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Non-Traditional Noise and Distortion Sources in Headphones and Earbuds and their Impact on System Performance and Ear Fatigue

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ABSTRACT

Non-Traditional dynamic noises and distortions that couple into earbuds and headphones are measured and analyzed. The effective noise and distortion level relative to the signal level for a number of commercially available headphones and earbuds are reported. The impact of this noise and distortion on listener experience is quantified and discussed. Finally, the impact on listener fatigue is quantified. Results presented show that the non-traditional sources studied are significant, audible and that they present a fundamental limitation to the performance of many earbuds and headphones. In many cases, these sources reduce the effective signal to noise ratio (SNR) of the audio system into the 30-40 dB range, well below the SNR level that would result from by a 0.1% total harmonic distortion (THD) system and even below that of a 1% THD system. In addition to limiting system performance, the non-traditional noise and distortion are found to increase ear fatigue experienced by the user when ear fatigue tests are conducted with identical audio levels. Otoacoustic Emission (OAE) results from tested subjects show degradation that is significantly greater when the impairments are present vs. when they are mitigated.

1. Introduction

Professional musicians are almost four times as likely to develop noise induced hearing loss as the general public [1]. Additionally, they are 57% more likely to develop tinnitus, one of the first indicators of permanent hearing loss. Statistically, hearing loss occurs in roughly 90% of tinnitus cases [2]. The ideal solution to hearing loss in musicians and other sound professionals is to reduce the dosage of sound pressure reaching the ear. In other words, listening at lower volumes and for less time. In many cases, this may not be practical due to the realities of their jobs and livelihood.

Volume and time are key factors in noise exposure and ear health. A third and very important factor in the equation is the performance of earbuds and headphones used in studio and stage environments. This has received minimal study in literature.

Commercially, earbud and headphone performance have been improved and fine-tuned for many years. Even so, many of the most popular brands marketed to the professional audio industry do not include specifications related to the quality of sound reproduction. Those that do typically specify Total Harmonic Distortion (THD).

Although a THD specification is important and provides an informative figure of merit for a given driver, it does not always reflect the performance of the unit under real world, dynamic conditions where music and vocals are being rendered by the system instead of sine waves or test signals. Under such conditions, and outside of the test lab, several sources of noise and distortion are present that limit system performance long before the THD becomes a problem. These sources are large enough that they limit the clarity and separation that could otherwise be achieved by the system. In fact, for many artists and engineers, a vicious circle begins: separation and clarity limitations along with volume lead to ear fatigue, the ear fatigue leads to increasing volume to compensate, increasing volume lead to additional ear fatigue, and so on. When the contribution by these sources are reduced, artists and sound engineers can perform their jobs more effectively, often listening to mixes at lower levels and with less impact on their ears.

In this paper, we present an analysis of key noise and distortion components introduced into headphone and earbud systems in studio and on stage environments. Specifically, In Section 3, a noise source termed ghost current is explained and analysed. Measurements are presented to quantify this distortion and the limitations it provides to system performance. In Section 4, the impact of outside environmental noise, or stage noise, coupled back into the earbud and amplifier system is analysed. Measurements are presented from sample In-Ear Monitor (IEM) units and headphones. For each of the sources in Sections 3 and 4, the impact of the source is presented as an overall impact on the effective signal to noise ration of the audio signal (SNR). In Section 5 a method to mitigate each of the discussed modes of noise and distortion is reviewed, quantified with respect to effective SNR and qualitatively discussed from listener evaluation. Finally, in Section 6, we analyse the impact of this noise and distortion on ear fatigue with the thesis that not only does volume impact ear fatigue but also signal quality.

2. Quantification Methodology

In order to analyze non-traditional noise and distortion impact, four commercially available devices were chosen for measurements and analysis. They will be referred to as Unit A, Unit B, Unit C and Unit D throughout the remainder of this paper. A short description of each follows.

- Unit A is a mid-range, multi-driver In Ear Monitor (IEM) marketed for on-stage usage
- Unit B is a premium multi-driver IEM marketed for on-stage usage
- Unit C is a headphone unit marketed to musicians and sound engineers for studio work
- Unit D is a headphone unit marketed to the DJ community for both studio work and performances

To provide a common framework for comparing the various non-traditional noise and distortion components, an effective Signal to Noise Ratio (SNR) figure is provided for each. In each case, the signal is simply average or RMS level of the desired audio signal. The noise is a summation of any distortion or noise component. In most cases, the results are provided as a function of frequency. In some cases, to provide context, the effective SNR of a reference system with 0.1% THD or 1% THD is shown or discussed. Note that in the effective SNR explained above, a 0.1% THD system is equivalent to an effective SNR of 60 dB and a 1% THD system is equivalent to an effective SNR of 40 dB.

