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Ultralight circumaural open headphones

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ABSTRACT

Audio rendering in AR/VR applications is typically combined with acoustically transparent headphones to facilitate immersion. When developing such headphones today, the challenge is no longer the absence of signal processing capacity. Consequently, hardware development can focus on the electro-acoustic core properties. This allows to consider radical acoustic headphone designs without sacrificing audio quality. We present ultralight circumaural open headphones with ear cups based on bionic design and their step-by-step tuning. The prototype is open access, 3D-printable, and avoids any excess material. Hereby excellent acoustic transparency is accomplished and verified in comparative measurements with industry-standard headphones.

1 Introduction

Audio playback via headphones in augmented/virtual reality needs to be both acoustically transparent and of the high audio quality. These prerequisites target a seamless integration of the virtual/augmented reality with physical reality that surrounds the listener. An extra-aural prototype was presented in [1, 2], and a modification of existing headphones to enhance transparency was presented in [3]. As an alternative to acoustic transparency, closed headphones can be equipped with integrated hear-through microphones to accomplish transparency electro-acoustically.

Measurements of the headphones' passive attenuation curve can provide valuable insights. In research, some studies utilize acoustic transparency or evaluate its qualities more intensively. Listening experiments involving the transparency of various headphones were conducted to compare, e.g., the localizability of virtual and real sources, or the front-back confusions introduced, cf. [4, 5, 6, 7]. A model of the perceptual transparency was introduced in [4]. Moreover, it appears from this recent study that currently there are only a few suitable headphones that provide perceptual transparency.

This work aims at the development of acoustically transparent headphones taking augmented reality binaural rendering capacities into account, in the sense that it can always implement digital equalization easily. Digital equalization also offers the opportunity to work on a hardware design whose target frequency response curve needs not be perfectly flattened by acoustic construction and damping. This saves weight and material-consuming efforts of sound tuning.

What can the slimmest and lightest, and yet powerful pair of open headphones look like, when the benefits of digital equalization are all available?

2 Development and Verification

The main goal was to design headphones whose developing takes into account the specific use of equalization. The second goal was to keep the construction as simple as possible, based on 3D printing, and easy to build and repair. And the third goal was to find a lightweight, durable design that supports the illusion of not wearing any head-worn device, at all.

With multiple components rather than just the loudspeaker contributing to the frequency response of headphones appears difficult to pursue one specific target goal when prototyping. The fact that equalization will be used in the final application helps to circumvent this difficulty and permits to divide the development process into two parts: the hardware design and, independently, the work on a frequency response target for the headphones. Work on both interacting topics can almost be carried out separately.

With this approach, also unusual designs become thinkable. Yet there are certain features that the hardware must deliver, and on which we focus, here. Strong sound reproduction capabilities at low frequencies are among the most important goals, and limitations are mostly determined by the hardware itself. If low frequencies are meant to be boosted, the resilience of the loudspeaker to additional electric power as well as to higher diaphragm excursion has to be ensured.
A minimum of acoustic reflections and acoustic/electro-acoustic resonances is also more reliably ensured by hardware design than through signal processing.

For performance verification of headphones, it is common to rate them mainly by their frequency response. A frequency response of this prototype without equalization however reveals only a little about the final performance, when the target application includes digital equalization.

To ensure an overall high performance, the frequency response is only meaningful when at the same time low harmonic distortion can be ensured for the desired sound level. Both are therefore analysed in the non-equalized and equalized condition, as well as with and without a bass-boosting felt ring.

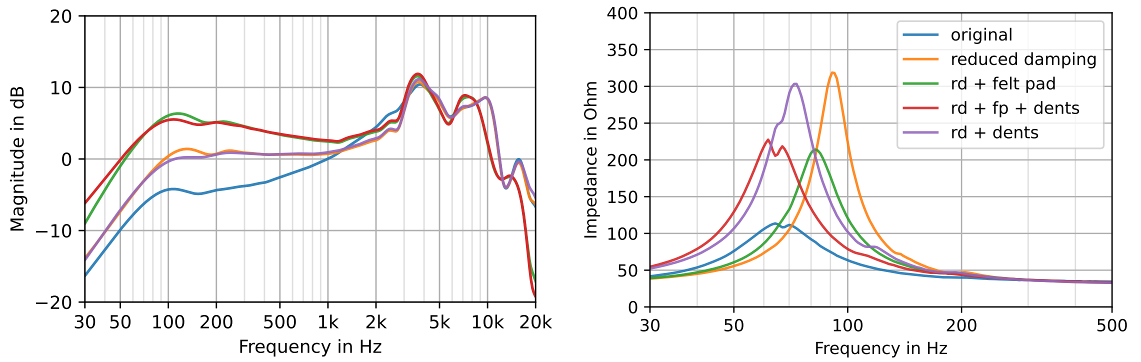
Fig. 1: Graphically rendered CAD model of proposed ultralight circumaural open headphones

