

EVALUATION OF A MATLAB-BASED VIRTUAL AUDIO SIMULATOR WITH HRTF-SYNTHESIS AND HEADPHONE EQUALIZATION

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ABSTRACT

Virtual audio simulators are the basic tools for localization experiments focusing on the parameters of the applied HRTFs. This paper presents a software solution capable of playback monotic wave files, setting the individual ITD information based on head-diameter data, HRTF filtering in 1-degree spatial resolution for static and dynamic sound sources and record output stereo wave files for headphone playback. Furthermore, a headphone equalization tool is implemented based on measured and averaged transfer functions. Based on this, generated IIR or FIR equalization filters can be applied on the sound data for scientific purposes.

1. INTRODUCTION

Virtual audio displays (VADs) try to simulate sound environments, where listeners are embedded or, at least, exposed to sound sources with directional information. This is usually achieved by setting the Interaural Time and Level Differences (ILD and ITD), extended by filtering of the outer ears, the Head-Related Transfer Functions (HRTFs) [1]. The virtual or augmented reality simulators may include visual and tactile interfaces as well. Regarding sound, the playback system should be able to perform digital filtering and signal processing methods to create binaural signals over headphones. Fig.1. shows the usual description of the transmission and required measurements based on *Wightman and Kistler* [2].

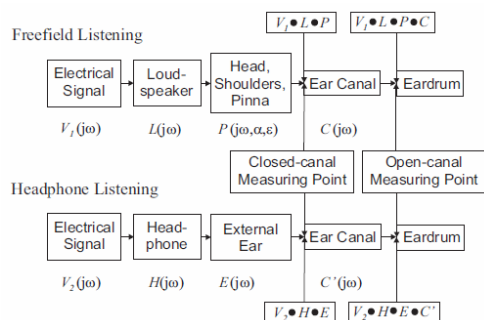


Figure 1. Virtual audio simulation over headphones, compared to free-field listening presented by *Wightman and Kistler* [2].

Several parts and elements of this transmission can be investigated. The focus of experiments includes:

- overall quality, spatial resolution of applied HRTFs (number, length, frequency resolution), as well as the effect of interpolation of missing directions,
- the use of individual, non-individual (generic) and dummy-head HRTFs, that is, the effect of „quite similar looking” but different HRTFs (role of fine structure in the frequency),
- the effect of the minimal-phase reconstruction, which means HRTF filtering only by the magnitude characteristics followed by additional ITD settings, based on mathematical modeling (rigid sphere, head-diameter),
- the effect of headphone equalization including measurement and averaging,
- possible effects of dynamic, real-time adaptation based on head-tracking and room reverberations.

Our former research focused on the measureable effects in the spectral fine structure of dummy-head HRTFs. It revealed how the environment near the head influences the HRTFs [3-5]. HRTFs of the naked torso as well as HRTFs using clothing, glasses, hats, hair etc. were measured with high accuracy. Automated evaluation based on the spectral differences (HRTFDs) showed differences up to 5-15 dB from the same direction in the fine structure of the HRTFs indicating strong effects of the acoustic environment near the head. However, real-life localization usually does not suffer from decreased performance with and without glasses or before and after having a haircut. On the other side, virtual simulation is very sensitive to small changes in the HRTFs. Our goal is to test whether participants are able to recognize different customized HRTF sets on a VAD, based on the mentioned database. Virtual localization tests are planned with different HRTFs to determine the effect of everyday objects near the head. With other words: are subjects able to determine HRTFs with or without hair, or at least detect differences in their localization performance? Furthermore, the system has to be capable of evaluate other parameters such as head-tracking, headphone equalization and minimal-phase assumption.

Fig.2 shows the usual head-related coordinate system in which HRTFs and sound sources are defined (so called “hoop” coordinate system).