3. Non-Traditional Noise and Distortion #1: Ghost Current

There has been no mention in literature of a phenomena called ghost current so it bears an explanation to what it is and why it exists. Consider the earbud situated inside an ear in Figure 1. Current (Label 2) intended for the earbud renders acoustic energy (Label A) toward the eardrum. Since the eardrum does not absorb 100% of the incident energy, some is reflected back toward the earbud (Label B). When this energy hits the driver inside the earbud, the driver behaves similar to a microphone and a current (Label 1) is created that flows back toward the amplifier. This current is called ghost current. This current will add destructively with actual current intended for the driver and the result will be noise and distortion in the next audio rendering of the earbud driver. The noise and distortion audio rendering is termed ghost echo (Label C). The term ghost current is coined due to the similarity to the ghosting phenomena on CRT screens with moving pictures.

An average human ear canal is approximately 2.5 cm long. Thus, the round trip length for acoustic energy to travel to and from the earbud is 5 cm. Estimating the speed of sound at 340 m/s provides an estimated round trip time for the acoustic energy of approximately 147 us. Because the driver inside the earbud is not completely flush with the opening of the ear canal and is often outside the opening, the round trip time in practice if measured to be slightly longer.

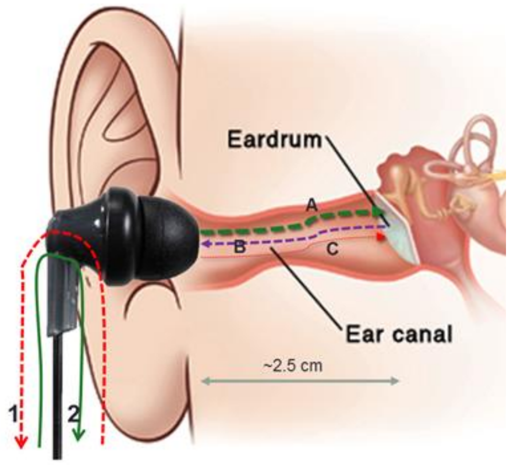

Figure 1. Model of Ghost Current due to eardrum reflection.

If the ear canal were a perfect cylinder and the eardrum was a uniform cap on the cylinder, we would expect the echo to be uniform and with a narrow impulse response. In reality, the ear canal has a non-uniform profile, slightly curves and the eardrum is also non-uniform. Thus we would expect some spreading in the echo impulse response.

Headphones are similar to earbuds in that they are subject to a ghost current due to refection from the eardrum but additionally, they can experience some reflections from the side of the `head and the pinna as well. These reflections have less distance to travel and thus are present more quickly. However, the drivers in headphones typically reside further away from the ear canal entrance than earbud drivers. Thus there is some added distance externally.

Figure 2 shows a measured incident current and ghost current impulse responses in an earbud. The ghost current is amplified for the graph by 40 dB in order to see more detail and be able to compare it to the Incident Current impulse response.

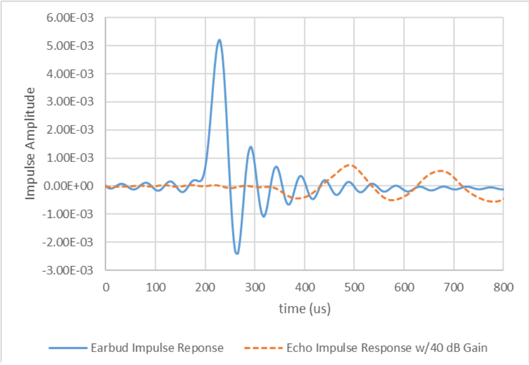

Figure 21. The incident current impulse response and ghost current impulse response of an earbud.

Carefully reviewing figure 2, the ghost current impulse response is clearly delayed from the earbud impulse response. Additionally, many of the higher frequency components are removed. The delay from the first positive peak of the earbud impulse response to the first negative going peak of the echo impulse response is approximately 161 us which correlates with earlier analysis predicting a delay of slightly higher than 147 us. The fact that the first echo peak is opposite in polarity to the earbud impulse is intuitive since the current from the echo will flow in the opposite direction of the current of the incident earbud impulse response.

To quantify the limitation that noise and distortion due to ghost current present to the performance of the system, figure 3 shows the effective SNR of the four units under study due to ghost current. This analysis considers all of the ghost reflection as noise.

