Zoltán Mikovity [78]
Óbuda University Doctoral School of Applied Informatics and Applied Mathematics, Budapest/Hungary
Péter Odry[79]
Institute of Information Technology, University of Dunaujvaros/Hungary
Zoltán Vizvári [80]
Multidisciplinary Medical and Engineering Cellular Bioimpedance Research Group, Szentagothai Research Centre, University of Pecs/Hungary
John von Neumann Faculty of Informatics, Obuda University, Budapest/Hungary
Bioimpedance Technologies Research Center, University Research and Innovation Center, Óbuda University, Budapest/Hungary

ELECTROSTATIC TRANSDUCERS IN ACOUSTICALLY POLLUTED ENVIRONMENTS

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Abstract:
This paper presents a novel approach to refining the parameters of electro-acoustical transducers aimed at achieving the highest quality, most precise sound reproduction, with a primary focus on headphones. It outlines the motivations, objectives, and outcomes of research dedicated to creating a new type of electrostatic headphone system, usable in highly noise polluted environments for personal noise protection. Achieving accurate design for electro-acoustic transducers it is crucial to control the frequency, phase, and polar responses of the speaker or headphone systems. Most audio devices on the market tend to prioritize frequency response, with varying levels of success. The behavior of the newly developed headphone system is demonstrated through various measurement techniques and listening tests.

Keywords: *Electro-acoustic sound reproduction, Active noise cancelling, DSP processing*

Introduction

From the human perspective, sound is a mechanical vibration that transfers energy and information through a flexible medium, typically within the 20Hz to 20kHz frequency range. Sound can be characterized by properties such as propagation velocity, wavelength, particle velocity, sound intensity, sound pressure, mechanical impedance, and more [1].

Human auditory perception can be described as follows [2]:

[78] info@soltanusacoustics.com, ORCiD: 0009-0002-8993-387X
[79] podry@uniduna.hu, ORCiD: 0000-0003-2395-5259
[80] vizvari.zoltan@nik.uni-obuda.hu, ORCiD: 0000-0003-0313-9959

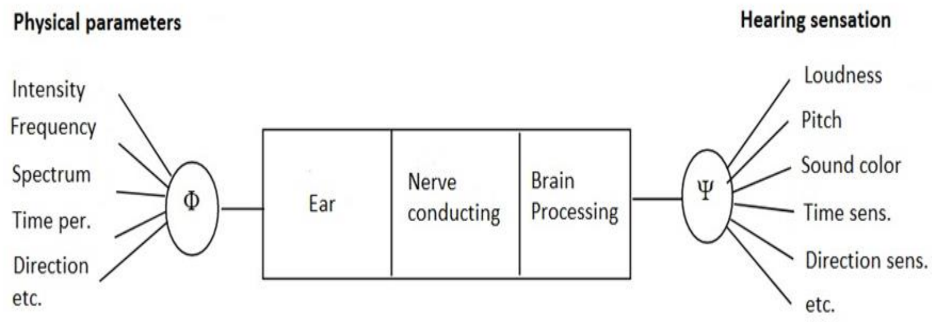

Figure 1. *Human auditory perception [2]*

The input parameters from the sound source or transducers include: Sound intensity, Frequency, Harmonic spectrum, Duration of sound components, direction(s) of the sound source(s).

The human auditory processing involves: outer ear with earcups and auditory canal, tympanic membrane (eardrum), nerve pathways between the cochlea and the brain processing.

The hearing experience can be characterized by the following sensations: loudness, pitch detection, timbre (sound color), temporal perception, directional perception.

The hearing threshold refers to the minimum sound energy that an average human can detect at 1kHz, which is $I_0=10^{-12}\text{W}/m^2$. This threshold is frequency-dependent, as shown in Figure 1. The pain threshold is approximately 120dB.

Noise pollution can have significant psychological effects on humans, including increased stress, anxiety, and irritability. Prolonged exposure to high levels of noise can disrupt sleep patterns, leading to sleep deprivation, which in turn affects mood, cognitive function, and overall well-being. Additionally, chronic noise exposure has been linked to a higher risk of mental health issues such as depression and reduced quality of life.

Human hearing is susceptible to damage from prolonged exposure to sound levels that exceed certain thresholds, and the risk varies depending on both the sound level and the duration of exposure.

