. The main window of the HRTF measurement control software.

4.5 Parameters of the device

The HRTF measuring device has 16 sound sources. The reason for using such number of loudspeakers is the need to conduct tests for many various spots in the listener's surrounding in the shortest time possible. The different positions are found in the following way: the participant in the test turns around his vertical axis while taking a step in defined direction. The distances between the steps define the spatial resolution of the measurement in horizontal dimension. The vertical dimension of spatial resolution is determined by the arrangement of loudspeakers placed on the arc including range of vertical angles between -45° and +90°.

For the precision of the measurement it is important to use a point sound source. The source should produce test signals in the entire operational frequency range of the device. In order to fulfill these conditions two-way car loudspeakers were applied. According to producer data the loudspeakers should operate within a small box. Figure 4 presents an example of amplitude frequency response of the used loudspeakers. The loudspeakers′ operational range of frequency is between 200Hz and 20kHz. It should be noted that the frequency responses are not equalized and differ slightly for each loudspeaker less than 4dB. The applied measurement of reference response in the device for each tested spot neutralizes the influence of measuring set on the results of the tests.

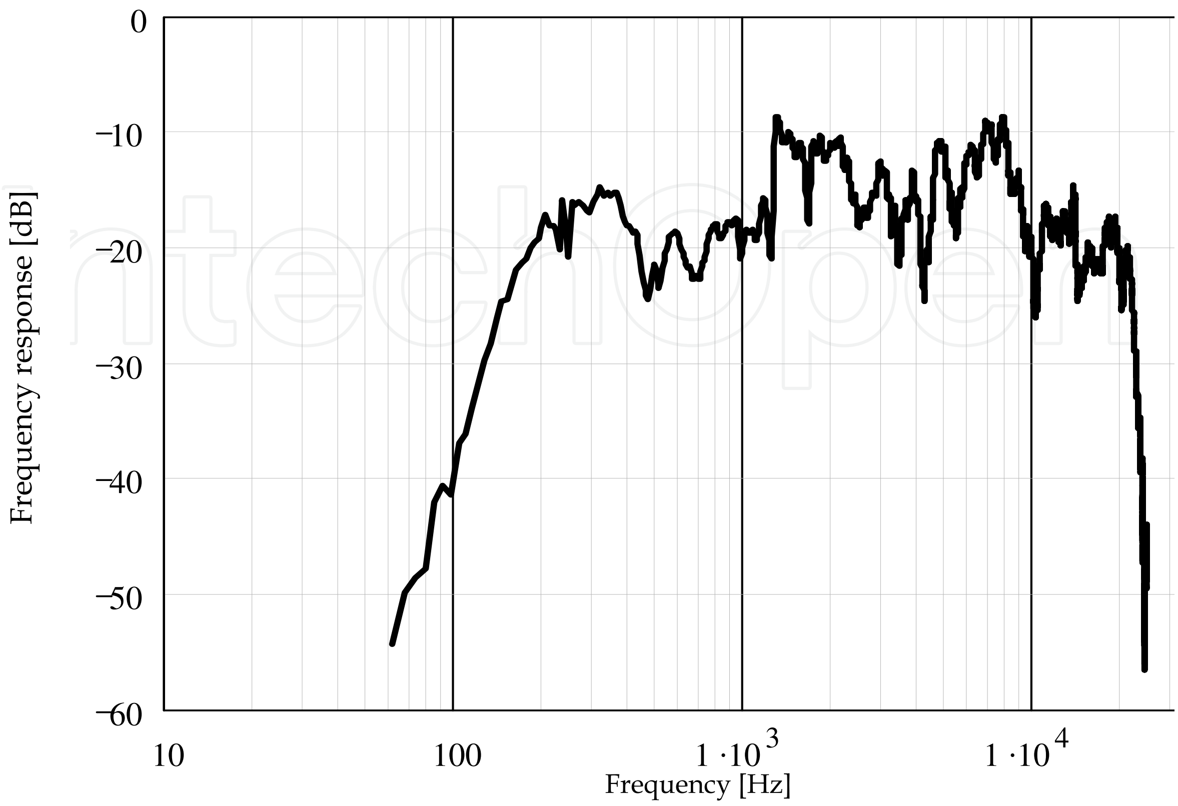


Fig. 4. An example of frequency response of the loudspeaker used in the HRTF measuring device.