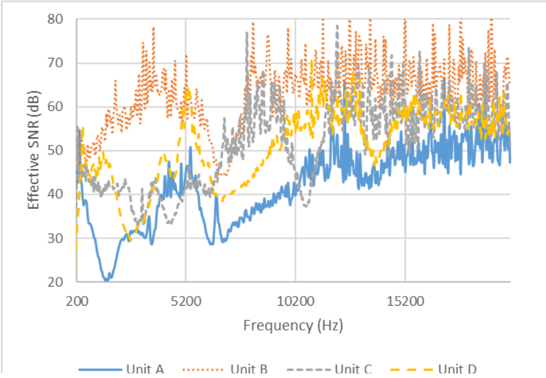

Figure 3. Effective SNR of units under study due to ghost current.

Analyzing Figure 3, Unit A is severely limited by ghost current across much of the audio band. In most cases, below 10 kHz, the effective SNR is less than 40 dB and will be clearly noticeable by the user. Unit B has more robustness to ghost current however between 5 kHz and 8 kHz, this unit dips well below 60 dB SNR and even below 50 dB SNR so there are point areas of improvement that can be made for this unit. Unit C and Unit D also have multiple areas in the audio band that are below 50 dB SNR and in some cases below 40 dB SNR. Clearly, all of the units exhibit performance below a reference 0.1% THD system across some or most of the band and most of the units exhibit performance below a reference 1% THD system across some of the band.

4. Non-Traditional Noise and Distortion #2: Microphonics

Consider a musician on stage wearing earbuds. The earbuds are typically fed a mix from a monitor engineer on the side of the stage. This mix comes from microphones around the stage on the various instruments and vocals. Thus, the pickups from the microphones travel to the monitor engineer's mixing station, are mixed together and then travel back to the musician's ears either wirelessly or through a wired connection.

Additionally, the stage environment contains stage noise from all instruments playing, from the various speakers supporting the performance and from crowd noise. When all of this stage noise is incident upon the driver in the musician's earbud, the earbud act as microphone and create a current that travels back toward the amplifier. This is very similar to the ghost current phenomenon except that the acoustic energy that results in current is due to stage noise rather than reflections. The process of stage noise turning into current via the earbud drivers is termed microphonics. Note, a studio musician may face similar stage noise elements, even though a crowd is not present in the studio.

To analyze the impact on the units under study, measurements were taken and simulations were done to produce an environment with stage noise of 105 dBSPL. It was assumed that this was made up of a flat spectrum from 20 Hz to 20 kHz. For the study, the mix presented to the musician's ears was 95 dBSPL. Figure 4 shows the effective SNR of the four units under study when subjected to this environment. It was assumed that all of the microphonics picked up by the system constitute noise.

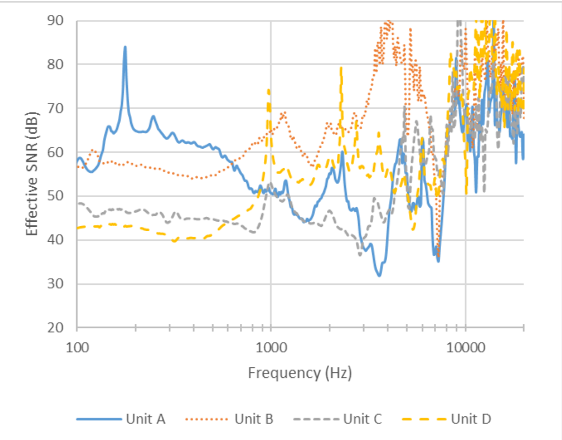

Figure 42. Effective SNR of units under study due to microphonics.

Analyzing Figure 4, Unit A is above 60 dB SNR between 200 Hz and 800 Hz but then drops considerable between 1 kHz and 8 kHz, even dipping below 40 dB SNR in some cases. Unit B has a large area below 800 Hz that is beneath 60 dB SNR and an additional region between 7 kHz and 9 kHz where it drops below 50 dB and even approaches 40 dB SNR. Units C and D are beneath 60 dB for most of the 100 Hz to 10 kHz region. Note that above 10 kHz, the microphonics effects decrease and most SNRs are above 60 dB. In comparison to our reference systems. All of the units dip below a 0.1% THD performance system and most of the units approach a 1% THD system over some portion of the band.

5. Methods to Reduce Non-Traditional Noise and Distortion

Having reviewed two non-traditional noise sources, it is clear that their magnitudes in many cases will far exceed the noise induced by reference systems of 0.1% and 1% THD. Methods to reduce the magnitude of these non-traditional sources will be beneficial to artists and sound engineers or listeners in general.