1. **Long-Term Exposure**: Prolonged exposure to sound levels above 85dB(A) can cause hearing damage over time, especially when exposure exceeds 8 hours per day. For each 3dB increase in sound level, the safe exposure duration is halved. For instance, at 88dB, the safe exposure limit drops to 4 hours.
2. **Short-Term Exposure**: Sounds at levels of 100dB or higher can begin to cause hearing damage within 15 minutes of exposure. Typical sources of such noise include loud music or machinery.
3. **Impulse Noise**: Extremely loud, brief sounds (impulse noise) like gunshots or fireworks, reaching levels above 120dB, can cause immediate and permanent hearing damage. The damage is more severe with higher sound levels, even if the exposure is brief.
4. **Frequency-Dependent Risk**: The risk of hearing damage is frequency-dependent. Sounds at higher frequencies (e.g., 4kHz to 8kHz) are more likely to cause damage than lower frequencies (e.g., 500Hz), even at the same decibel level.

Overall, the combination of high sound pressure levels and prolonged or repeated exposure, especially at certain frequencies, can significantly increase the risk of hearing loss [2-3].

1. Main Headphone Types on the Market

Sealed Dynamic Headphones

The sealed chamber design leads to significant reflections between the diaphragm and the chamber walls. These irregularities in frequency response, including peaks and dips, make these headphones unsuitable for high-performance sound reproduction, though they are the most affordable option.

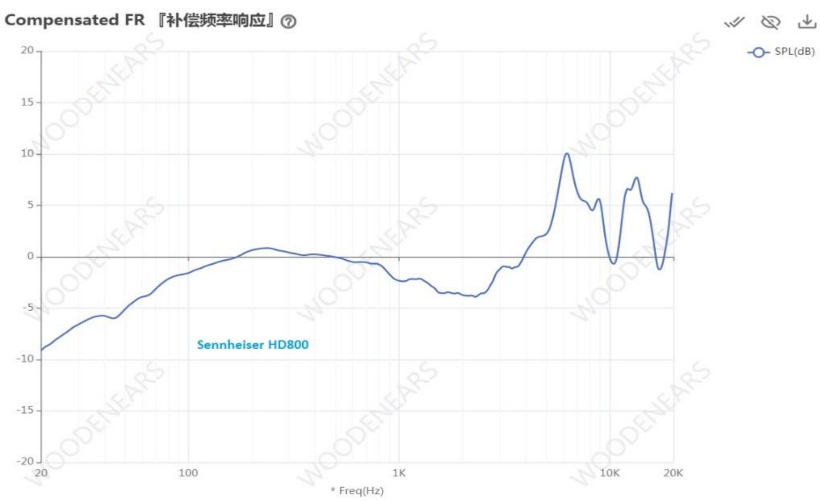

Figure 2. *Frequency response of dynamic headphone [4]*

Magneto-static Headphones

Magneto-static headphones offer a more linear frequency response and faster impulse response compared to dynamic headphones, due to their operational principle. The voice coil is evenly distributed across the membrane's surface within a more uniform magnetic field. However, the mass of the voice coil still contributes to partial oscillations, resulting in a moderate impulse response [1].

