On the Effectiveness of a Simple Headphone Amplifier

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1 Abstract

To explore the full potential of my newly bought ER4SR earphone on an UR22 USB Audio Interface, a headphone amplifier with a simple op-amp-based design is investigated. Several measurements on the effect of different loads are taken and the data is plotted to evaulate the performance of the amplifier. All experiments are carried out under a tight budget to ensure the replicability for individuals (unfortunately including the author) without access to extensive devices and facilities. Results are discussed in the end and serveral implications on practical aspects of high-fidelity audio playback are listed.

2 Introduction

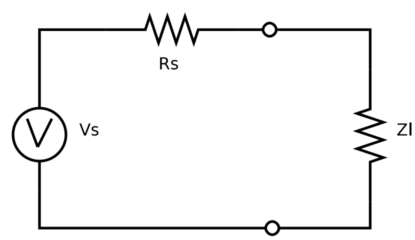


Figure 1: Thevenin-equivalent circuit of a soundcard loaded with headphone Z_l.

There is a known problem that soundcards with relatively high output impedance, such as UR22 whose output impedance is 40Ω, suffers from a voltage drop when driving low-impedance transducers (such as ER4 with an impedance of 45Ω). Figure 1 illustrates a simple mono-channel model for the problem, where the soundcard has a Thevenin voltage source V_s and an inner resistance R_s and the headphone has a load impedance Z_l. When the port is open (i.e. $Z_l = \infty$), the voltage across the port equals to the source voltage. In the case when a headphone is connected, the voltage across the headphone is determined by the voltage divider equation.

$$V_l(s) = V_s(s)\frac{Z_l(s)}{R_s + Z_l(s)} \tag{1}$$

Assuming the impedance of the load is constant across frequency, and in our case plugging in the values $R_s = 40\Omega$, $Z_l = 45\Omega$, the loaded voltage is expected to be 53% of the input according to Eq. 1. Thus the output volume is reduced by nearly half. In practice the result could be worse as the impedance of speakers, especially earphones often changes with respect to frequency; in such case the voltage gain of the voltage divider basically becomes a damped version of the load impedance, giving non-uniform amplification and phase shifts on the audio spectrum.

3 Initial Investigation

The above analysis based on data from the specs sheet does not account for frequency-dependent load impedances. To get a better understanding of the problem, the open-circuit voltage and loaded voltage at soundcard line-out port are measured and voltage drop is analyzed in this section.

3.1 Oscilloscope on a Budget

The soundcard is doubled as an oscilloscope. UR22 has two line-in jacks with 24 dBu (12.2 V rms) maximum input level and 20 kΩ input impedance. Given that its input impedance is well-above the range for headphones and earphones, the line input-based oscilloscope is appropriate for our purpose. To further reduce its influence on the circuit to be measured, an OPA1652 operational amplifier is inserted between the measurement port and line-in. The measurement amplifier circuit is shown in Figure 2 and it has a 15.5 dB voltage gain.

In the following measurements, the input gain knob on UR22 is set at 12 o'clock position and the soundcard is operating at a 96 kHz sampling rate. It is found that under such setup, the input signal has a peak value of 0.5 when the rms voltage at the measurement port is 0.2 mV. In other words, the rms sensitivity is 0.566V/input level.

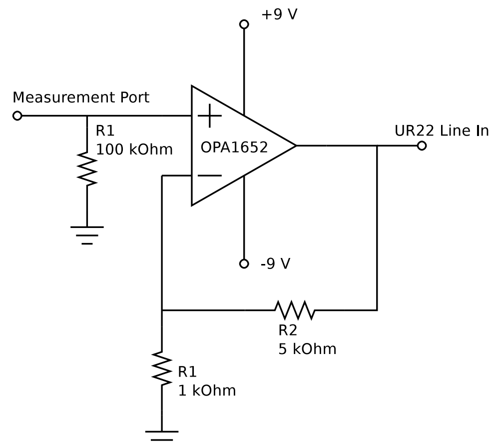


Figure 2: Circuit schematics of the measurement amplifier.