A patent-pending REV33 device (www.REV33.com), produced by REVx Technologies, can mitigate the non-traditional noise and distortion sources discussed. The REV33 can be implemented in a variety of ways. The professional version is implemented as a passive device with a forward transfer function (amplifier to earbud) that passes all of the audio current intended for the earbud driver and a reverse transfer function (earbud to amplifier) that resists the flow of current. Thus, as it sits in line with the earbud driver, it allows music content sourced by the amplifier to pass unaltered but reduces current that is sourced from the earbud itself. Since all of the non-traditional sources involve current flowing from the bud to the amplifier, the REV33 can be effective in reducing all of the non-traditional noise sources that may be present.

For the first non-traditional component, ghost current, measurements were conducted with a

REV33 similar to those done in Section 3. The results were then compared to the results shown in figure 3 and the resulting SNR improvements due to the REV33 are shown in figure 5 .

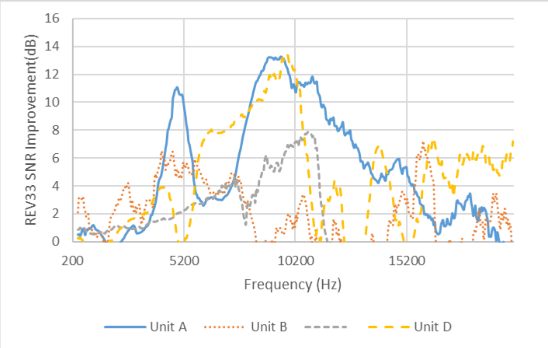

Figure 5. Effective SNR improvement for ghost current due to the REV33.

From figure 5, the REV33 provides peak gains of 6 to 13 dB for each of the units under study. Listening tests conducted for this improvement indicated improved timbre separation, improved depth of field of the sound stage along with better transients and tonality. Several listeners have also commented about a reduced harshness of the audio with the REV33 in line.

For the second non-traditional noise and distortion of microphonics, measurements were conducted with a REV33 similar to those done in Section 4. These results were compared to figure 4 and the effective SNR gains due to the REV33 was calculated and are shown in figure 6.

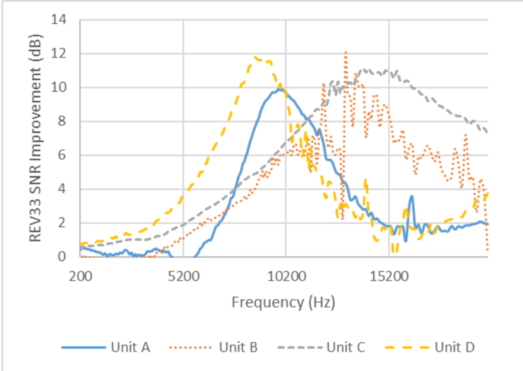

Figure 6. Effective SNR improvement of microphonics due to the REV33.

From figure 6, the REV33 provides peak improvements of 8-12 dB on the effective SNR limitations due to microphonics. It is difficult to do A/B testing for stage noise given the environment necessary for a valid test. Qualitatively, artists that use the REV33 have indicated that they can hear and experience the improvements of the REV33 in studio environments and on-stage environment**s** when stage noise is present. Additionally, artist indicate that they are able to maintain the initial level of their mix on-stage when using a REV33 instead of incrementally increasing mix volume throughout the duration of the performance. In fact, some artists have indicated that they actually can decrease their mix level when using a REV33 due to the better clarity provided.

6. Ear Fatigue

It is well known that listening to music at loud volumes for a prolonged period of time will cause ear fatigue, also known as temporary threshold shift (TTS). Symptoms of TTS include ear ringing (temporary tinnitus), headaches, a hollow feeling in the ear, an inability to hear details in a mix (muddiness), and the need to increase music level in order to hear along with other hearing related issues. It is widely accepted that when TTS occurs often in an individual, long term hearing damage results.

The focus of this study is to evaluate the impact of non-traditional noise and distortion on TTS.

Although this is ongoing work, we present here our early findings.

In a first study, a volunteer (the author of this paper) was subjected to loud music at approximately 105 dBSPL for 40 minutes once with a REV33 in the system and once without a REV33. The tests were conducted two days apart to provide an adequate rest period for the ears to recover. Otoacoustic Emissions(OAE) measurements were used to quantitatively measure the TTS of the ears. It should be noted that no stage noise was present for this test. Figures 7 and 8 show the OAEs measured in the ear at two different frequencies. The measurements were taken prior to the exposure and then at 1 minute, 10 minutes, 20 minutes, 30 minutes and 40 minutes after the exposure. In both graphs, the OAEs drop considerably more when no REV33 is used with the in-ear monitor relative to the OAEs measured when a REV33 is used with the same in-ear monitor. This indicates a more extreme TTS when no REV33 is used. Additionally, the recovery time of the OAEs with the REV33 is faster indicating that it is taking longer for the ears to return to normal when no REV33 is used. Anecdotally, it was noted that ear ringing was much more pronounced when no REV33 was used and ringing lasted longer.

