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Active Noise Cancellation Distortions in Headphones

Steve F. Temme[1]

[1]Listen, Inc.

Correspondence should be addressed to Steve Temme (stemme@listeninc.com)

ABSTRACT

Active Noise Cancellation (ANC) in Headphones effectively attenuates external background noises from droning airplane engine noise to everyday annoying environmental sounds. This permits greater enjoyment of music or speech, but at what cost? Like most signal processing, its benefits come with trade-offs such as added electronic noise and distortion. This paper uses several types of electroacoustic measurements to reveal some of these hidden trade-offs and attempts to explain how they affect the overall headphone playback sound quality.

1 Introduction

Headphone designers generally try to optimize performance at any given price point. One important performance parameter is minimizing background noise. This is achieved both passively through physically sealing the ear from outside noises, and actively by measuring the noise and mixing it out-of-phase with the intended input signal, e.g. music or speech. As always, there are trade-offs with different implementations.

Based on my experience listening to and measuring over 30 pairs of ANC headphones, I've found that while background noise attenuation has greatly improved, the sound quality often gets worse when ANC is turned on, particularly with high-quality music.

Others share this view. Indeed, the consensus among audiophiles is that active noise cancellation degrades the sound quality. While many varied sources make such claims, it is well summarized in this excerpt from GRADO headphones' Blog post [1]:

"Everything feels compressed and closed off, especially for high-frequency audio. If you have experienced hi-res music on state-of-the-art headphones and earbuds, ANC can be a pain in the back. The good thing about ANC headphones is that most of them have a switch to turn the noise cancellation on and off.

Turning on ANC waters down the sonic output quality. Choosing noise-cancelling ANC headphones is choosing to forego the clarity, crispness, rhythm, energy, and superb sound arrangement of a non-ANC headphone.

Non-ANC headphones have impressive sounds that capture the entire range of frequencies in the movement of the sound. They can handle messy and challenging songs in a way that ANC cannot."

This paper attempts to quantify and prove or disprove such widely stated subjective claims by objectively evaluating three different brands of popular, high-quality, over-the-ear headphones priced from $360 to $550. Distortion metrics, including THD, intermodulation distortion, POLQA, and frequency response, are measured, and attempts are made to reconcile the measurement with the subjective statements above. Initially, many more brands were measured to identify the metrics that best correlate with subjective assessment and refine the measurement methodology; these particular three

were chosen to highlight examples of different ANC implementations and qualities.

2 ANC Headphones Designs

An ANC headphone actively attenuates an acoustic disturbance signal by creating a control signal that destructively interferes with the disturbance signal, thereby cancelling it out. There are two feedback circuits commonly used to achieve this: a feedforward circuit and a feedback circuit.

A feedforward circuit uses an omnidirectional microphone or microphones on the outside of the headphone, acoustically isolated from the speaker, to record the external disturbance signal before it reaches the ear. The acoustics of the headset are modelled to determine how the frequency, phase, and amplitude of the noise are affected by the time it reaches the ear. This transfer function is used to create a noise-cancellation signal, which is inserted between the microphone(s) and speaker. With this approach and sufficient acoustic isolation between the speaker and the feedforward microphone(s), there is no influence on the playback path. This means that music playback still sounds good if the noise cancellation is switched off, or the battery drains, and the headset operates in passive mode. The feedforward topology also makes it very simple to create an "assisted" hearing mode where the immediate acoustic environment can be amplified and equalized, removing the need to take the headset off to listen to someone, or to compensate for a mild hearing loss. Feedforward systems are effective at cancelling higher frequency external sounds but are sensitive to wind and sudden changes.

A feedback circuit places the microphone inside the ear cup, as close to the speaker as possible, to minimize propagation delay. The sound arriving at the ear is captured, and the playback from the speaker is subtracted from the total signal to capture the noise arriving at the ear. This is a more accurate representation of the noise than the simulated effects used by feedforward, although performance may be limited by the speed of the system's response. The control signal, a phase-shifted version of the residual noise, is then played from the headphone's driver to cancel the unwanted sound. Since the microphone in the feedback headset cannot differentiate between noise and playback, headsets using feedback typically experience some signal distortion. To overcome this, it's common to add an equalization circuit in the playback path to ensure the sound is the same with and without ANC activated. Feedback systems are better than feedforward systems at cancelling internal and low-frequency noise, but audio playback can be subject to distortion artifacts.