The measurement microphones used in the device are the same as those used in hearing aids. It should be underlined that the particular type of microphones has equal frequency response in its entire operational range of ca. 60Hz and 8kHz (Figure 5). It means that these microphones are not commonly used in the hearing problems treatment. The choice of microphones was determined by the importance of the quality of the device and therefore the similarity of frequency responses of each microphone was achieved. The other advantage of this particular type of microphones is their small size. That is indeed a significant feature since it allows reducing the size of the outer cover. This minimizes cover impact on the acoustic field around the head of the test participant.

The operational frequency range of the HRTF measuring device is limited by the lower cut-off frequency of the anechoic chamber in which the tests are conducted. The other factor influencing lower frequency is the operational frequency range of loudspeakers. The lower cut-off frequency within the operational range of the loudspeakers is higher than the value of the cut-off frequency of the anechoic chamber thus the operational frequency range for the entire device starts at around 200Hz.

The upper cut-off frequency limit of the device is determined by the frequency range of the microphones. Hence the upper cut-off frequency is about 8kHz. The other factor carrying impact on operational frequency range of the device is the influence of microphones' covers on the acoustic field around the head of the test participant. The microphones are placed in ca. 5-mm diameter tubes. The wave phenomena for this type of construction elements have a significant impact for 10 kHz frequency and above (Dobrucki, 2006). But that is transversal dimension of applied elements; the length of the microphones cover is more significant dimension in this case and can influence acoustic field within the operational range of the device.

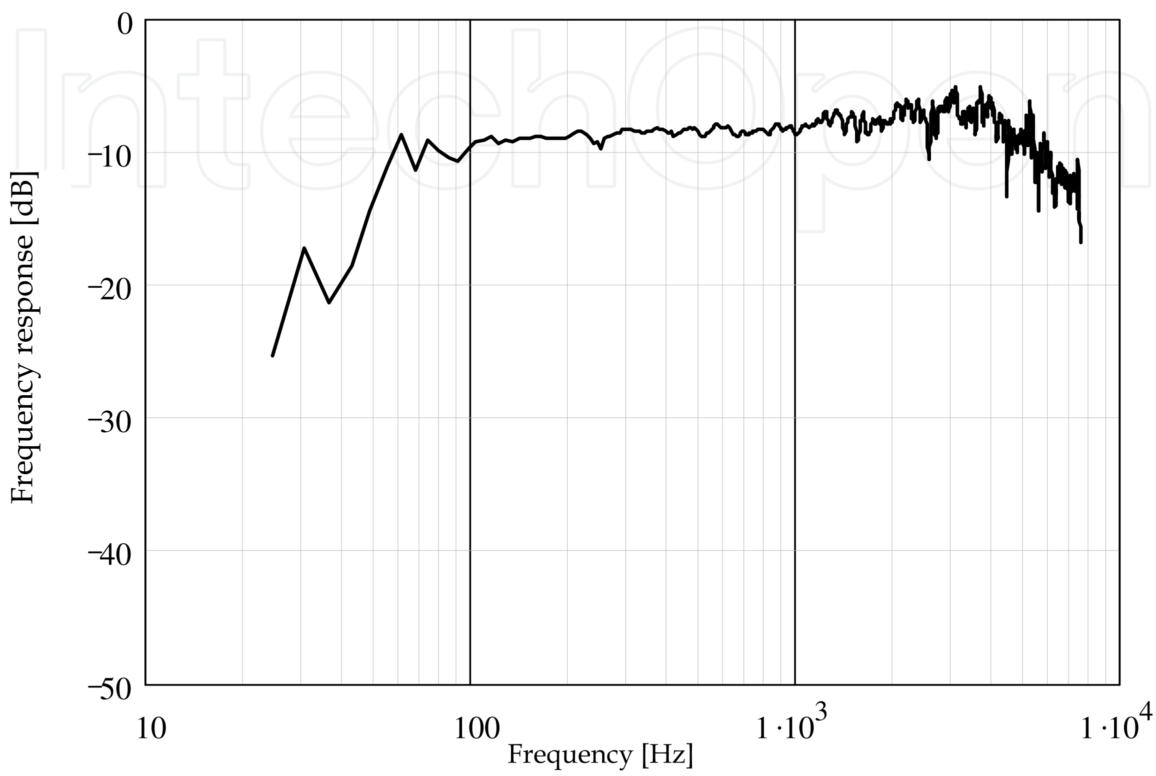


Fig. 5. An example of the measurement microphones frequency response.