3.2 Measurement Calibration

The filtering and DAC/ADC components in the soundcard could introduce a slightly non-flat frequency response to the measured signal. If the input-output relation is modeled as a cascaded transfer function $H(s) = O(s)H_l(s)I(s)$ where $O(s)$ is the soundcard line-out transfer function, $H_l(s)$ is the voltage transfer function of the load and $I(s)$ is the soundcard line-in transfer function, the line-in and line-out errors can be factored out, as long as the voltage to be measured is a linear function of the line-out voltage.

Figure 3 shows H_{fb}, the soundcard feedback transfer function obtained by sending a 10 Hz to 48 kHz chirp signal from UR22 line-out back into its line-in. It comes clear that $H_{\mathrm{fb}} = O(s)I(s)$, in terms of the cascaded input-output model. In the following measurements, the spectrum of the measured signal is divided by H_{fb} to recover the voltage tranfser function.

3.3 Effect of Different Loads

In the following analysis, the voltage drop induced by different loads (headphones and earphones) connected to the soundcard is investigated. Defined as the ratio between loaded voltage and open-circuit voltage, the soundcard loaded voltage transfer function H_{sl} is computed for each playback device. The test signal is a 10 Hz to 48 kHz chrip signal at 0.2 mV rms. The rms voltage is chosen as such to match the test signal amplitude used in the official ER4 datasheet, which should give an acoustic pressure of 104 dB SPL at 1 kHz. Unless otherwise noted, in this report the data is obtained form the left channel as the two channels should be identical. In regard to the changes in electrical impedance due to different acoustic and mechanical loads on the transducer, in this report open-air upward-oriented load condition is applied.

The earphones tested, aside from Etymotic ER4SR, also include Sony EX (model number known) and Apple EarPods (3.5mm audio jack version); the headphones tested include Superlux HD681 and Beats