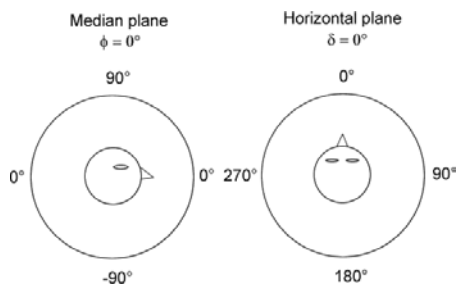


Figure 2. The Head-Related “hoop” coordinate system. Lateral movements are identified by $0^\circ \leq \varphi \leq 359^\circ$, elevation by $-90^\circ \leq \delta \leq 90^\circ$ in the horizontal plane and median plane respectively.

Figures 3 and 4 show examples from the database in the horizontal plane for the naked dummy-head using different plotting methods of MATLAB. Figure 5 however, shows three examples of the effect of hair, glasses and a baseball cap applied on the dummy-head.

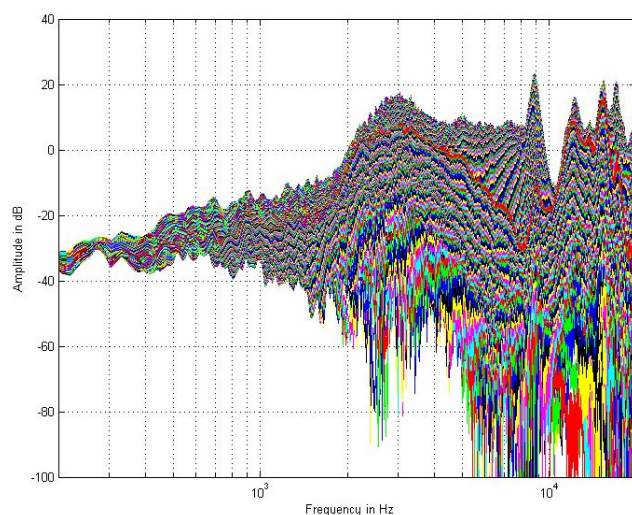


Figure 3. 360 monaural HRTFs in one-degree resolution in the horizontal plane ($\delta=0^\circ$, logarithmic frequency scale) plotted under MATLAB [8].

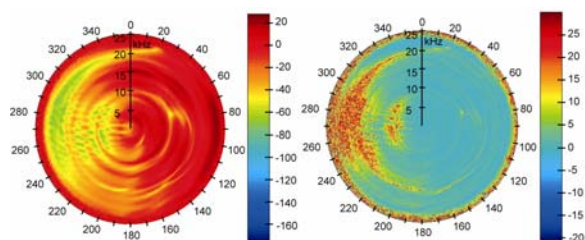


Figure 4. 360 monaural HRTFs in one-degree resolution in the horizontal plane ($\delta=0^\circ$, linear frequency scale) plotted on polar diagrams in MATLAB. Note the large dynamic range due to the head-shadow area (left) and the HRTF differences (HRTFDs) based on re-measured HRTFs (right) [8].

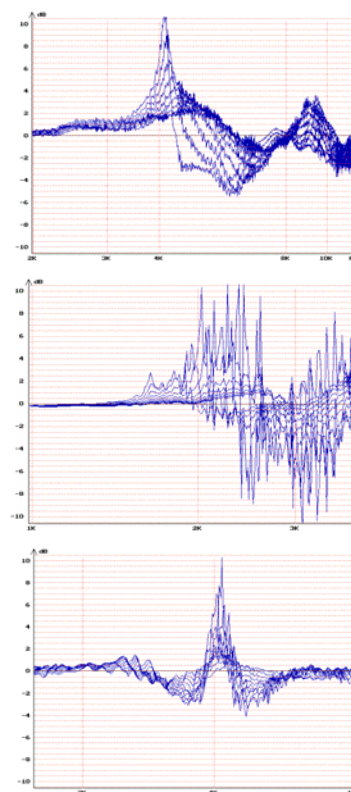


Figure 5. Examples for HRTFDs from the middle frequencies using hair ($\varphi=150^\circ\text{--}195^\circ$, 5° steps, top), baseball cap ($\varphi=230^\circ\text{--}260^\circ$, 2° steps, middle), and glasses ($\varphi=105^\circ\text{--}150^\circ$, 5° steps, bottom).