One of the methods to eliminate the impact of microphones' cover elements on the acoustic field around the head of the test participant is using microphones placed directly in the matter closing ears' canals (Møller et al.,1995). In this case the usage of cover elements could be avoided and the solution is more advantageous for the precision of the results. On the other hand, the use of plain microphone without a rigid support construction attached to the measurement device gives way to the uncontrolled head motions. The impact of this fact on the tests' results is described in section 5.2. It should be noted that the use of the microphones without rigid support increases the amount of time needed for exact positioning of the participant's head and also makes the measurement of the reference response more difficult.

5. Practical aspects of using the HRTF measuring device

5.1 Verification of the measurements results using dummy head

It is not impossible to verify results of measurements given by presented device directly, but the correctness of measurement results can be verified in indirect process. The first method is a subjective test for a person who had been measured using this device. During the test the signal convolved with a result of HRTF measurement is presented – this operation sets up a virtual sound source in specific point in space around a listener (Dobrucki et al., 2010). The consistence of point determined by convolution process and point indicated by listener is tested. If the consistence is correct, the result of measurement is also correct. Other method for verification of measurement result is a comparison of measurement results with the results of numerical calculation (Dobrucki & Plaskota, 2007).

The correctness of a measurement result was examined by measurement of dummy head (Neumann KU100). The result of measurement was compared to the results of numerical calculation. The dummy head had been placed in measurement device, next the whole measurement process was conducted. The use of a dummy head can eliminate some inconvenient occurring during measurement of a person, i.e. the head movement that provides to large measurement deviation.

The Boundary Elements Method (BEM) has been used to perform the numerical calculation of HRTF (Dobrucki & Plaskota, 2007). The numerical model is a representation of geometrical shape of dummy head, especially with emphasis on accordance of pinna model with geometry of real object. Differences between real object and numerical model are smaller than 0.1 mm (Plaskota, 2007; Plaskota & Dobrucki, 2005). The measurement of acoustical impedance of dummy head has been done (Plaskota, 2006) and the result was used as a boundary condition.

Figure 6 show HRTF measurement and numerical calculation results for azimuth 90°, elevation 0°, for ipsilateral ear (located closer to the sound source). There are three graphs in