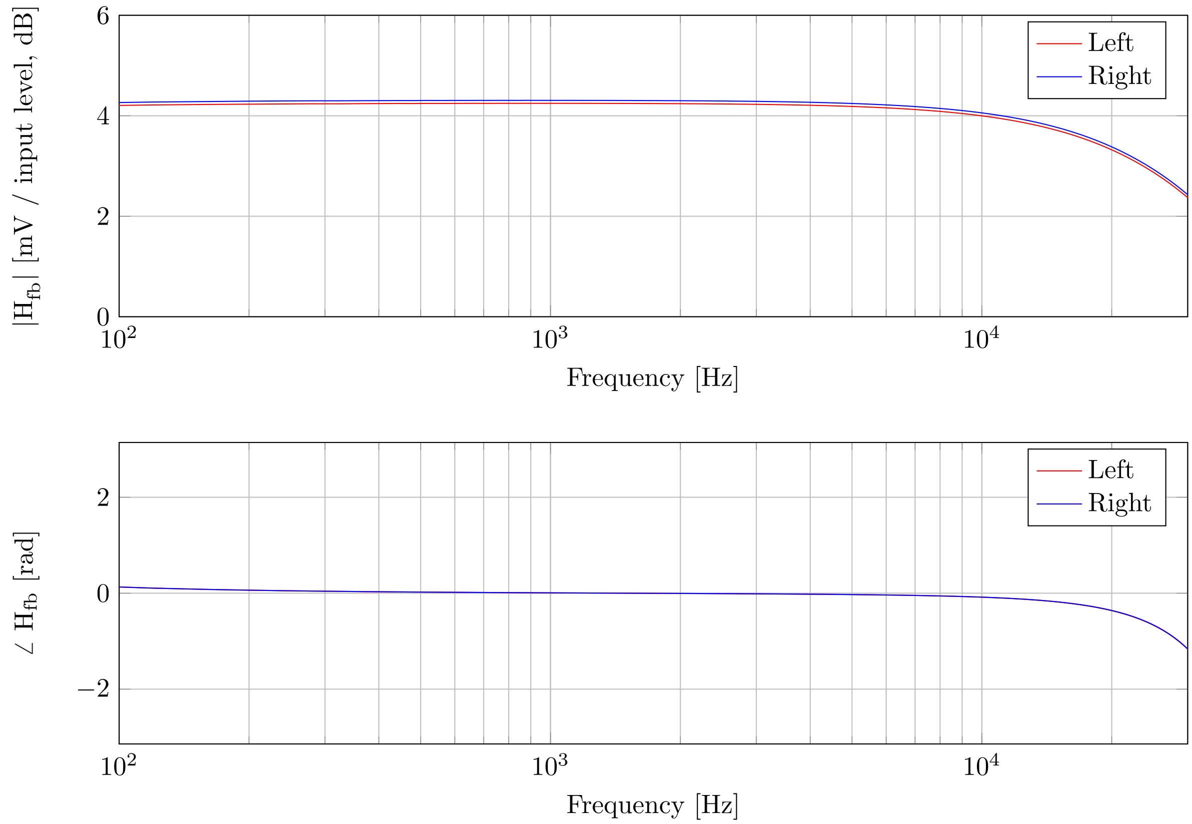


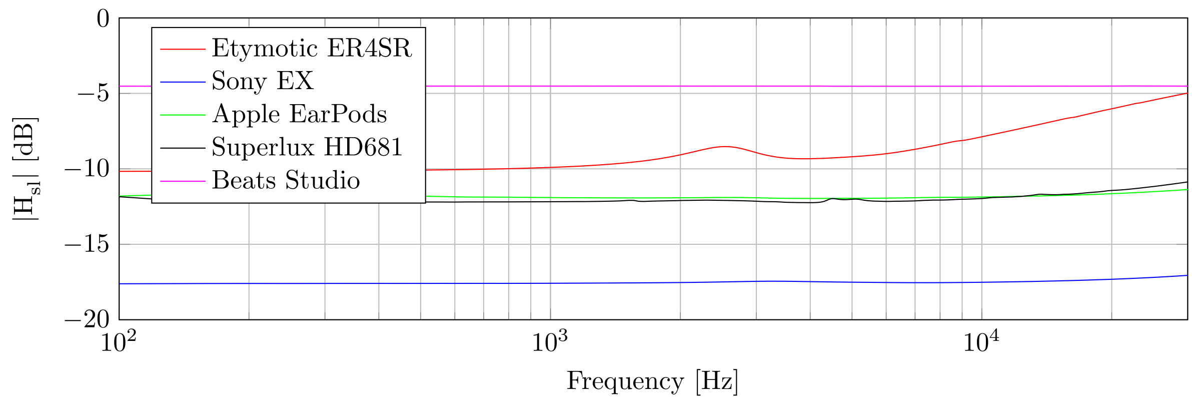
Figure 3: Soundcard feedback transfer function.

Studio[1].

Figure 4 shows the loaded voltage transfer function for the selected earphone/headphone models. Different degrees of voltage drop from 4.5 dB to 17.5 dB are observed. Most of the voltage drop curves are uniform along frequency axis within audible range, meaning that the sound receives little distortion besides amplitude scaling. However, the transfer function of ER4SR has a spectral slope that increases by 4 dB at high frequency and a 1 dB bump at 2.5 kHz. Knowing that the loaded voltage transfer function has a close relation to input impedance of the transducer, the non-uniform voltage gain of ER4SR can be attributed to its special design that compensates for ear canal resonance (whose first harmonic is around 2.5 kHz) and the radiation effect at pinna. On the other hand, the phase distortion is generally below 1 rad in audible range, and almost flat under 10 kHz. Thus phase distortion in this context is not a prominent issue affecting sound quality.

A better visualization of the spectral amplitude distortion is obtained by normalizing the transfer functions against their values at 1 kHz, shown in Figure 5. It is clear that ER4SR is the only device subjected to audible spectral distortion, and an amplifier is required to reduce such distortion. It is also seen that Beats Studio receives little or no distortion across all frequencies, despite having a rated impedance of 139Ω, not much larger than that of UR22. A highly possible explanation is that internally Beats Studio uses an op-amp to combine the audio with phase-inverted external noise captured through its microphone, for noise cancellation. However, this result should not be interpreted as Beats Studio achieving the best sound quality since the measurement does not determine the pressure response.

[1] The author is not a big fan of headphones so do not expect for having really good and pricy headphones tested here. The models listed here are virtually all what he has access to.