Measurements and results of listening tests aiming at the effect of the acoustical environment with hair and clothing are rare in the literature, especially if high resolution and accuracy are needed. Measurements of Tarnóczy, Riederer and Treeby suggested effects similar to ours [6-18]. Note, that the use of a dummy-head allows increased measurement accuracy, and using the method of spectral differences (HRTFDs) individual properties can be eliminated.

2. THE “3D SOUND GENERATOR” VIRTUAL AUDIO SIMULATOR

The main part of the setup is the virtual audio simulator. Mono wave files can be loaded, played back and analyzed (time and frequency domain plots). The dummy-head HRTF files can be loaded for the left and right ear respectively for a given angle (static source) or for dynamic simulation in the horizontal plane. In this case, a circling movement around the head is simulated in a user-determined spatial resolution. The best resolution is one-degree. The HRTFs are automatically plotted for visual feedback. After clicking „PROCESS!”, the input file will be filtered by the HRTFs in the frequency domain. Using the minimal-phase assumption, only the HRTF magnitude is used for filtering. Finally, based on the head diameter data, the ITD information is calculated and added (HRTF customization). Currently the program uses the Woodworth-formula for this:

$$ITD \approx \frac{d(\varphi + \sin \varphi) \cos \delta}{2c} \quad (1)$$

where d is head diameter, c is speed of sound, φ is azimuth, δ is elevation if applies [19, 20]. The resulting stereo wave file can be played back and saved. Currently, HRTFs of the naked torso from the horizontal plane are used, but they can be changed by replacing them with different sets in the dedicated subfolder (e.g. those with hair, glasses or with different elevation). The system works off-line: exported wave files can be played back without having MATLAB installed. The saved stereo wave files can serve as input files for the headphone equalization module. Fig.6. shows the screenshot of the GUI.

The main goal of the system is to test different HRTF sets and audible effects of the modified acoustical environment (hair, glasses, clothing) during virtual simulation. Furthermore, we would like to test different ITD approximation methods, whether there is any noticeable difference between the Woodworth-method and other formulas (to be implemented). Finally, the system is planned to be extended by head-tracking using a simple „smartphone” instead of having expensive motion-trackers such as the NEC/TOKIN 3D motion sensor or the Polhemus tracker. An Android-based program helps to get the gyroscope and accelerometer information of the cellphone and communicates with the laptop in real-time via the infrared or bluetooth connection. Spatial accuracy and latency has to be investigated.

3. THE HEADPHONE EQUALIZATION TOOL

Headphone equalization can be made using a separated MATLAB software. First, two headphones were measured in the anechoic chamber using the same Brüel & Kjaer dummy-head and individual measurements were made with the Brüel & Kjaer 4101 binaural microphones (Fig.7.) [21]. Left and right side were measured parallel but independently. Measurements were repeated ten times after re-placement of the headphone on the head, and results were stored in the PULSE LabShop format. These files, as well as other input formats (wave files, txt files etc.) can be used by the program for calculations.



Figure 7. The BK 4128 dummy-head (left), individual measurements (middle) and the BK 4101 binaural microphone (right).

The MATLAB application can import various data formats of other measurements if needed and calculates averaged complex transfer functions for left and right side respectively (Fig.8). Window-functions are also available as well as setting of the DC attenuation.

Table 1 and Figures 9-11 show the possibilities of creating filters in MATLAB. All three methods are implemented and can be selected by the user.