Most modern day, high-end headphones combine both feedforward and feedback for enhanced performance, although this introduces additional complexity and cost. The signal processing applied to the signals from both microphones is combined before being provided, along with any playback signal, to the speaker. All three approaches are more fully described by Liebich et al [2].

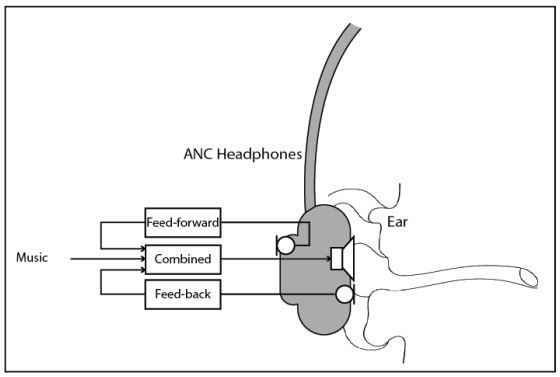

Figure 1. Microphone and speaker placement in an ANC headset featuring hybrid feedforward and feedback operation.

3 Practical Design Considerations

The biggest challenge with feedforward solutions is ensuring a controlled environment around the user's ears. Users have different ear shapes and sizes, and their headsets will fit differently. These different physical fits require different transfer functions to achieve optimal noise cancelling. This means that the headset either needs to fit everyone well or must be designed so the effects of variations from head-to-head have a minimum effect on the transfer function. This is usually achieved via a controlled leakage path [3].

Feedback solutions present different challenges. One of the most significant issues is where to place the microphone to achieve controlled acoustic behavior across the frequency range; numerous patents exist concerning the position of the microphone and the dimensions/ratios of the front and back cavities.

In making design trade-offs, it is common to prioritize the audio response. In this case the ANC behavior is typically limited in frequency band but can achieve adequate or even significant noise-cancelling levels.

This approach ensures that the headset sounds good even when the battery is dead. The alternative is to prioritize ANC performance, in which case the audio response must usually be corrected to sound good. In this case, the headset should always remain powered, or alternatively, some passive in-line equalization is needed to recreate the “pleasant” sound.

4 Levels of Noise Cancellation

Above a few kilohertz, most headsets provide some degree of passive noise isolation due to insulating materials that block ambient sound from reaching the ear - typically 20 to 30dB. High-quality, noise-isolating earphones can offer as much 10 to 20 dB of passive attenuation even at lower frequencies, delivering quiet listening without the need for power. However, effective passive isolation comes with a downside: occlusion. The occlusion effect is easily demonstrated by plugging your ears with your fingers and speaking. Your voice sounds dampened and distorted as it travels through the bone structure of your jaw and nose rather than through your ears. This effect typically causes users to raise their voices while speaking, which can be uncomfortable and disruptive. To mitigate this, some devices implement side-tone, a technique that picks up the user's voice with an external microphone and plays it with slight attenuation, encouraging more natural speech [4].

Active noise cancellation offers advantages over passive isolation at lower frequencies, e.g. speech band, as it is easily toggled on and off with a switch. This makes it useful in situations such as on airlines where it's advantageous to toggle isolation on/off when you need to speak to your neighbor or the flight attendant.

Feedforward solutions, with the microphone on the outside of the headset, have a sweet spot, that is, a narrow band of frequencies where the noise-cancelling performance can be maximized. In addition, feedforward makes it possible to cancel noise over a broad frequency spectrum, typically up to 4 or 5 kHz [5].

Feedback ANC typically delivers a more uniform noise reduction across its operating frequency range. However, this range is usually limited to around 1 kHz. The restriction is necessary for system stability as variations in ear geometry or headset fit can alter the acoustic transfer function enough to risk positive feedback and potential oscillation. Feedback ANC designs commonly achieve up to 30 dB of noise cancellation within this 1 kHz bandwidth [5]. Hybrid designs benefit from the positive sides of both topologies while minimizing their drawbacks.

5 Measurements

A range of different headphone parameters was measured on three popular over-the-ear, major brand headphones, referred to as A, B, and C. All measurements were made using SoundCheck audio analysis software with the AmpConnect 621 audio interface, a Brüel and Kjær Type 4128C head and torso simulator (HATS), a SoundConnect 2 microphone power supply, and a BQC4149 Bluetooth interface for Bluetooth connection to the headphones. For measurements requiring background noise, a KEF Q300 was used. These were configured as shown in Figure 2 and depicted in Figure 3.