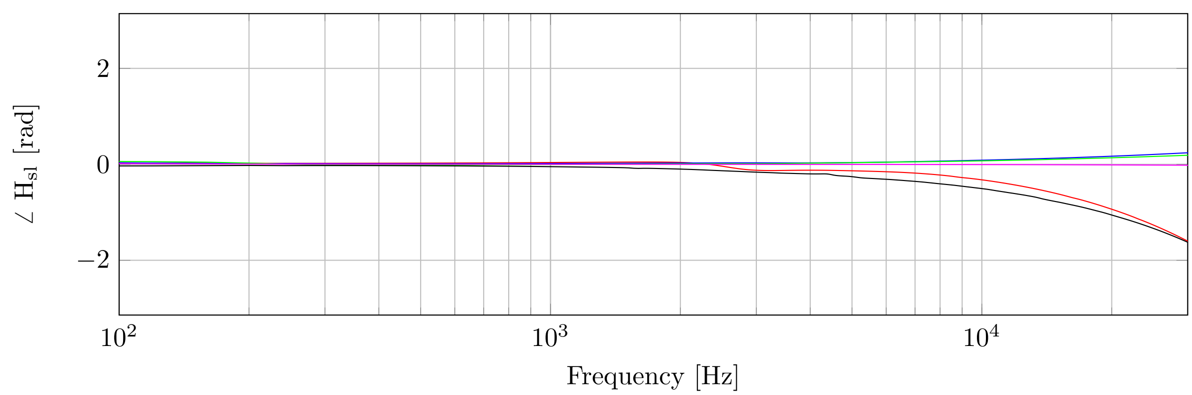


Figure 4: Soundcard loaded voltage transfer function for various headphones and earphones.

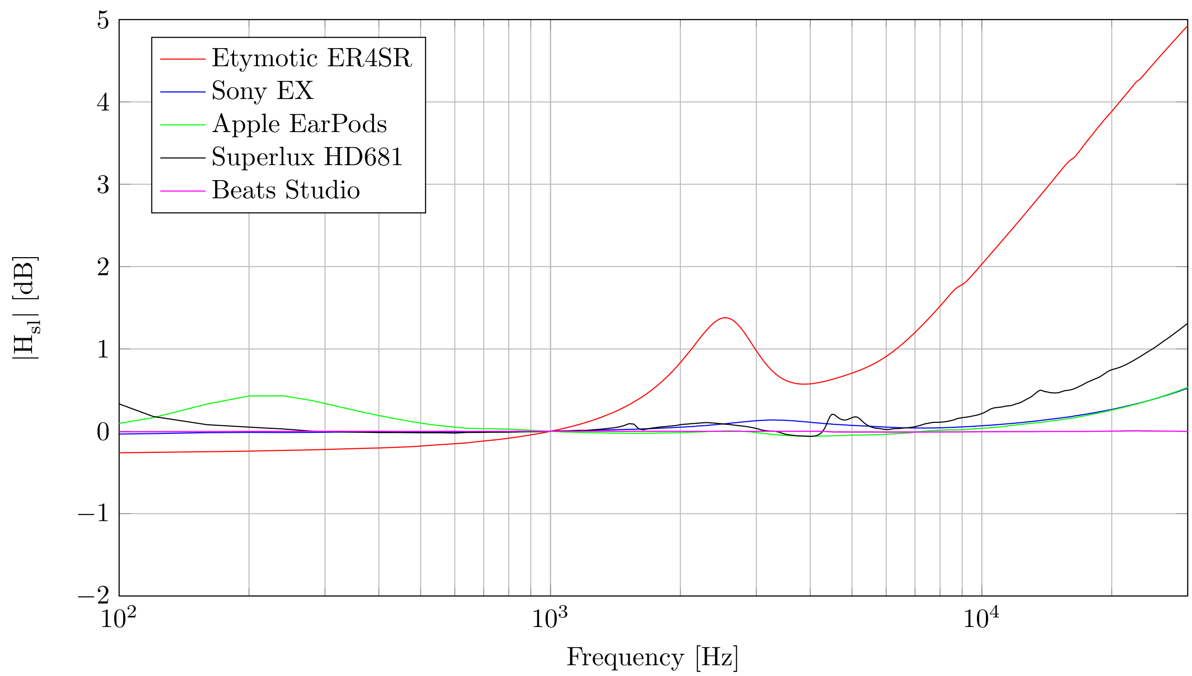


Figure 5: Magnitude of the soundcard loaded voltage transfer function normalized at 1 kHz.

4 Investigation on Headphone Amplifier

It has been found that when ER4SR is connected to UR22, the voltage drop is around 6 to 10 dB within the audible range. To compensate for such non-uniform voltage drop, A simple circuit[2] built around an OPA1652 is investigated in this section.