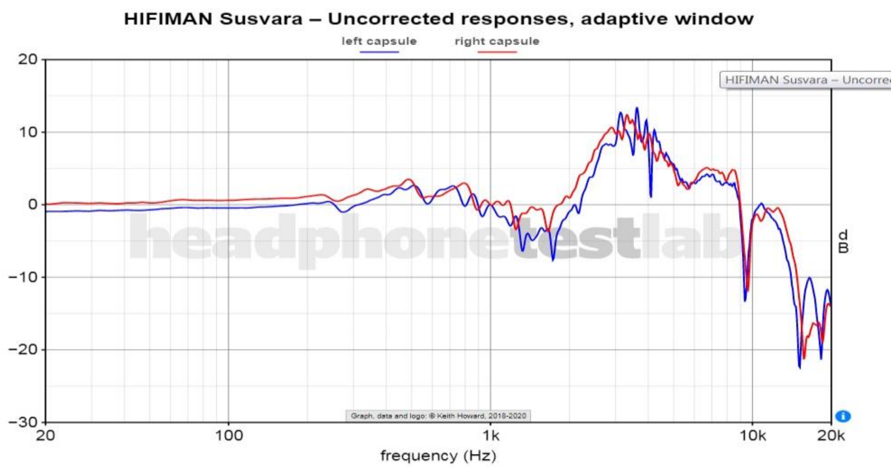

Figure 3. *Frequency response of a mahneto-static headphone [4]*

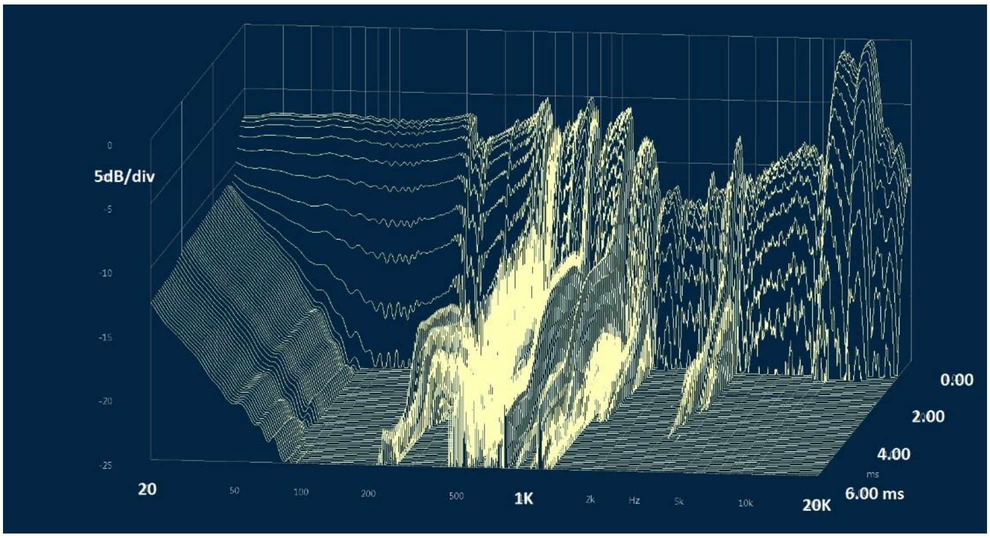

Figure 4. *Waterfall response of a magneto-static headphone*

From the solutions discussed above, it is clear that the only viable option for achieving a more linear frequency response with a faster impulse response is an electrostatic design.

2. Methods and Development Directions

To develop headphones with the highest possible performance, the following criteria should be adhered to: Electrostatic design, The membrane should be large in respect to the earcups to enable plane wave behavior, The internal earpad must be larger than the earcups to prevent deformation or obstruction during use, ensuring the earcups' acoustic properties are fully utilized and to achieve perfect acoustic sealing to ears from the environment.

The benefits of electrostatic transducers include: Plane wave behavior in the vertical and horizontal plane, Vectored polar response in the vertical and horizontal plane within the critical frequency range, Dipole polar pattern to minimize side reflections, Linear frequency response, Low distortion, Quick impulse response.

3. Experiments and Results

In the first step, frequency responses are measured using a semi-dummy head. A calibrated measurement condenser microphone is employed with the Audiomatica CLIO (2016) Electrical and Acoustical Measurement System in two stages: first without the earcup, and second with an artificial earcup to demonstrate the earcup's frequency response [4,6].