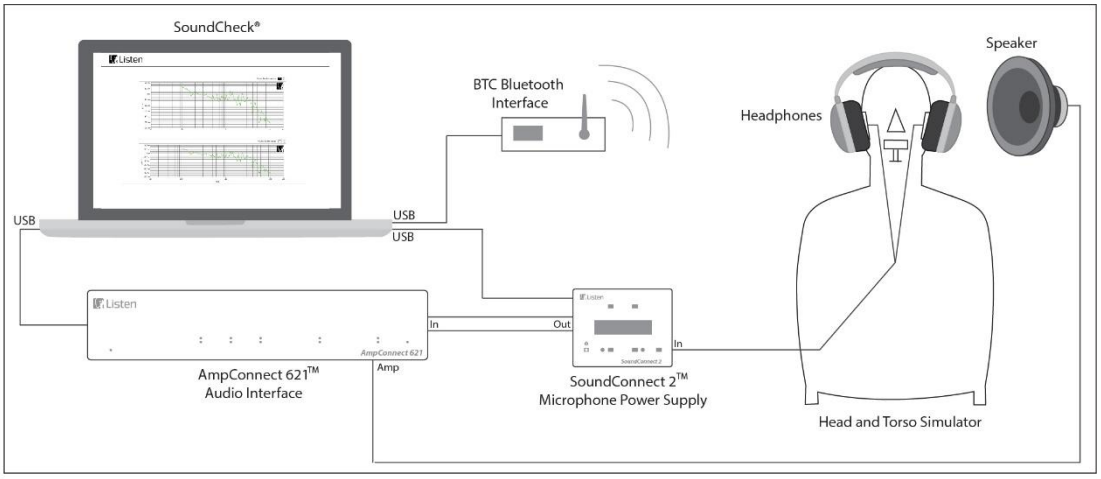

Figure 2. Test configuration for all measurements.

Figure 3. Measurement Setup with Head and Torso Simulator Type 4128C and KEF Q300 coaxial speaker.

6 Noise Attenuation

The most obvious benefit of applying active noise reduction is the attenuation of unwanted background noise. Passive attenuation effectively reduces high-frequency noise above 1kHz, while active noise cancellation (ANC) offers strong performance at low frequencies, typically below 1kHz.

To measure headphone noise cancellation, we first equalize a KEF loudspeaker to have a flat frequency response of +/- 0.5dB from 50Hz to 10kHz at 90dB SPL measured at the ear simulator's reference point. Then, with the headphone's active noise circuitry turned on, which includes its passive attenuation, we measure the SPL at the ear simulator's reference point versus frequency using a 1/12th Octave Real Time Analyzer and playing pink noise out of the equalized KEF loudspeaker. Last, we subtract the measured level from the 90dB reference level to get the attenuation at each frequency.

Figure 4 shows noise attenuation with the ANC circuit turned on for three popular over-the-ear headphones. It is quite common to achieve 10-20dB and sometimes as much as 40dB of overall noise attenuation.

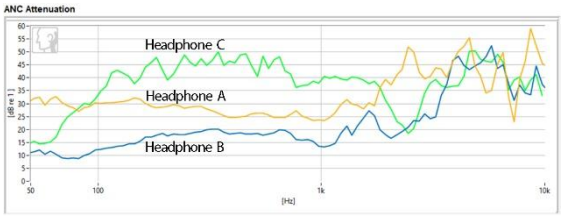

Figure 4. ANC attenuation for 3 different popular over the ear headphones, A, B & C.

ANC circuits, particularly the feedback type, can also reduce distortion. Figure 5 demonstrates this using Headphone C. The graph shows the distortion and noise over the frequency spectrum for a 109Hz test signal, a frequency selected for its more significant distortion. Frequencies below 5kHz, the background noise and low-order harmonics are considerably reduced when the ANC circuit is turned on, compared to when ANC is off. Most of the noise and harmonics fall below the masking and threshold of hearing curve. There is minimal reduction at higher frequencies, and some audible stray high-frequency pure tones from the test environment are evident above the masking curve around 2-6kHz. Other headphones also exhibited a reduction in distortion when ANC was activated.