The acoustic transparency of the headphones is another essential property that needs to be evaluated over a representative set of surrounding arrival directions.

2.1 Enhancements of the Transducer Response

As a consequence of the open design, a transducer with high excursion and large diameter is required. For the proposed prototype, the Peerless HPD-50N25PR00 was selected as a suitable loudspeaker.
Although the maximum peak-to-peak excursion of 1.2 mm is only average, the transducer combined with an effective surface area of 16 cm^2 is capable of producing enough acoustic flow in the low end of the frequency scale. Moreover, it currently appears to be the best transducer available to the ordinary customer on the market, with a high cost-benefit ratio.
Measurements of the loudspeaker for further performance optimization were made in its near free field at a distance of 5 mm.

This measurement setup was chosen to evaluate the performance of the transducer itself, isolated from the



(a) Frequency response of the ear-/free-field sound pressure

(b) Frequency response of the electric impedance

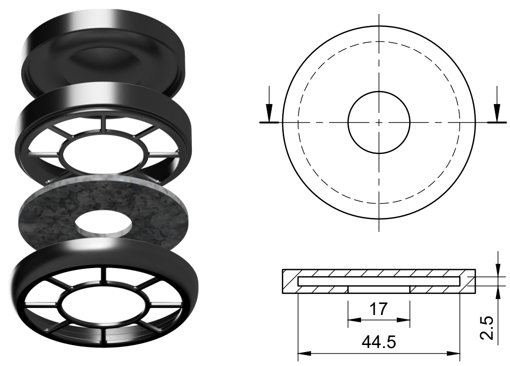
Fig. 2: Measurements of the selected loudspeaker in original condition and after several modifications enhancing the transducer's low frequencies. 1/6 octave smoothing applied

impedances of the rest of the construction and the proximity to the ear. This choice is justified by the fact that the loudspeaker itself will be operating in the environment of an open headphone, almost as if it was in free field.

To increase the performance and make it fit the given needs, several modifications were applied to the loudspeaker.

In a first step, the mesh on the back was partly removed to increase efficiency by reducing the damping. This becomes visible in the impedance peak in Fig. 2(b) that rises from the light blue (original) to the orange curve (reduced backside damping). This boosts the frequency response by 5 dB below 500 Hz in Fig. 2(a). The fact that only low frequencies are boosted indicates that of the transducer only the outer part is effective above for frequencies below 1 kHz.

The next step was to create an air cavity with an opening, smaller in diameter in front of the loudspeaker by adding a felt ring, see Figs. 3. As can be formally argued by Appendix D, the felt ring and the emerged air cavity act as an additional moved mass that reduces the resonance frequency from the orange curve in Fig. 2(b) to the green curve, but also as an additional damping of the resonance peak. In terms of sound pressure, there is an increase at low frequencies caused by the reduction of the effectively radiating orifice, see Appendix C. Fig. 2(a) shows a boost accomplished below 500 Hz, and a lowered cut-on frequency. Since the orifice in the felt pad is large enough compared to the paper dome



