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SoundShape – Headphone Transfer Function Database

Szymon Jasiński, Bartłomiej Mróz, and Bożena Kostek

***Abstract*—This article introduces the SoundShape database, which contains measured headphone transfer functions (HTFs). Details of the various stages of SoundShape's implementation, including project assumptions, software used, and the measurement environment, are shown. The measurement process is explained. Moreover, the construction and processing of signal files within SoundShape are discussed. The *AKtools* script in MATLAB is employed to derive the HpTF functions. Analyses of selected audio signal samples from the database highlight similarities and differences among the three headphone models tested. The paper concludes with a summary of the results, including recommendations on how the database can be utilized. The presented SoundShape HpTF database is publicly available from https://doi.org/10.34808/4wya-z425.**

***Keywords*—SoundShape; Headphone Transfer Function; HpTF; 3D sound**

I. Introduction

RESEARCH on creating individualized sound impressions with headphones is increasingly the subject of analysis and measurement, as included in the state-of-the-art literature. Developments in technology are paving the way for new opportunities to implement solutions derived from spatial hearing research, which enables the listener to perceive 3D sound. Such areas include, among others, the fields of virtual and augmented reality, computer games, military training, pilot training, geographic information systems [1],[2],[3], but also purely sound-oriented fields, such as, for example, music production and GPS systems for visually impaired people [4]. Furthermore, there is potential to apply such innovations in radio dramas and teleconferences, where the speakers' voices could be spatially separated to create the illusion of emanating from different directions. An interesting branch of acoustics, adapting this kind of solution, is the acoustic measurement sector. Such solutions are used, for example, in subjective noise measurements. Listeners parameterize the annoyance of noise differently when it is emitted from the real environment and when it has been recorded and reproduced by a loudspeaker. The acoustic properties of rooms, such as concert halls, auditoriums, recording studios, etc., can also be compared. Not only can the quality of music be compared in this way, but also the speech of speakers or the sound from public address equipment.

To support the above definition, it is becoming increasingly popular to create HpTF databases for different types of headphones. Some of the most popular such datasets are PHOnA, the ARI HpIR database, and the FABIAN database, etc. [5],[6],[7],[8].

In addition, headphone transfer functions are included in binauralization tools; one such tool with a broad range of included headphone filters is "Virtuoso" [9]. The SoundShape dataset is part of this trend in creating such collections. In addition to including some of the most well-known headphone models, SoundShape also comprises HpTF filters for models not present in the previously mentioned databases.

II. Methodology and Project Assumptions

A. *Definition and tasks of HpTF filters*

The headphone-to-ear transfer function (HpTF) is a concept used in audio engineering and acoustics to describe the relationship between the audio signal produced by a pair of headphones and the sound pressure that reaches the listener's eardrum. Specifically, it quantifies how the headphone's output is modified by the physical characteristics of the ear (including the pinna, ear canal, and surrounding head structures) before it is perceived as sound [10].

In technical terms, the HpTF is a complex-valued transfer function that captures the filtering effects of the ear's anatomy on the headphone's sound output to enhance the listening experience. Additionally, HpTF filter is designed to manipulate the acoustic signal so that the listener feels as if they are in an open field while using the headphones.

The created database of headphone transfer functions (HpTF) can be used for music production or to simulate the sensation of immersion in a given acoustic environment. This is possible thanks to the human ability to naturally localize sound in space, which is intended to be recreated using the studied headphone models.

The study of HpTF often overlaps with the study of HRTF. Both functions aim to capture the unique dependencies responsible for creating the perception of spatial hearing; however, they focus on different elements of the system. HRTF places greater emphasis on recording the individual characteristics of the listener. At the same time, HpTF focuses on accounting for the acoustic features created by the sound-emitting equipment—in this case, headphones.

B. *Design assumptions*

In carrying out the measurements, the researchers replicated the techniques outlined in the publication [11]. After reviewing the scientific literature describing HpTF measurements and the conclusions expressed in the reviewed papers, the following

Szymon Jasiński and Bartłomiej Mróz are with the Department of Multimedia Systems, Gdańsk University of Technology (e-mail: s143014@student.pg.edu.pl; bartlomiej.mroz@pg.edu.pl).