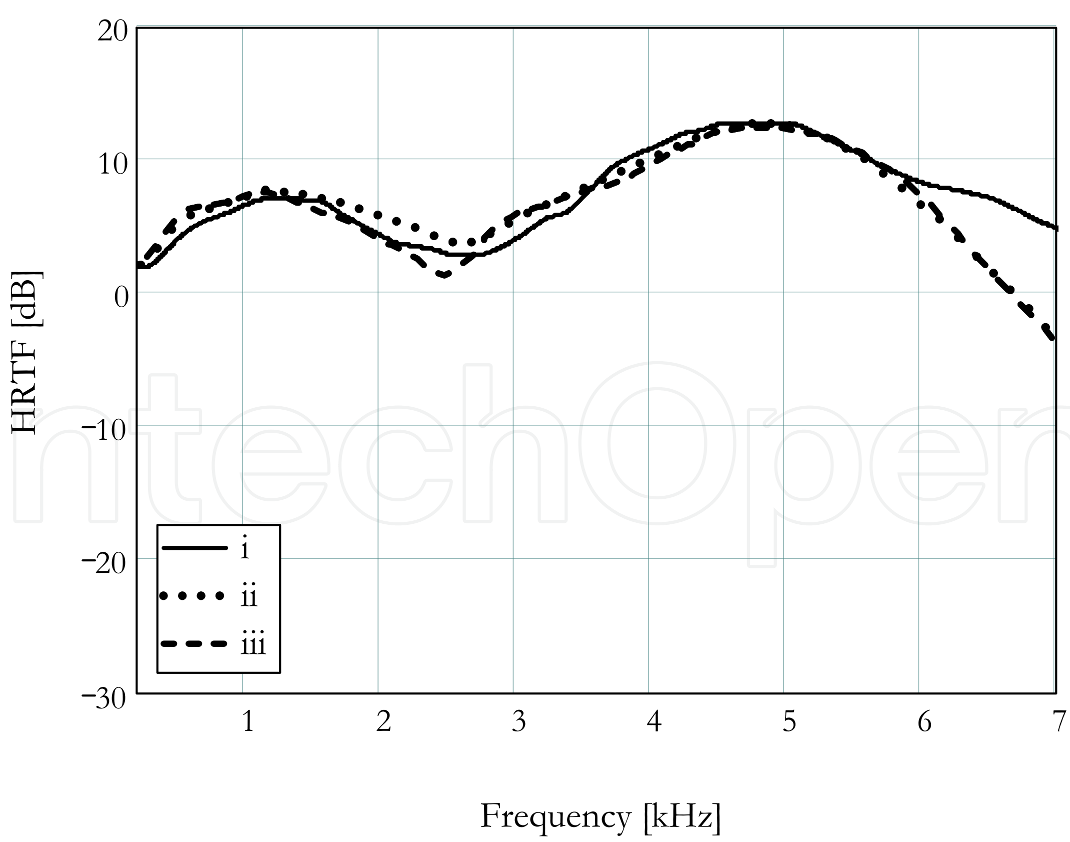


Fig. 6. Measurement and simulation results: azimuth 90°, elevation 0°, ipsilateral ear. Detailed description of symbols in text.

the diagram. The particular letters represent the following cases: i – the measurement result, ii – the result of simulations without impedance boundary conditions (the rigid model), iii – the result of simulations with impedance boundary conditions in whole modeled area except for the pinnas, for which the same boundary condition as for the rigid model was assumed.

Measurements results are in good accordance with calculation results below 6 kHz. On the basis of comparison between the measurement and calculation results, it was found that measurements results are proper. There are some reasons of difference between measurement and calculation results above 6 kHz. At first, the microphone set has been not taken into consideration during the numerical calculation: microphone enclosures probably produce the wave phenomena in frequency range of 8-10 kHz. Secondly, the high cut-off frequency of a numerical model is about 7 kHz.

5.2 Discussion of problems encountered during measuring process

One of the major challenges faced during the tests was positioning of the listeners relatively to the microphones. In the first tryout the microphones were fixed in a way similar to medical stethoscope. Microphones were coupled with flexible wires; these were attached to ears in such a way that the microphones were suspended and their transducers were on the level of ear canals entrances. The head of the human subject was placed on a holder fixed to the extension of the armchair's back. The distance between the head and the head holder was adjusted using cushions of different sizes. By increasing or reducing the amount of cushions the head of the test participant was placed at varied distances from the holder. The position of the head was controlled trough electronic visual system. On the screen the researcher could see the lines matching the position of ear canals entrances and adjust the position of the head accordingly.

This method was verified negatively. The participants during the tests do move their heads slightly. Using a band to fasten the head to the holder did not bring any significant improvement. Those minimal head motions have an impact on the geometry of the measurement arrangement. In the case of high-resolution measurement performance the stability of geometrical configuration: the sounds source – the microphone, is crucial for the accuracy of the measurement.

The other method of attaching measurement microphones was then proposed and tested. The microphones were fixed on a nonflexible construction. The construction had the possibility of adjusting the position of the microphones, though. The microphones were placed on the level of ears' canals entrances like before. Applying the fixed construction resulted in the fact that the test participant felt the microphones support structure limitation. In this case it was easier for the test participant to control head motions: when they appeared, it was a simpler task to put the head back in right position. The other advantage was that the distance between the microphones and the head holder was preset. The researcher avoided long process of positioning the head in relation to the holder. The only thing to be done was locating the listener in a proper elevation according to the sound sources. This solution is presented in Figure 2.