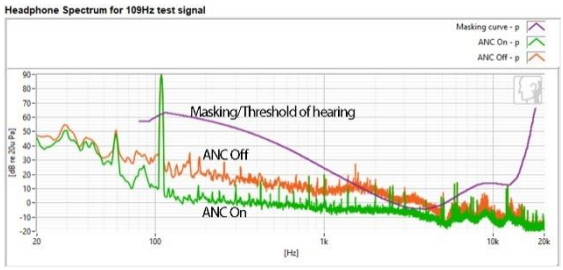

Figure 5. Reduction in noise and distortion when ANC is activated for Headphone C using a 109Hz test signal.

7 Headphone Frequency Response

In addition to reduced distortion, the ANC compensates for a poor seal with the ear by measuring it in real time and boosting the low frequencies.

Figure 6 shows the Headphone A frequency response for both left and right earphones with ANC on versus off. The left earphone is not sealed around the ear as well as the right, and receives almost a 20dB boost at low frequencies when ANC is turned on. This reduces the difference in frequency response between the left and right ear from about 6dB to only a couple of dB in the <100Hz frequency range.

Although this seems beneficial, it may also limit the dynamic range of the earphones, pushing them into compression or even clipping. The ANC circuit also provides some equalizing attenuation between 200 - 600Hz. This could be by design or a side-effect of the ANC implementation.

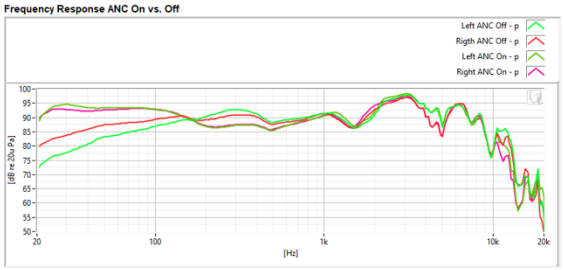

Figure 6. Headphone A Frequency response for both left and right earphone with ANC On vs. Off.

Subjectively, there was a noticeable difference in the sound between ANC on versus off. I could hear more bass with ANC turned on, but the sound was not as clear and open as when ANC was turned off. The soundstage seemed to narrow, especially with vocals in the music.

Figure 7 shows the same measurements on Headphone B. This headphone demonstrated an inherently good seal and almost no difference between frequency response, both magnitude and phase, with ANC on versus off, indicating no discernible equalization.

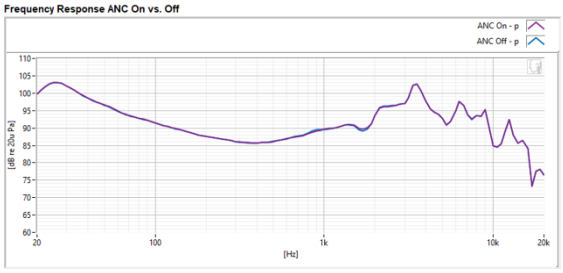

Figure 7. Headphone B Frequency response at 90 dBA for the right earphone with ANC on vs. off.

Although the subjective difference in the sound between ANC on versus off was less noticeable than with Headphone A, some degradation in the sound quality, similar to that heard in Headphone A, was still perceptible. Specifically, the bass and treble sounded a little more prominent compared to Headphone A and the reference Stax electrostatic headphones. Also, the background noise reduction was less than that of Headphone A, therefore it was harder to hear music on a noisy plane.

Headphone C, shown in Figure 8, similarly demonstrates little or no change in frequency response when the ANC is activated. Although there is a significant drop in frequency response between 5-6kHz, it did not sound as bad as expected. With ANC off, this headphone sounded good, although it sounded a little 'mushy' with the ANC activated.

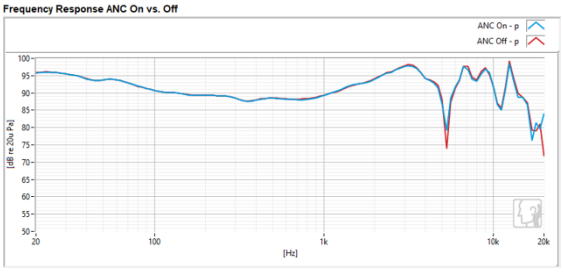

Figure 8. Headphone C Frequency response at 90dBA for the right earphone with ANC on vs. off.

8 Total Harmonic Distortion Normalized

Based on my subjective analysis, I expected distortion to increase when the ANC was activated, particularly with high levels of background noise, as the speaker would need to play at higher volumes to overcome the noise. I expected the speaker to be driven into compression or clipping, at which point it would be unable to reduce distortion. However, attempts to demonstrate this by playing pink noise and pure tones at high levels above 110dB and at low frequencies below 100Hz to induce large speaker excursions did not yield obvious results, as it was impossible to separate distortion components from the background noise.