4.1 Amplifier Design

The circuit shown below (Figure 6) has a −9.5 dB constant voltage gain that roughly matches the voltage drop induced by ER4SR when directly connected to UR22. Since the circuits for left and right channels are identical, only one channel is shown.

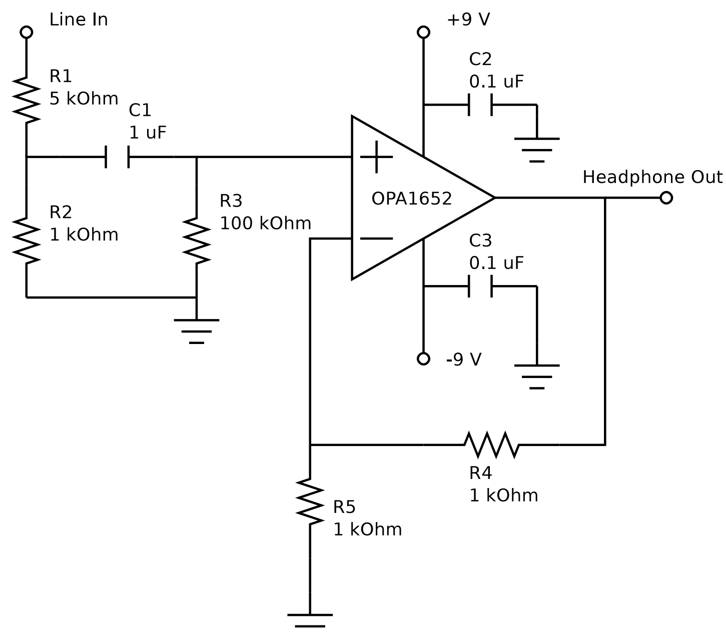


Figure 6: Circuit schematics of the headphone amplifier.

4.2 Performance Evaluation

The headphone amplifier circuit in Figure 6 has an input impedance of 6 kΩ. It is found that when connected to the soundcard, the amplifier has a negligible effect on input voltage and the voltage drop is on the order of 0.1 dB. The loaded voltage at the amplifier output ports is measured in a fashion similar to measuring the soundcard loaded voltage and the amplifier voltage transfer function H_{a} is computed by dividing the voltage across amplifier output ports by the soundcard output voltage. The results are shown in Figure 7. To investiate the amplifier's capability at driving small impedance loads, a 10 Ω resistor and a 1 Ω resistor are also included in the test loads.

The result indicates that phase distortion is negligible for all test loads. As for the amplitude, Etymotic ER4SR, Sony EX, Superlux HD681 and Beats Studio perfectly meets the designed voltage gain of −9.5 dB within audible range; Apple EarPods shows a 1 dB uniform voltage drop at all frequencies, for it having the smallest impedance among all products tested. The 10Ω resistor gives a voltage drop slightly deeper than Apple EarPods by half dB. Finally, a significant voltage drop of 6 dB compared to open-circuit voltage is

[2]This type of headphone amplifier is referred to as CMOY by the audio DIY community, named after its designer Chu Moy.

observed on the 1Ω resistor. The loaded rms voltage in such case is $200\text{mV} \times 10^{-16/20} = 31.7\text{mV}$ and the rms current is hence 31.7mA, close to the 50 mA maximum output current of OPA1652.