The most important of all the advantages of this particular way of setting the microphones is the possibility of the precise microphones positioning while measuring the reference response and while conducting the tests with human participant, as well. It is very significant for the accuracy of measurements, particularly when the impact of the measuring set and that of the research room should be minimized.

Although conducting the measurement of reference response for each assessment spot excludes the impact of the measurement set, some acoustic phenomena cannot be reduced this way. During the tests it was observed that for the 90° elevation angle and for the angles close to this value, in the reference impulse response the sound reflection from the seat of the armchair was observed. (Figure 7, Time ≈ 7 ms). During the test involving the participant the reflection does not occur because the person is seated in the armchair and therefore covering the seat surface. The phenomena of reflection while measuring the reference response, after the sound reaches the seat of the armchair, could be eliminated by using additional sound diffusion device.

Summing up, in the case of sound reflection from elements covered by the test participant, the use of the reference response is not sufficient. Similar phenomena were observed for different angles but never to such extent as in the case of 90° elevation angle.

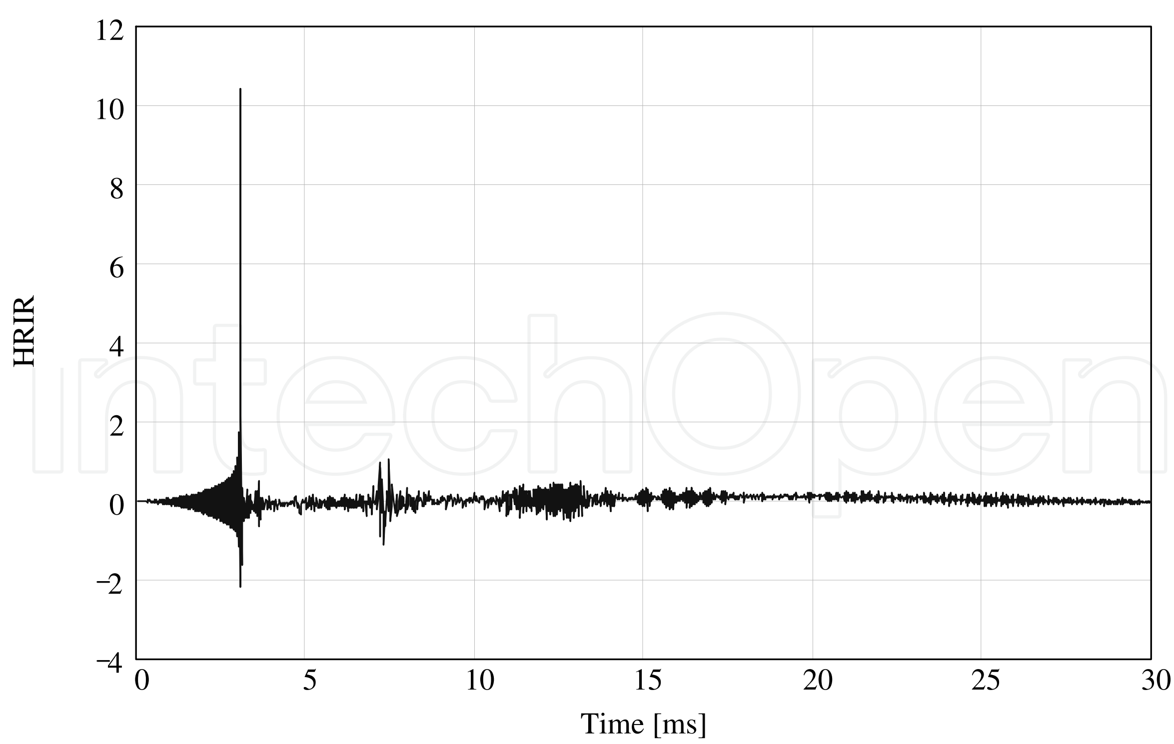


Fig. 7. The impulse response for vertical 90 ° angle.