Bożena Kostek is with the Audio Acoustics Laboratory, Gdańsk University of Technology (e-mail: bozena.kostek@pg.edu.pl).

design assumptions were established:

1) The best environment to ensure acoustic isolation from the environment and exclude any interference is an open field or a room simulating its conditions. An anechoic chamber was chosen as the environment for making measurements.
2) Measurements should be made for an average head and torso, providing average acoustic conditions.
3) Measurements should be taken with the ear canal closed.
4) To block the ear canal, foam plugs with a hollow tube hole in the center should be used.
5) Microphones should be placed securely with the plug inside the ear canal of the dummy so as not to damage any of the microphone's component wires.
6) The dataset signal should be a sweeping, sinusoidal chirp signal (sine sweep).
7) The signal should be generated twice, separately for the left and right channels, at an interval of 1 s, to exclude the possibility of the two measurements influencing each other. This is particularly important, especially when measuring unclosed headphones.
8) Record at least 15 repetitions of a single measurement for each model or configuration collected and measured.
9) For each single measurement, the pair of headphones under test should be removed and reapplied to simulate the average way in which the general population wears this model of headphones. Publications [12],[13] note that the human ear is more sensitive to acoustic signals from headphones than from speakers. Therefore, the measurement must represent the averaged headphone overlap positions.

C. Hardware and software

The tools utilized for measurements include Knowles FG-23629-P16 microphones, which have an omnidirectional polar pattern and a sensitivity of -53 dB (±3 dB) at 74 dB SPL [14].

The microphones were additionally measured, as the original datasheet does not include information on the microphone's characteristics outside the 100-10000 Hz spectrum; the measured frequency response of the microphones is presented in Fig. 2. The measurements were performed with Genelec 8331A loudspeaker and NTi M2230 measurement microphone in an anechoic chamber; the soundcard was calibrated with the measurement software. The software used for this measurement was Room EQ Wizard [15].

For the HpTF measurements, the microphones were connected to the ZOOM F4 MultiTrack Field Recorder, which served as an audio interface [16]. Additionally, the Brüel & Kjær Head and Torso simulator type 4128-C was employed [17]. A Dell XPS L702m computer was employed in conjunction with PureData software, wherein a script was developed and associated with the SoundShape database as part of the comprehensive measurement documentation. Audacity software is responsible for pre-processing all component files, with a thorough description of this process provided in Section III. Furthermore, MATLAB 2024a software, accompanied by AKTools scripts [18],[19], is utilized, with details on their application also provided in Section III. The following diagram in Fig. 1 shows the arrangement of connections between the various components of the measuring apparatus. It was inspired by the diagram posted in the literature [2].

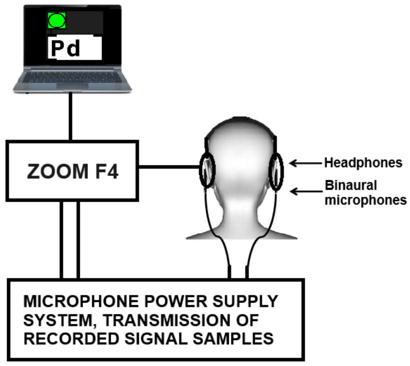

Fig. 1. Wiring diagram of the measuring apparatus.

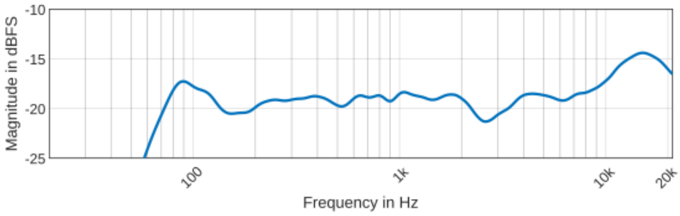

Fig. 2. Knowles FG-23629-P16 frequency response.

III. SIGNAL PROCESSING IN AKTOOLS

The analysis of the acquired impulse responses was segmented into two phases: the initial phase of pre-processing, executed utilizing Audacity software, and the subsequent phase of HpTF processing, carried out within the MATLAB environment, employing a considerable application of AKTools scripts [18],[19].