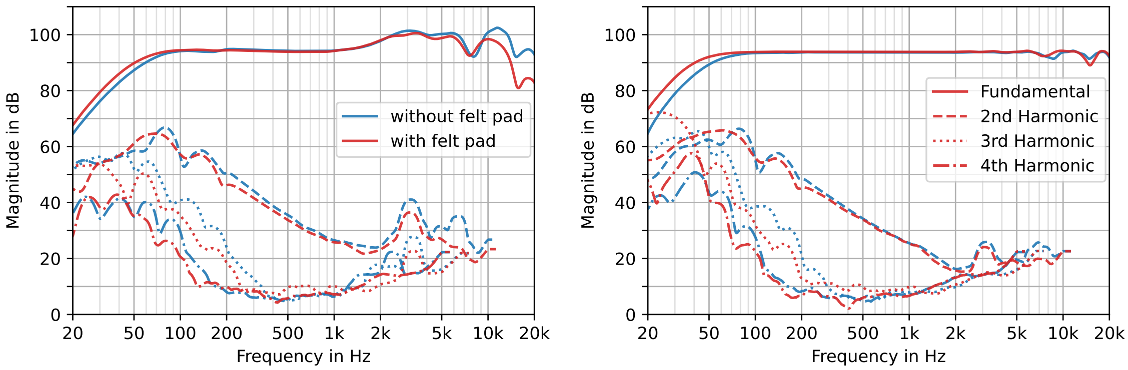
(a) Loudspeaker housing

(b) front air cavity

Fig. 3: Loudspeaker housing including the felt ring/pad and its mounting that causes the air cavity and reduces the front orifice (dimensions in mm)

that it exposes, the mid to high frequencies are apparently not affected. Only above 8 kHz, frequencies get slightly damped by the felt pad. The constellation cannot cause an effective Helmholtz resonance, as formally argued in Appendix B.

In the final step, the pattern of the diaphragm was given small dents to reduce the stiffness of the transducer suspension, cf. Appendix D. As seen in Fig. 2(a), the frequency response without equalization (green vs. red) is not affected by this. It mainly helps to further reduce the resonance frequency, see Figs. 2(b), which in turn makes the subsequent digital equalization easier.



(a) SPL before equalization

(b) SPL after equalization

Fig. 4: Sound pressure frequency response of headphones worn by a dummy head, w/wo felt ring (red/blue), linear response: fundamental (solid); distortions: 2nd (dashed), 3rd (dotted) and 4th harmonic (dash-dot). 1/3 octave smoothing applied

2.2 Distance, Angle and 3D Model

Beside the trade-off between sound pressure level and openness, another factor needs to be considered when determining the distance of the transducer to the ear. There is a comb filter resulting from the reflection between the human head and the loudspeaker that cannot be entirely avoided. This effect is reduced by the damping of the reflection, like when inserting the felt pad. Since the distance between the transducer and the head is responsible for the position of the comb filters in frequency, it was chosen in such that peaks in the frequency response are not amplified, but rather suppressed. Additionally, the distance of the transducer is fixed, so the effect on the frequency response can be reliably equalized to some extent. To make a decision based on measurements, the B&K 4128 was used. The distance was set to 32 mm to the ear and to an inclination angle to the side of the head of 12°, towards the front.

Inspired by the admired AKG K1000, an entirely open design was chosen. Experiments with a similar design as the K1000 showed that without circumaural support, repositioning on the head varied too much and was therefore problematic for measurements and for robust equalization.

Instead of a traditional design, a highly acoustically transparent but circumaural design approach was chosen. 3D printing as a manufacturing method offers unusual design options and ensures easy reproduction. A thin, organic-like frame was designed as open structure to hold the loudspeaker in place relative to the ear, see Fig. 1.

2.3 On-Ear Response and Harmonic Distortions

The frequency response and the corresponding distortion at a given level were measured on the Neumann KU100, which is readily diffuse field compensated by design.

The fact that the KU100 does not fully simulate the acoustic impedance of ears including ear canal was not considered a problem, because for the proposed fully open design, there would not much of an effect of the ear-canal impedance back on the transducer.

Diffuse field was chosen as the target for frequency response equalization as there currently appears to be no other well-defined target other than the Harman target, which requires an GRAS KEMAR dummy head.

The prototype's frequency response and distortion when targeting 94 dB SPL at 1 kHz are shown in Figure 4(a) with and without felt ring. The same measurements were made in Fig. 4(b), but with diffuse field equalization that leads to a flat frequency response in the KU100.
With the felt pad on, the loudspeaker distorts slightly less in the lower frequency range and can therefore be

equalized down to a cut-on frequency of 35 Hz (-6 dB). Without the felt pad, 45 Hz was chosen as the lower limit to keep the distortion at roughly the same.

The harmonic distortions always increase towards the lower frequencies and with the felt ring, they are 1% at about 140 Hz and slightly higher without the felt ring. This behaviour is pretty much in line with the specifications of the AKG K1000.