The impact of the research room is neutralized as much as possible by measuring the reference response. While measuring the reference responses the components with frequencies around 80 Hz were singled out (Figure 8). It could be said that it was the effect of the wave interference inside the room. Although the tests are conducted in anechoic chamber, it is a place designed basically to make measurements involving machines and there is a concrete platform in the middle of the chamber intended for placing machines. This can contribute to forming interference phenomenon. Repositioning the device inside the chamber reduced the presence of the interference occurrence. Nevertheless, the phenomenon was observed only for frequencies outside the operational range of the device.

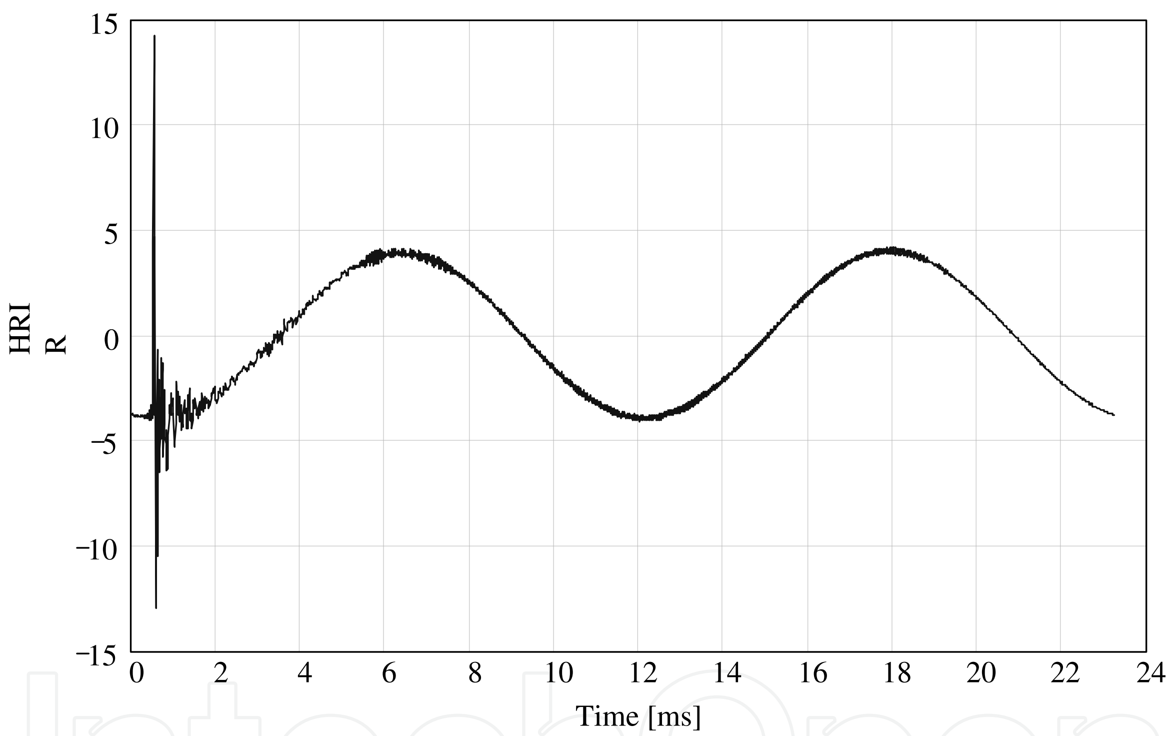


Fig. 8. The impulse response containing a small frequency component.

6. Conclusions

The HRTF measurement system allows a very fast measurement of HRTF with high spatial and frequency resolution. The applied operational algorithms of the system guarantee repeatability of measurements and minimalization of the influence of many disadvantageous factors on measurements results. Compact structure and modularity of construction of the system allows an easy transport of the device. The encountered problems were discussed together with the eventual solutions to them. On the basis of conducted measurements and subjective tests it could be assumed that the device measures the HRTFs accurately enough to recreate the position of the sound source in the space surrounding the listener. The scope for future tests is to verify if the proposed adjustments eliminate the impact of the research room by conducting tests in the reverberation room sufficiently. To eliminate the influence of physical movements of the participant it is recommended that the tests should be conducted using a dummy head.