A. Pre-processing in Audacity

As a first step of the pre-processing stage, the silent parts of the signals were removed. The duration of the signal sample for each of the repeated measurements ranges from 1.834 s to 1.85 s, depending on the model. However, for each headphone model, all measured impulse responses last the same duration. It was noted that the extremes, i.e., very low and very high frequencies, were not explicitly recorded – no components were observed, either on the time preview or the spectrograph. In addition, it was found that limiting the recorded sample below 1.8 s truncates important signal sample components and leads to grossly flawed results in determining the HpTF function.

The length of the test signal is, in principle, always longer than the length of the recorded signal—this is especially true for room acoustics measurements. Therefore, during the measurements conducted, the test signal, a linear sine sweep, lasted 2 seconds. Each recorded sample used for further processing in the AKTools scripts was standardized and stripped of segments containing 'recorded' noise. The samples were often adjusted to the precision of one-thousandth of a second.

A requirement for further signal processing in the AKTools scripts is that the signals must be as clean as possible, with minimal extraneous components. As already mentioned, the recorded signal typically ended around 1.8 seconds, so any further trimming or shortening would interfere with essential signal components. Importantly, the processed recorded signal samples are of equal length for each specific headphone model.

The component signals were processed in this manner and exported in stereo, in PCM format, with 32-bit floating-point encoding and a sampling frequency of 48 kHz.

The chirp signal master file was also exported according to the above parameters. It was necessary for the subsequent generation of impulse responses.

B. Processing with AKTools

To accurately determine the HpTF function, the collected and processed signal samples must first undergo a process to extract the impulse response (HpIR) from them. Then, the impulse responses thus extracted are averaged and subjected to an inverse process [20].

A collection of AKTools scripts, developed by Fabian Brinkmann and Stefan Weinzierl [18], [19], was utilized for the aforementioned tasks. It is a collection of scripts made available under the European Union Open Source Software License (EUPL), which allows the code to be used, changed, and redistributed for any purpose.

They mainly used the scripts and functions contained in *AKdeconv.m* and *AKregulatedInversion.m*. However, two other scripts are used to trigger and control the functions contained in these scripts: *AKdecovolutionDemo.m* and *AKregulatedInversionDemo.m*. In these two demo scripts, it is possible to directly change the type and quality of calculations. Additionally, note that for the entire process to work correctly, it is necessary to download and implement the entire collection into MATLAB using the *AKtoolsStart.m* script.

The *AKdeconvolutionDemo.m* script offers two basic functionalities. The first generates test data with simulated calculations. The second acquires the input data, displays the results in graphs, and saves the calculated signal file. The script does not impose a rigid framework and leaves it free to the user's familiarity with the MATLAB environment.

The *AKregulatedInversionDemo.m* script shows how to use adjustable inversion to invert the transfer function of headphones. It encompasses various approaches to regularization, ranging in complexity and quality, and handles tasks from averaging the transfer function to saving the generated filters. The structure of this code is described in extensive detail and clearly divided into specific blocks.

The scripts were carefully adjusted to obtain the headphone transfer filters for the presented SoundShape database. Most importantly, the *s.APPLY_SMOOTHING* function was used to average the values. Thanks to this averaging, the final filter is clearly linear. Also, the parameter responsible for normalization – *s.f_norm* – was adjusted, which was set to 200 Hz by default. The lower the value of this parameter, the less bass attenuation becomes. This is important because the authors of this tool take special care not to set too high attenuation values for low frequencies in the final filter. Should the low-frequency attenuation in *s.f_norm* be too high, however, necessary in the context of the quality of the overall filter, the *s.margin* parameter is at one's disposal. Setting a lower value can help mitigate excessive low-frequency attenuation.

The *AKregulatedInversion.m* script offers six regularization methods. The script's authors recommend choosing the fourth or sixth method for headphones. For the implementation of this work, the sixth method was selected. It allows for manual adjustment of the filters for each channel.