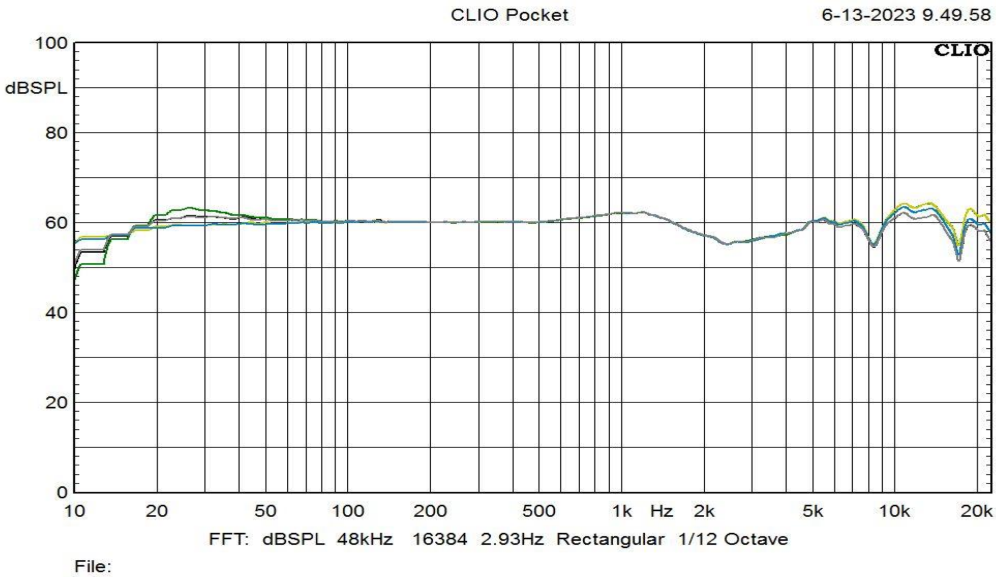

Figure 5. *Frequency response of the self-developed electrostatic headphone [7]*

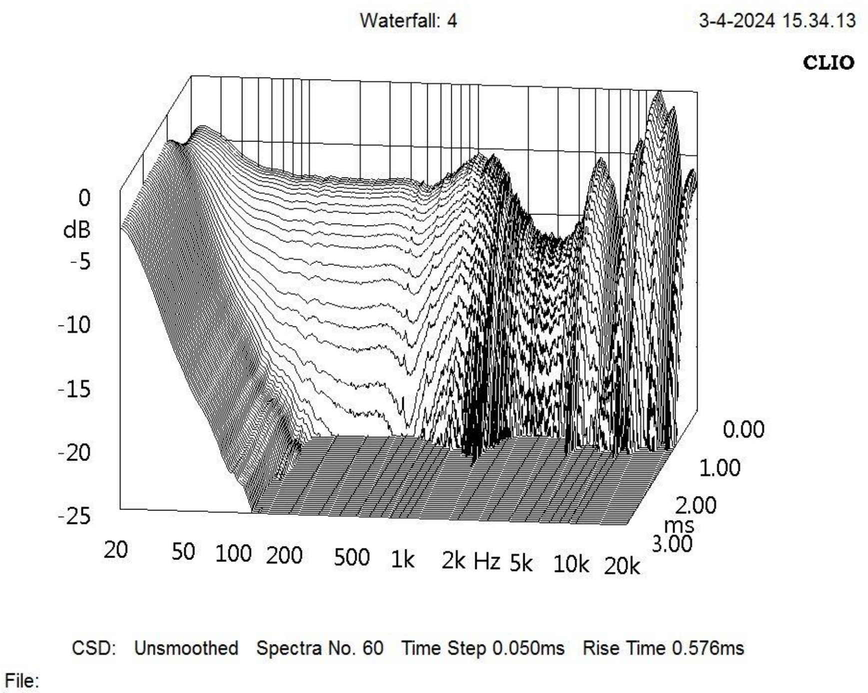

Figure 6. *Waterfall graph of the self-developed electrostatic headphone [7]*

The frequency response is notably more linear and the impulse response is faster, compared to measurements from dynamic and magneto-static headphones [4].

These well designed electrostatic transducers can play a crucial role in mitigating noise pollution in urban environments, enhancing well-being by reducing external noise. Their energy-efficient design reduces power consumption compared to conventional headphones, contributing to lower carbon emissions. These headphones help reduce dependency on high-emission audio devices, aligning with global sustainability goals. The use of durable, sustainable materials and the long lifespan of electrostatic transducers further promote sustainable design in the audio industry. In urban areas, electrostatic headphones provide an effective solution to noise pollution, reducing the need for large-scale noise control infrastructure. In occupational settings, they can improve health and safety by offering personal noise protection, preventing hearing loss and stress-related disorders. Their noise-canceling technology also enhances cognitive performance, improving focus in noisy environments.

4. Conclusions

This paper presents measurements demonstrating that a more linear frequency response, relative to the human hearing system, has been achieved. Furthermore, impulse response measurements, as shown in the waterfall diagrams, reveal significantly faster responses—nearly independent of frequency (within 2ms)—compared to magneto-dynamic transducers, which exhibit response times at least twice as long and are highly dependent on frequency due to partial oscillations of their membranes. The results indicate that the electrostatic design can effectively be employed in active acoustic noise-canceling systems, yielding superior performance compared to conventional magneto-dynamic transducers. This personal protective active noise-canceling system can be driven by DSP processing, incorporating integrated microphones and amplifiers.

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