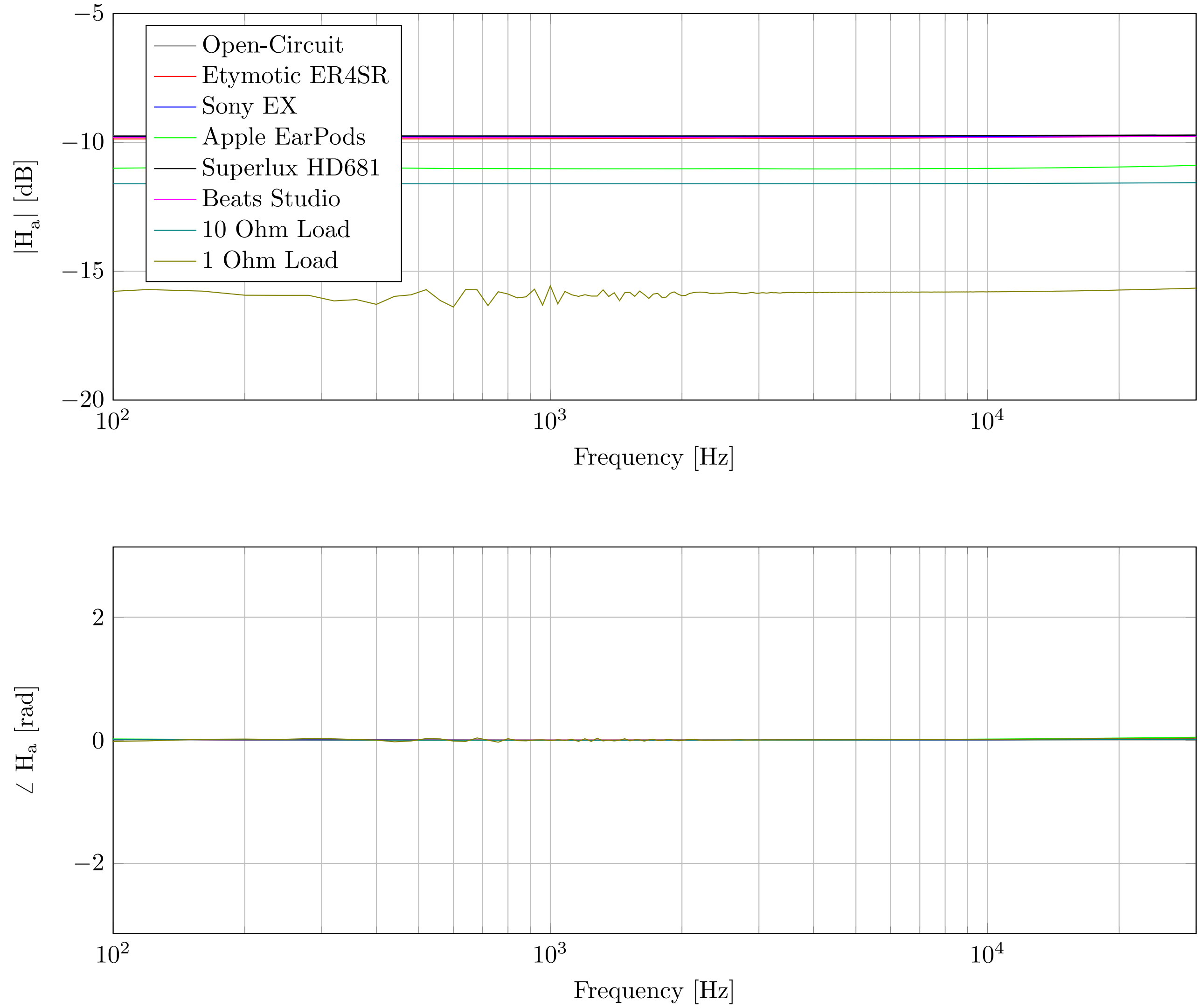


Figure 7: Amplifier voltage transfer function with different loads.

5 Discussion and Conclusion

Results from the initial investigation on the output capability of UR22 show that while the 40Ω source impedance of headphone-out do cause voltage drop when loaded with small impedance transducers, the voltage drop is often uniform (within ± 0.5 dB range after normalization) along frequency axis and thus does not affect the sound quality besides loudness. However there is an exception on ER4SR which has a damped anti-resonance at 2.5 kHz and an impedance slope at high frequencies; the voltage distortion exceeds 1 dB at 2.5 kHz and above 6 kHz and are thus considered audible.

The OPA1652-based amplifier circuit successfully eliminates the voltage drop when ER4SR is connected. For most of the headphones and earphones tested, the influence from the load is reduced to a negligible level.

Although it is important to note that in the case of small impedance loads ($\leq 10\Omega$), voltage drop is observed before reaching the maximum output current.

There however is an assumption that may not always hold, that 200 mV rms is assumed to be within the normal operating voltage of all headphones and earphones used in this test. Although audio devices generally have a large input dynamic range, 200 mV rms, close to the maximum operating voltage for ER4SR, may exceed such limit on other devices tested. A refined test procedure should adjust the input level with respect to the sensitivity of the device being tested.