IV. SOUNDSHAPE DATABASE

Fifteen models of headphones were used to create the SoundShape dataset. Among them are closed headphone models and open-back models. The headphones were selected to ensure that the created database included models widely used in the field of acoustics, such as the Beyerdynamic DT 770 Pro, as well as to ensure a diverse range of high-quality headphones used in specialized measurements, including the Stax SR-007 mk2. Also measured were slightly cheaper headphones, less prevalent in the acoustics community but used by a wider audience and qualitatively considered satisfactory, such as the Sennheiser HD203.

The published database consists of two parts, organized into two folders. The first part comprises all 15 headphone transfer filters along with the characteristics of the obtained filters. The second folder contains all the measurement files used to get the final HpTFs. This folder includes all the measurement files of the component signals, pre-processed signals, and generated headphone impulse responses. In addition, a PureData script is included, along with the chirped sine signals and images of the measurements performed.

The entire SoundShape database can be downloaded from https://doi.org/10.34808/4wya-z425. Table I lists all models of headphones included in the database.

TABLE I
SOUNDSHAPE – RECORDED MODELS OF HEADPHONES

No.	Model	Type	special features/modifications of the model
1	AKG K451	closed	earcups directly adhere to the entire plane of the auricle
2	AKG K514	closed	no significant modifications
3	AKG K550	closed	no significant modifications
4	Audiotechnica ATH-M40x	closed	no significant modifications
5	Audiotechnica ATH-M50x	closed	no significant modifications
6	Beyerdynamic DT770 Pro	closed	no significant modifications
7	Superlux HD681 Evo	closed	no significant modifications
8	HyperX Cloud II (type 1)	closed	earcups made of foam
9	HyperX Cloud II (type 2)	closed	earcups made of leather
10	Phillips SBC HP195	closed	no significant modifications
11	Sennheiser HD203	closed	no significant modifications
12	Sennheiser HD380 PRO	closed	no significant modifications
13	Sennheiser HD650	open	no significant modifications
14	SteelSeries Arctis 7	closed	can be switched to wireless mode
15	Stax SR-007 mk2	open	external power supply

V. Selected characteristics of HpTF

This section outlines the features of several HpTF filters that were acquired, along with a concise overview of each. In the subsequent sections, the results obtained are evaluated against one another, highlighting the key similarities and disparities. Additionally, there is a discussion regarding the results in comparison to the HpTF filters developed by other researchers in various publications.

A. Selected characteristics

Figures 3, 4, 5, and 6 illustrate the characteristics of four selected HpTF filters from the SoundShape database.

Fig. 3 illustrates the characteristics of the HPTF function for the Phillips SBC HP195 closed-back headphones. It can be observed directly that the obtained characteristics for the left and right channels are similar to each other.

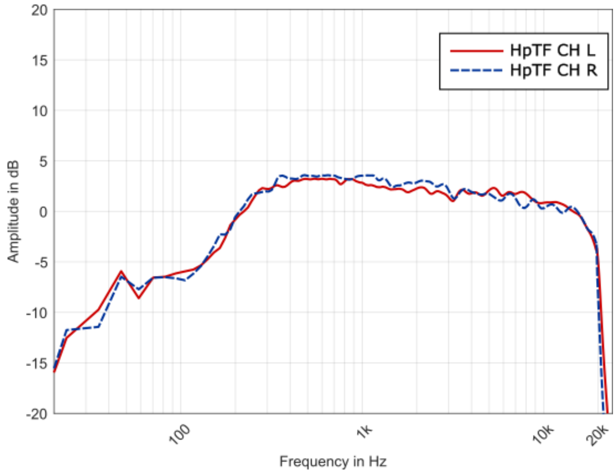

Fig. 3. HpTF function graph of Phillips SBC HP195

In Fig. 4, a chart depicting the transfer function for the Sennheiser HD650 open headphones is presented. This model exhibits a noticeably distinct shape compared to the other headphone models. The manufacturer also states that this particular model is designed for individuals with discerning audiophile preferences. These characteristics are likely attributed to the unique features of these headphones, rather than being solely influenced by their classification as an open headphone type.