2.4 Acoustical Transparency and Comparison to other headphones

To evaluate the transparency of headphones, the KU100 dummy head was placed in an anechoic chamber with eight loudspeakers distributed horizontally around it. Then for every loudspeaker, the differences in frequency response were measured at ear of the dummy with and without headphones. To automate the measurement sequence through all loudspeakers, a Python script was written.

The difference in acoustic transparency with and without felt ring can be observed in Figs. 5(a),5(b). Even with felt ring, the headphones are more open than usual open-back headphones. For optimal transparency in hear-through applications, it is suggested to use the headphones without felt rings.

To compare the result, other headphones were measured. The AKG K1000 was measured because it serves as a model for acoustic transparency in headphones. Although it is old and only available second-hand, it is still used in various current researches. The Sennheiser HD600 was chosen because it represents a well-established industry standard.

The comparison of Figs. 5(b),5(a) and Figs. 5(c),5(d) shows that the proposed prototype performs remarkably well. Both in terms of its directional consistency and flatness of its passive attenuation.

3 Conclusion

The main goal of this work was to develop a DIY low-cost, open headphone that is easy to build and yet practical enough to be used in practice. Its open design is made available online `https://github.com/adude995/DIY-Open-Headphone`.

The resulting prototype successfully demonstrates a radically new design for ultra-lightweight headphones, which are ultra-transparent, and cost-efficient, with equalization moved to a pre-processing step. We documented useful incremental modifications and verified them by measurements.

The verification measurements employed different measurement setups that permit focusing either on optimizing the frequency-response behavior or on the final evaluation of the equalized prototype, in separate steps. To support reproducible research, measurement scripts are found in the online repository provided.

The results showed that our main hardware design goals were accomplished. Especially in terms of transparency, the prototype could outperform other headphones we tested. Its frequency response is comparably flat and its harmonic distortions comparably low, despite its low costs.

Further work is planned that employs measures and predictions of acoustic transparency according to the method presented in the article by Lladó et al [4].

Finding a suitable sound target other than diffuse field compensation turned out to be more complex than expected. This problem should be addressed by future work.

4 Acknowledgments

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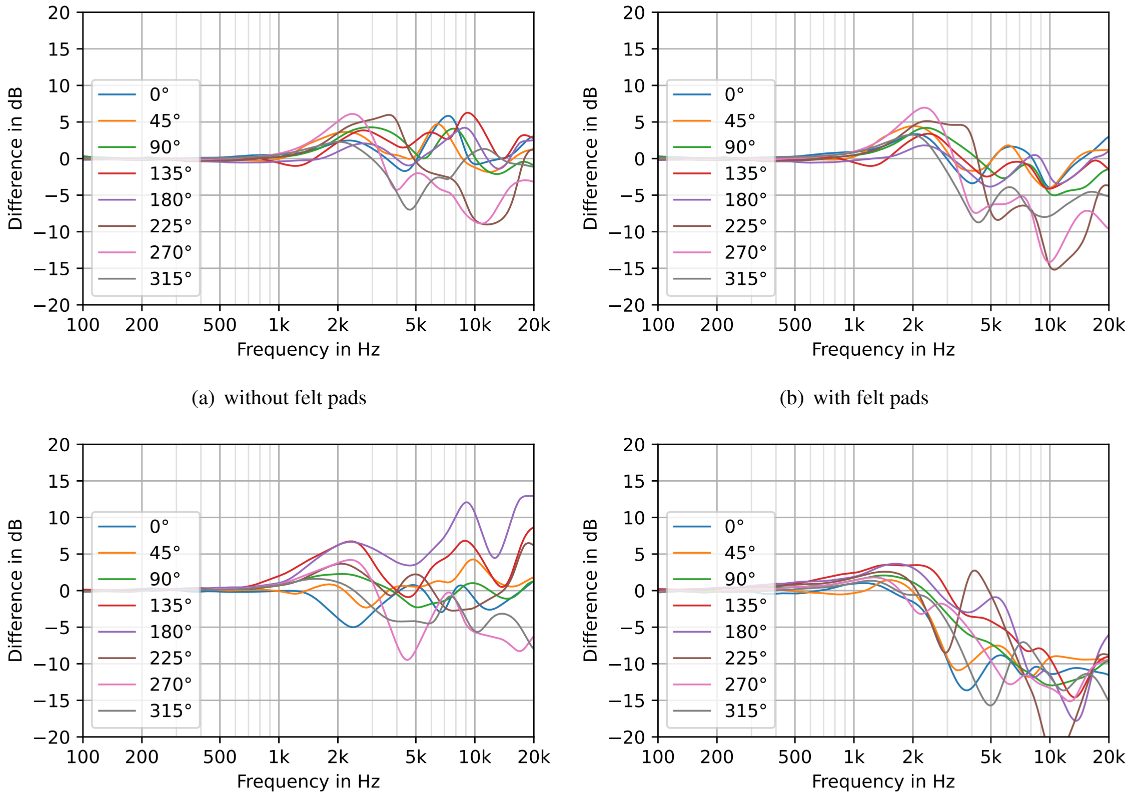
A Radiation impedance