IIR filter		FIR filter	
Method	Function	Method	Function
Yule-Walker („Least-Square”)	yulewalk	Sampling	fir2
Identify discrete-time Filter	invfreqz	Least-Square	firls, fircls
		Windowing	fir1
		Interpolation	intfilt
		P-normed	firlpnorm
		Nyquist-filter based	firnyquist

Table 1. Methods and functions in MATLAB for creating IIR and FIR filter coefficients.

YULEWALK creates an IIR filter without phase information. Order of nominator and denominator is the same. A low order filter is suitable for the estimation of the target magnitude and the filter is usually stable (zeros are inside the unit circle). However, calculations seemed to be depending on the hardware configuration.

INVREQZ also creates an IIR filter but with phase information. Order of nominator and denominator is different. Although the filter is usually not stable, it can be used for emulation. Computation time is the largest.

Using the FIR2 method, only the nominator coefficients have to be calculated, the denominator is one. It is always stable, has a larger order, but it is without phase information.

The program is able to create and save the filter coefficients, filter input wave files and check the stability of the filters based on the poles and zeros (Fig.12).

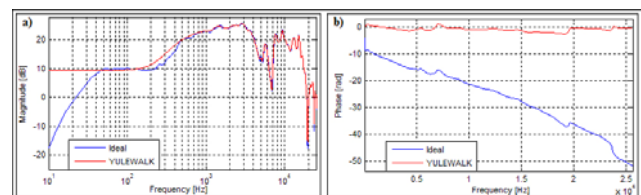


Figure 9. YULEWALK method, 77-order estimation without phase information.

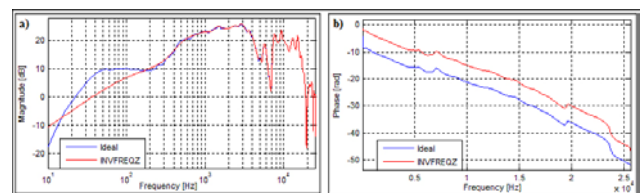


Figure 10. INVREQZ method, 64-order nominator and 96-order denominator estimation with phase information.

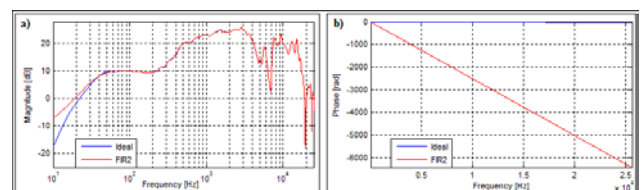


Figure 11. FIR2 method, 4096-order estimation without phase information.

4. CONCLUSIONS

This paper presented a MATLAB-based virtual audio simulator for scientific purposes. It includes real-time or off-line filtering of input data with the applied HRTF set. HRTFs originate from a dummy-head measurement system in different environmental conditions (naked dummy-head, clothing, glasses, hair etc.). The HRTFs can be customized by setting the ITD information based on the individual head-diameter and the Woodworth-formula. Output sound files can be exported in stereo for off-line applications. Static sources in 1-degree resolution as well as moving sound sources around the head can be emulated. Furthermore, the system can use several measured data formats of headphone transfer functions. Based on the mean transfer function, IIR and FIR filters can be generated as equalization filters for the playback. Future works includes listening tests with sighted and maybe blind participants primarily to test various HRTF sets and the audible effects and artifacts caused by the variations of the environment near the head; the effect of different ITD setting methods and the extension with head-tracking using a smartphone's gyro and accelerometer.