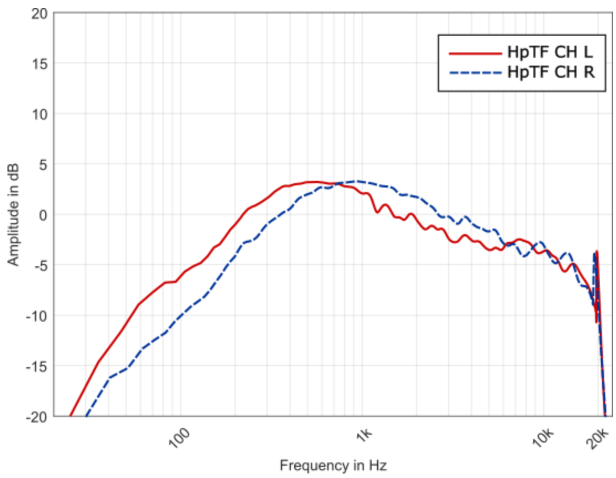

Fig. 4. Graph of the HpTF function of the Sennheiser HD650

Figure 5 shows the HpTF for the SteelSeries Arctis 7 headphone model. This type of headphone is widely used in the consumer sector, particularly in gaming. An additional feature of such headphones is their ability to operate wirelessly. This is an added advantage, as most of the HpTFs measured so far have concerned only wired headphones. Figure 5 also shows the similarity between the left and right channels.

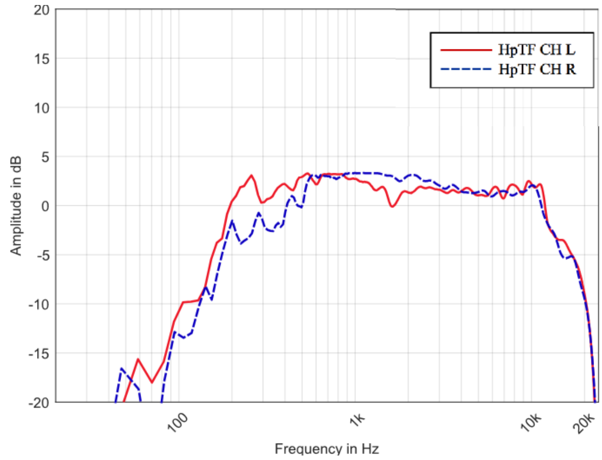

Fig. 5. Graph of the HpTF function of the Steelseries Arctis 7

As an additional illustration, Fig. presents an HpTF plot for electrostatic open headphones, specifically the Stax SR-007 mk2 model. It is evident that despite classifying these headphones as electrostatic, their characteristics exhibit similarities to those of other models cataloged within the database.

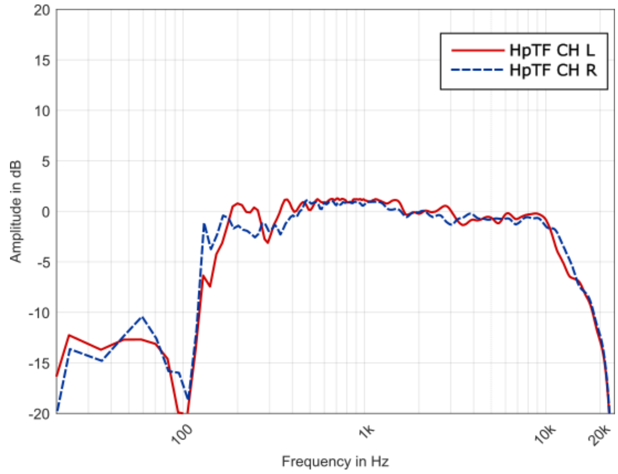

Fig. 6. HpTF function graph of Stax SR-007 MK2

B. General analysis of all HpTF functions obtained

The analysis of the obtained HpTF filters shows that the symmetrical properties of the graphs for the left and right channels were preserved. This was not obvious given so many variables, such as:

- Signal recording at different time intervals;
- The occurrence of random components each time the headphones are put on and off for a single measurement;
- Preparation of signals by manually cutting out the silent parts of delays.