A piston loudspeaker of the radius a is typically loaded by an added mass of air

$$M_0 = \rho \, \frac{8\,a^3}{3}$$

at low frequencies $ka \ll 1$, cf. [8, p.484,665], both for a piston in an infinite baffle with one-sided acoustic load, or one that is unbaffled and drives a two-sided load. At high frequencies $ka \gg 1$, the acoustic load becomes $(\pi a^2)\,\rho\,c$ for one-sided, $2(\pi a^2)\,\rho\,c$ for two-sided load. $a = 2\,\mathrm{cm}$ yields for $ka < 1$ the limit $f < 2.7\,\mathrm{kHz}$.



(a) without felt pads

(b) with felt pads

(c) AKG K1000, ear cups inclined by 45°

(d) Sennheiser HD600

Fig. 5: Measurements of the acoustic transparency, at the right ear (at 90°) with headphone worn referenced by response without headphones for several directions in 45° direction steps. Figures are shown for the proposed headphones, both with and without felt pads as well as two reference open headphones for comparison.

B Helmholtz resonance

A cylindrical enclosure with the volume $V = (\pi a_1^2)\,h$ of the height has the stiffness

$$S_2 = \frac{\rho\, c^2\, (\pi a_2^2)^2}{V}$$

to displacements $x_2 = v_2/(\mathrm{i}\omega)$ at its piston-shaped orifice of the radius $a_2 < a$. If the piston is only virtual, it would still need to move a one-sided added mass of air $M_2 = \rho\, \frac{1}{2} \frac{8a_2^3}{3}$ as its radiation impedance $\mathrm{i}\omega M_2$. The total output force consists of both this mass and the stiffness $F_2 = [\mathrm{i}\omega M_2 + S_2/(\mathrm{i}\omega)]\, v_2$. No force is needed if $\omega^2 M_2 = S_2$, which defines the Helmholtz resonance

$$f_\mathrm{H} = \frac{1}{2\pi}\sqrt{\frac{\rho c^2 (\pi a_2^2)^2}{(\pi a_1^2) h}\,\frac{6}{\rho\, 8\, a_2^3}}.$$

$h = 2.5\,\mathrm{mm}$, $a_1 = 22.25\,\mathrm{mm}$, $a_2 = 8.5\,\mathrm{mm}$ would yield $f_\mathrm{H} = 29.4\,\mathrm{kHz}$, which is far beyond the $ka_2 = 1$ limit at $f = 6.4\,\mathrm{kHz}$; the orifice impedance is no mass, there.

C Orifice reduction

Reducing the radius a_1 of the loudspeaker port to

$$a_2 = a_1/\alpha$$

of the output orifice, i.e. by $1/\alpha^2$ of the original surface, increases the velocity by a factor of α^2 to maintain a continuous acoustic flow $v_1\,(\pi a_1^2) = v_2\,(\pi a_2^2)$,

$$v_1 = v_1/\alpha^2$$

as the air enclosed is stiff at frequencies below f_{H}. As $h \ll \lambda$, the sound pressure p_1 loading on the piston loudspeaker is the same as p_2 at the reduced orifice $p_1 = p_2$. The force on the piston is $F_1 = p_1\,(\pi a_1^2)$, while at the orifice it is $F_2 = p_1\,(\pi a_2^2)$, so that the piston is loaded with