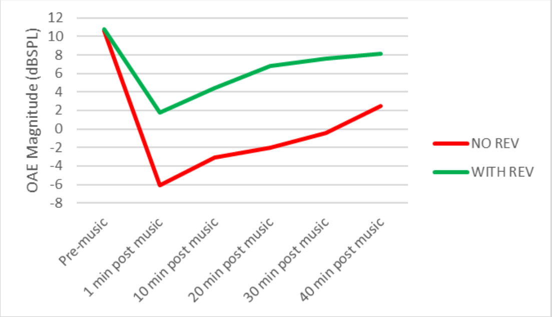

Figure 7. Otoacoustic emissions at 1.5 kHz.

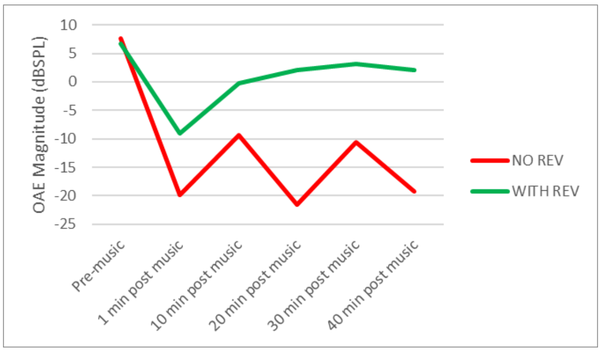

Figure 8. Otoacoustic emissions at 2.0 kHz.

In an additional study, an OAE study was done on a band for three shows. During each show some members of the band were given REV33s and other members were given a device that looked like a REV33 but was a placebo that simply passed the signal through in both directions. Each night, the units were redistributed so that each member got to play at least one night with a real REV33 and at least one night with a REV33 placebo. Figure 9 shows the resulting OAE shift after all shows for ears that did not use a REV33 and Figure 10 shows the OAE shift for ears that did use the REV33.

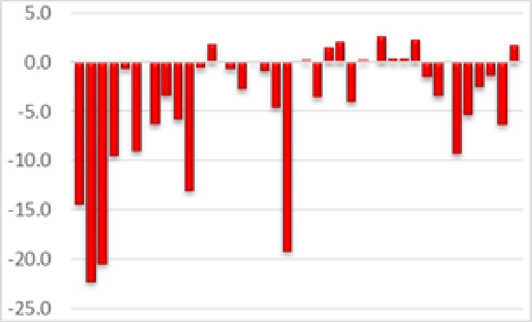

Figure 9. OAE change - no REV33.

Figure 10. OAE change - with REV33.

Analyzing the figures, it is clear that more shift occurred with ears that did not use a REV33 than with ears that did indicating larger TTS and thus more ear fatigue for non-REV33 ears. Again, subjective comments from the band members indicated that they felt less symptoms of TTS, including less ear ringing when the used a REV33.

The results of the studio and on stage experiments suggest that noise and distortion does play a role, along with audio level and duration, in causing TTS. Additional work is ongoing to prove deeper into this phenomenon.

7. Conclusions

Two non-traditional noise and distortion sources related to earbuds and headphones have been discussed. The limitations that these sources place on the system are quantified as an effective SNR. In four units placed under study, the limitation is severe – SNR is limited to the 30 dB – 40 dB range at some frequencies. The concept of using a REV33 to mitigate the noise and distortion shows significant SNR gain for both sources. Listener feedback has qualitatively confirmed that the non-traditional noise and distortion sources limit the quality of width of the stereo field, the sonic stage depth, the quality of transients and the timbre separation. Additionally, listener feedback has confirmed improvement in all of these factors with the introduction of the REV33. Objective ear fatigue testing suggests that reducing noise and distortion in a mix can positively impact the onset of TTS. Subjects tested with music exposure and using a REV33 showed improvements in TTS experienced less ear fatigue vs subjects not using a REV33

8. References

[1] Schink, Tania, et al, “Incidence and relative risk of hearing disorders in professional musicians”, *Occupational and Environmental Medicine*, April 2014.

[2] Hearing Health Foundation, “*Tinnitus By The Numbers*”, Sourced from www.hearinghealthfoundation.org/tinnitus_statistics.