Of course, there were asymmetries in the amplitude level for some frequencies (mostly high), which were compensated by using normalization filters. The selected regularization method (method no. 6 in *AKregulatedInversion.m*) enables such a direct projection of filters. It is worth noting that the authors of the scripts used several types of filters on a single headphone transfer function [18],[19]. In this database, however, only one low-pass filter was employed, as recommended by the authors of the scripts. It is also important to mention that the authors of the AKTools scripts recommend that the specific frequencies of the signal should not be excessively amplified and that as much of the signal as possible should oscillate within 0 dB. With the HpTFs obtained for the SoundShape database, this was usually met, especially for frequencies between 1 kHz and 10 kHz.

An example of a normalization filter that allows achieving the aforementioned criteria is presented in Fig. .

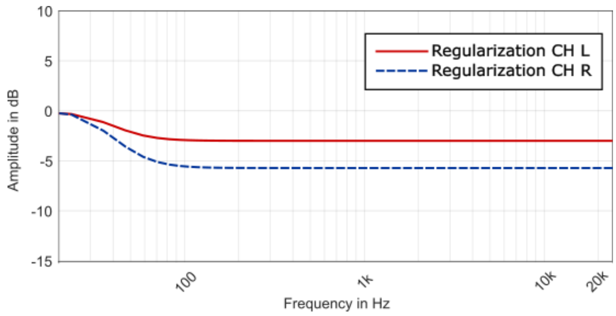

Fig. 7. Asymmetric regularization filter used in measurement no.8 for HyperX Cloud II (type 1).

An additional aspect noted is that both the test signals and those obtained in the calculations rapidly attenuate frequencies around 20 kHz. This is one indication that the functions were performed correctly. Additionally, another recommendation provided in AKTools, not to excessively suppress the lower frequencies, was followed.

Attenuating low frequencies in headphone freefield filters is crucial for achieving accurate sound reproduction and enhancing the listener's experience. Low-frequency correction in headphone compensation filters addresses the lack of excitation energy in this range during measurements, which is essential for accurately determining head-related transfer functions (HRTFs). This correction enables shorter impulse responses, thereby improving the interpolation of HRTFs via magnitude and phase with consistent phase information [21]. The significance of low frequencies extends beyond headphones, as they play a vital role in the perception of spatial impression and listener envelopment in concert halls and surround systems, where laterally-arriving low-frequency energy significantly contributes to the listener's sense of envelopment [22].

However, comparing the overall results of the obtained characteristics of the SoundShape dataset with the filters obtained by other authors, it is worth noting that in the band between 5-10 kHz, there is often a characteristic point of signal attenuation. This is noticeable, for example, in publications [23],[24],[25]. One factor that may be responsible for this type of attenuation may be the compensation for the microphone's time response, which most often falls around 8.5 kHz. The deconvolution test data also simulated this relationship (*AKdeconv.m*). In contrast, it remained unaffected by the shape of the HpTF filter obtained from the test data. Therefore, in this work, it was decided not to artificially add this cutoff frequency to the obtained filters, in order to interfere as little as possible with the signal, especially in such a decisive manner.

C. *Comparative analysis of selected HpTF functions*

Upon analyzing the individual charts, certain correlations were observed. For instance, the graphs of the HpTF function for AKG K451 headphones and those for Sennheiser HD650 headphones significantly differ in shape from the characteristics of the other functions. This is most likely due to the distinctly different construction in their design from the other models. The AKG K451 model is a consumer-oriented model, and its diaphragm, along with a sponge, adheres directly to the auricle, minimizing the possibility of the signal sounding out in the space between the ear and the earphone. The Sennheiser HD650, on the other hand, has two spacious headphone chambers.

Furthermore, for measurements 8 and 9 in the SoundShape database, the same model of HyperX Cloud II headphones was measured, but with different types of earcups: made of foam and leather. It was found that there were no significant differences in the characteristics of the two transfer filters; the characteristics retain their shape and differ only in detail. However, it can be concluded that the foam earcups have higher attenuation. Nevertheless, the level of difference between the amplitudes of the different frequencies is so small that a more likely aspect is the influence of the normalizing filter used. A positive aspect of the same graph shape in this case is also that the repeatability of the result was obtained. The same model was measured with a modification that, as determined by analysis, does not significantly affect the filter while adhering to the design assumptions. Despite so many variables, virtually identical characteristics were obtained.