$$F_1 = \alpha^2\,F_2.$$

The resulting impedance is

$$Z_1 = \frac{F_1}{v_1} = \frac{\alpha^2 F_2}{v_2/\alpha^2} = \alpha^4 Z_2.$$

The orifice impedance for $ka_2 < 1$ is dominated by the air mass $M_2 = \rho\,\frac{8a_2^3}{6}$ which for $a_2 = 8.5\,\mathrm{mm}$ becomes $M_2 = 1\,\mu\mathrm{g}$, acting as $Z_1 = \alpha^4 Z_2$ and hence virtual added mass of $\hat{M}_1 = 48\,\mu\mathrm{g}$ loading on the transducer. (For $a_1 = 22.5\,\mathrm{mm}$ and no reduction, the one-sided mass on the transducer would be $M_1 = 18\,\mu\mathrm{g}$.) The apparent mass increase is small compared to the $M = 700\,\mu\mathrm{g}$ mass of the transducer, but large enough to produces a small decrease of the transducer's impedance resonance frequency, which reflects the magnitude of the velocity due to the input voltage. Assuming this effect to be only local around the resonance of the transducer, we may model a change of the sound pressure above under the assumption that the velocity v_1 is unaffected by reducing the orifice. The sound pressure $p_2 = \frac{\mathrm{i}\omega M_2}{\pi a_2^2}\,v_2$ increases from the original one $p_o = \frac{\mathrm{i}\omega M_1}{\pi a_1^2}\,v_1$ through $M_2 = M_1/\alpha^3$, $v_2 = \alpha^2\,v_1$ by

$$\frac{p_2}{p_o} = \frac{\alpha^2\alpha^2}{\alpha^3} = \alpha$$

i.e. by 8.5 dB when $\alpha = 2.6$.

D Changes of the resonance peak

Shifts in the resonance $\omega = \sqrt{M/S}$ of the admittance curve $Y = 1/[\mathrm{i}\omega M + R + S/(\mathrm{i}\omega)]$ to lower frequencies can be interpreted as additional moved mass ΔM, judging by the mass of the cone and stiffness of its suspension. A relative downwards shift of the resonance $\frac{\omega_2}{\omega_1}$ yields with $\omega^2 = S/M$ the result $(M + \Delta M) = (\frac{\omega_1}{\omega_2})^2 M$. In some circumstances, reduction of the resonance frequency can be interpreted as a decrease in stiffness $(S - \Delta S) = (\frac{\omega_2}{\omega_1})^2 S$. A reduction of its resonance peak indicates an inversely proportional increase of damping R. The electrodynamic transducer, $F_1 = Bl\,I$, $U = Bl\,v_1$, maps the mechanical admittance $Y_1 = v_1/F_1$ to electric impedance $Z = U/I = (Bl)^2\,Y_1$.

References

[1] Schultz, F., Lindau, A., Makarski, M., and Weinzierl, S., "An extraaural headphone for optimized binaural reproduction," in *26th Tonmeistertagung*, Leipzig, 2011.

[2] Erbes, V., Schultz, F., Lindau, A., and Weinzierl, S., "An extraaural headphone system for optimized binaural reproduction," in *Fortschritte der Akustik (DAGA)*, Darmstadt, 2012.

[3] Meyer-Kahlen, N., Rudrich, D., Brandner, M., Wirler, S., Windtner, S., and Frank, M., "DIY Modifications for Acoustically Transparent Headphones," in *148th Conv. Audio Eng. Soc.*, Vienna, 2020, e-Brief 603.

[4] Lladó, P., Meyer-Kahlen, N., and McKenzie, T., "Predicting Perceptual Transparency of Head-Worn Devices," *Journal of the Audio Eng. Soc.*, 70(7/8), 2022.

[5] Satongar, D., Pike, C., and Teq, A. I., "The Influence of Headphones on the Localization of External Loudspeaker Sources," *Journal of the Audio Eng. Soc.*, 63(10), 2015.

[6] Pörschmann, C., Arend, J. M., and Gillioz, R., "How Wearing Headgear affects measured head-related transfer functions," in *EAA Spatial Audio Sig. Proc. Symp.*, Paris, France, 2019.

[7] Schneiderwind, C., Neidhardt, A., and Meyer, D., "Comparing the effect of different open headphone models on the perception of a real sound source," in *150th Conv. Audio Eng. Soc.*, 2021, paper 10489.

[8] Skudrzyk, E., *The foundations of acoustics*, Springer Wien, New York, 1971.