7. References

Algazi, V.R., Avendano, C. & Thompson, D. (1999). Dependence of subject and measurement position in binaural signal acquisition, *J. Audio Eng. Soc.*, Vol. 47, No. 11, (November 1999), pp. 937–947

Algazi, V.R., Duda, R.O., Thompson, D.M. & Avendano, C. (2001). The CIPIC HRTF database, *Proceedings of IEEE WASPAA 2001*, New Paltz, NY, pp. 99–102

Batteau, D.W. (1967). The role of the pinna in human localization, *Proc. R. Soc. London, Ser. B 168*, 1967, pp. 158–180

Blauert, J. (1997). *Spatial Hearing*, The MIT Press, Massachusetts, 1997

Bovbjerg, B.P., Christensen, F., Minnaar, P., Chen, X. (2000). Measuring the Head-Related Transfer Functions of an Artificial Head with a High Directional Resolution, *Presented at the 109th AES Convention*, 22-25 September 2000, Los Angeles, Preprint 5264

Bujacz, M., Strumiłło, P. (2006). *Stereophonic representation of virtual 3D scenes – a simulated mobility for the blind*, In: New Trends in Audio and Video, Vol. 1, Białystok 2006

Cheng, C.I., Wakefield, G.H. (2001). Introduction to head-related transfer functions (HRTFs): Representations of HRTFs in time, frequency, and space, *J. Audio Eng. Soc.*, Vol. 49, No 4, April 2001, pp. 231-249

Dobrucki, A.B. (2006). *Electroacoustic transducers* (in Polish), Wydawnictwa Naukowo-Techniczne, Warsaw 2006

Dobrucki, A.B., Plaskota, P. (2007). Computational modelling of head-related transfer function, *Archives of Acoustics*, 2007 Vol. 32, No 3, pp. 659-682

Dobrucki, A.B. Plaskota, P., Pruchnicki P., Pec, M., Bujacz, M., Strumiłło, P. (2010). Measurement system for personalized head-related transfer functions and its verification by virtual source localization trials with visually impaired and sighted individuals. *J. Audio Eng. Soc.,* 2010, vol. 58, No 9, pp. 724-738

Gardner, W.G. & Martin, K.D. (1995). HRTF measurements of a KEMAR, *J. Acoust. Soc. Am.* 97, 3907–3908

Grassi, E., Tulsi, J., & Shamma, S.A. (2003). Measurement of headrelated transfer functions based on the empirical transfer function estimate, *Proc. 2003 Intl. Conf. on Auditory Displays _ICAD 2003_*, Boston, MA, pp. 119–121

Hartmann, W.M. (1999). How we localize sound, *Phys. Today 1999*, pp. 24–29

Hartmann, W.M. & Wittenberg, A. (1996). On the externalization of sound images, *J. Acoust. Soc. Am.* 99, pp. 3678–3688

Horbach U., Karamustafaouglu, A., Pellegrini, R., Mackensen, P. & Theile, G. (1999). Design and Applications of a Data-based Auralization System for Surround Sound, *Presented at the 106th AES Convention*, 8-11 May 1999, Munich

Hen, P., Kin, M.J. & Plaskota, P. (2008). Conversion of stereo recording to 5.1 format using head-related transfer functions, *Archives of Acoustics*, 2008, Vol. 33, No 1, pp. 7-10

Minnaar, P., Plogsties, J., Olsen, S.K., Christensen, F. & Møller, H. (2000). The Interaural Time Diference in Binaural Sythesis, *Presented at the 108 AES Convention*, 19-22 February 2000, Paris, Preprint 5133

Møller, H., Sørensen, M.F., Hammershøi, D. & Larsen, K.A. (1992). Head Related Transfer Functions: Measurments on 24 Human Subjects, *Presented at the 92 AES Convention, February 1992, Viena*

Møller, H., Sørensen, M.F., Hammershøi, D. & Jensen, C.B. (1995). Head Related Transfer Functions of Human subjects, *J. Audio Eng. Soc.*, Vol 43, No 5, May 1995, pp. 300-321