Fig. shows a preview of the filter characteristics for the two left channels of the HyperX Cloud II headphones, featuring foam and leather earcups, respectively.

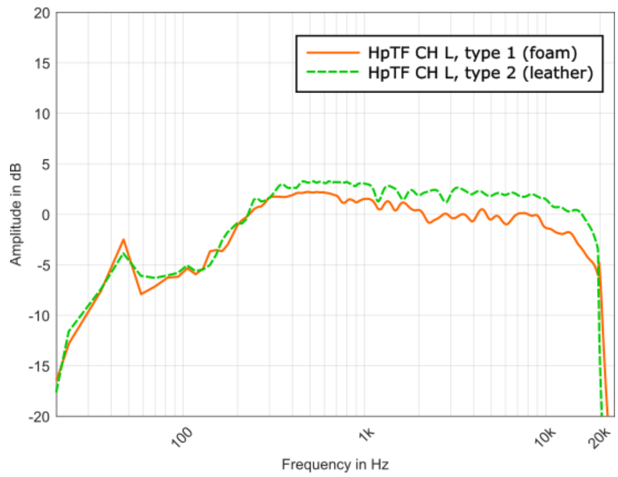

Fig. 8. HyperX Cloud II HpTF function graph for the left channel – comparison between foam and leather earcups

In this case, the authors of this manuscript performed a brief listening comparison. Although not rigorously tested, it is worth noting that there appears to be a clear difference in sound perception during subjective listening. For the transfer filters of the HyperX model with leather earcups, an unnatural treble boost is audible with some music, which aligns with the filter characteristics presented in Fig. .

VI. Conclusions

The SoundShape dataset was developed following the methodology and design principles found in other similar databases. The source data were accurately compiled and set up for subsequent processing. During the computational phase, the AKTools scripts were adhered to, resulting in comparable characteristics for the left and right channels, with each signal recorded and processed independently. A notable difference compared to the headphone transfer filters from other datasets with similar characteristics is the attenuation frequency of around 8.5 kHz, which is absent in the SoundShape filters developed. Recognizing this aspect, it can be identified as a potential avenue for enhancing or refining the characteristics of the filters obtained.

In addition to [23], [24], [25], a more detailed attempt at examining and describing notch attenuations was undertaken in publication [26]. The authors divide the occurrence of these attenuations into two characteristic ranges: between 8–9 kHz and around 14 kHz. A point attenuation may be related to the specific behavior of 4 cm wavelength waves as well as the shape of the auricle (outer ear). As a result, different directions of wave incidence are studied, ranging from 0 to 100 degrees, with particular interest in the incidence of sound waves directly from the side. Although these notches appear quite commonly in the publication, the authors point out that not all models exhibited these notches, which was influenced, among other factors, by the unique, specific design of the measured headphones. However, the authors also chose not to externally modify the signal when calculating the HpTF function in the cases where such attenuations were not recorded – this observation further reinforced our decision not to add this attenuation in the SoundShape database artificially and to leave the calculations in their original form.

To take advantage of the created filters, they can be implemented and played in digital audio workstations using VST plugins enabling impulse response convolution, such as X-MCFX [27]. It is also possible to use PureData, which offers functionality for mobile devices.

VII. Summary

This paper introduces the SoundShape database, which provides detailed headphone transfer functions (HpTFs) for diverse headphone models. The study outlines the methodology used to compile the database, detailing the measurement setup in an anechoic chamber, data acquisition, and processing steps involving AKTools in MATLAB to derive accurate impulse responses for each model. By examining HpTFs across fifteen headphone models, including open-back and closed designs, the study presents key characteristics that differentiate each model's sound profile, emphasizing the impact of design variations on acoustic output. This database is particularly valuable for applications in 3D sound reproduction, enabling audio engineers to tailor sound processing according to specific headphone characteristics.

Future work will involve expanding the database to include additional headphone models and enhancing measurement techniques to account for variations in real-world acoustic environments. Further improvements may also incorporate listener-specific adjustments to reflect individualized HpTFs for more personalized spatial audio experiences.

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