5. ACKNOWLEDGEMENT

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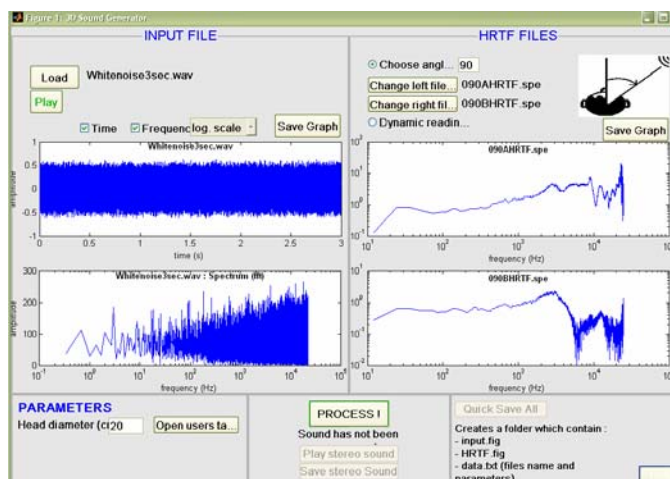


Figure 6. Screenshot of the GUI of the 3D Sound Generator program. You can load an input file, set the head diameter, select the left and right HRTFs for static or dynamic emulation of sound source direction and you can save the result as a stereo wave file. Headphone equalization can be made with a separated program.

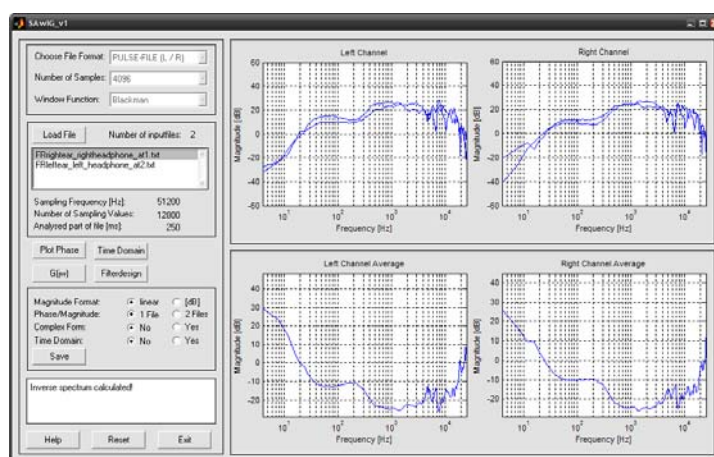


Figure 8. Screenshot of the GUI. You can display measured results, calculate the average of repeated measurements (up to 10 left and right) both for magnitude and phase. The inverse is calculated by a complex $1/x$ in the frequency domain. It is also possible to save impulse responses corresponding to the measured or calculated data.

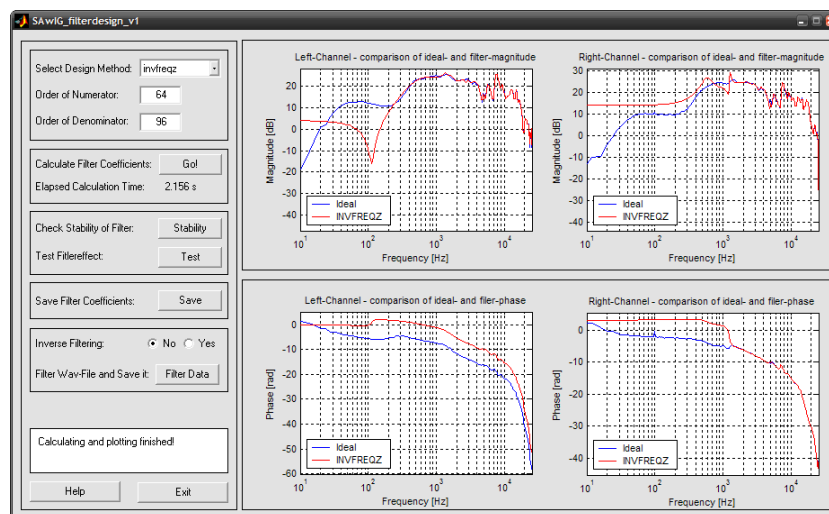


Figure 12. Screenshot of the GUI of the headphone equalization tool, as part of the measurement module. Based on the inverted transfer function it is possible to create FIR or IIR filter coefficients directly, save them for further use and use them as filter for wave files.