Møller, H., Sørensen, M.F., Hammershøi, D. & Jensen, C.B., (1996). Binaural Technique: Do We Need Individual Recordings?, *J. Audio Eng. Soc.*, Vol 44, No 6, June 1996, pp. 451-469

Moore, B.C.J. (1997). *An Introduction to the Psychology of Hearing*, 4th Ed., (1997) Academic, San Diego, 1997

Plaskota, P. (2003). Evaluation of microphone parameters for HRTF measurement (in Polish), *In: X International Symposium the Art of Sound Engineering. ISSET 2003.* Wrocław, Poland, 11-13 September 2003

Plaskota, P. (2006). Measurement of acoustical impedance of human skin, *In: The 6th European Conference on Noise Control EURONOISE 2006, Proceedings, Acoustical Society of Finland.* Tempere, Finland, 30 May - 1 June 2006

Plaskota, P. (2007). Acoustical model of the head for HRTF calculation, *In: LIV Open Seminar on Acoustics.* Rzeszów-Przemyśl, Poland, 10-14.09.2007

Plaskota, P. & Dobrucki, A.B. (2004). Selected problems of HRTF measurement (in Polish), *In: Metrology Congress,* Wrocław, Poland, 6-9 September 2004

Plaskota, P. & Dobrucki, A.B. (2005). Numerical head model for HRTF simulation, *In: The 118th AES Convention, Barcelona,* Spain, May 28-31, 2005, Preprint 6510

Plaskota, P. & Kin, M.J. (2002). The use of HRTF in sound recordings (in Polish*), In: IX New Trends in Audio and Video.* Warsaw, Poland, 27-28 September 2002

Plaskota, P. & Pruchnicki, P. (2006). Practical aspects of using HRTF measuring device, *Archives of Acoustics*, 2006, vol. 31, no 4, suppl., pp. 439-444

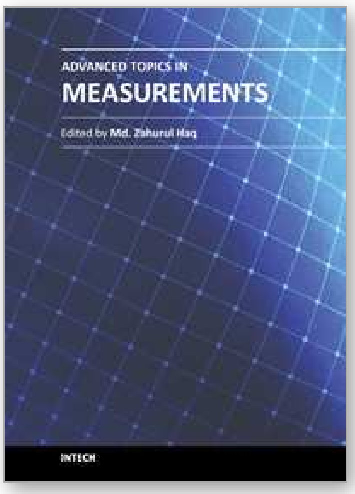
Plaskota, P., Wasilewski, M. & Kin, M.J., (2003) The use of Head-Related Transfer Functions in auralization of sound recordings (in Polish), *In: X International Symposium the Art of Sound Engineering. ISSET 2003.* Wrocław, Poland, 11-13 September 2003

Pralong, D. & Carlile, S. (1994). Measuring the human head-related transfer functions: A novel method for the construction and calibration of a miniature in-ear recording system, *J. Acoust. Soc. Am.* 95, pp. 3435–3444. 1994

Pruchnicki, P. & Plaskota, P. (2008). HRTF Automatic Measuring System, *Archives of Acoustics,* 2008, Vol. 33, No 1, pp. 19-25

Weinrich, S.G. (1992). Improved Externalization and Frontal Perception of Headphone Signals, *Presented at the 92 AES Convention, February 1992, Viena*

Zahorik, P. (2000). Limitations in using Golay codes for head-related transfer function measurement, *J. Acoust. Soc. Am.*, Vol. 107, No 3, March 2000, pp. 1793-1796



Advanced Topics in Measurements
Edited by Prof. Zahurul Haq

ISBN 978-953-51-0128-4
Hard cover, 400 pages
Publisher InTech
Published online 07, March, 2012
Published in print edition March, 2012

Measurement is a multidisciplinary experimental science. Measurement systems synergistically blend science, engineering and statistical methods to provide fundamental data for research, design and development, control of processes and operations, and facilitate safe and economic performance of systems. In recent years, measuring techniques have expanded rapidly and gained maturity, through extensive research activities and hardware advancements. With individual chapters authored by eminent professionals in their respective topics, Advanced Topics in Measurements attempts to provide a comprehensive presentation and in-depth guidance on some of the key applied and advanced topics in measurements for scientists, engineers and educators.