I therefore measured the total harmonic distortion of the headphones in a quiet environment with ANC turned on versus off. This was measured using the normalized harmonic distortion method [6], which compares the level of the harmonic at its measured frequency to the fundamental at the same frequency rather than the stimulus frequency. This removes the influence of the frequency response on the calculated distortion, making it clearer which stimulus frequency is causing the measured distortion, and simplifying THD comparison between headphones with different frequency responses.

All three headphones demonstrate a reduction in total harmonic distortion at low frequencies. This shows that the feedback microphone in front of the earphone

can compensate for both a poor ear seal and help reduce distortion.

In Figure 9, the ANC circuit clearly reduces the total harmonic distortion below 100Hz, and the overall THD is quite low and below the threshold of audibility.

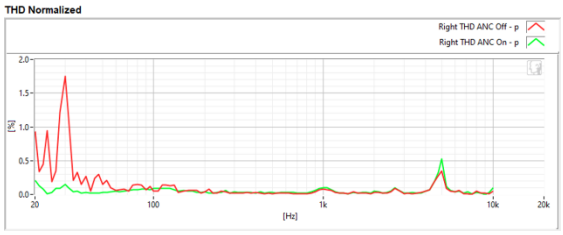

Figure 9. Headphone A: THD Normalized measured at 90dBA.

In Figure 10, the ANC circuit reduces the low frequency distortion quite significantly below 40Hz.

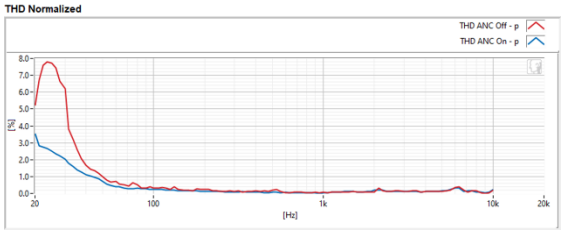

Figure 10. Headphone B THD Normalized measured at 90dBA.

In Figure 11, the ANC circuit reduces the low frequency distortion and noise all the way out to 1kHz. The THD level is on par with some of the best electrostatic headphones that I have measured, which is extremely impressive for dynamic headphones.

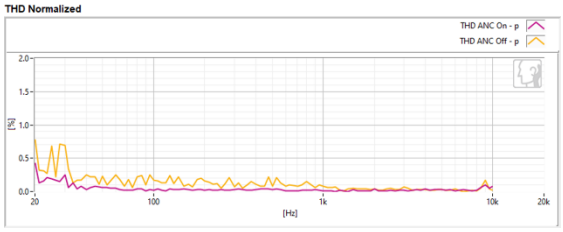

Figure 11. Headphone C THD Normalized measured at 90dBA.

Despite the distortion being quite low on all three headphones with ANC on, I felt the bass sounded worse and more 'fuzzy' than with ANC off.

9 Intermodulation Distortion

Although it is challenging to separate the distortion components from high background noise, an intermodulation distortion measurement allows us to identify if the earphone speaker is being overdriven and creating distortion when the ANC circuit tries to cancel the low frequency external sound.

The intermodulation distortion (IMD) was measured using a fixed lower frequency at 50Hz played by the external speaker, and a second sweep tone through the headphone earphones from 120Hz to 20kHz. The 2nd & 3rd order intermodulation products were measured and power summed to calculate the Total IM distortion [7].

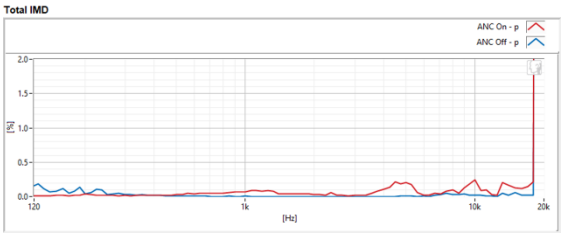

Figure 12. Headphone A Total IMD measured at 90dBA.

For Headphone A (Figure 12), the IMD at lower frequencies decreases due to the ANC linearization. At higher frequencies where the ANC no longer operates, the IMD increases slightly. This is likely due to Doppler distortion, where the high frequencies are riding on top of the lower fixed frequency with greater cone excursions. This is often avoided by having a crossover between a larger low-frequency driver and a smaller high-frequency driver – a technique more common in high-end, in-ear headphones.

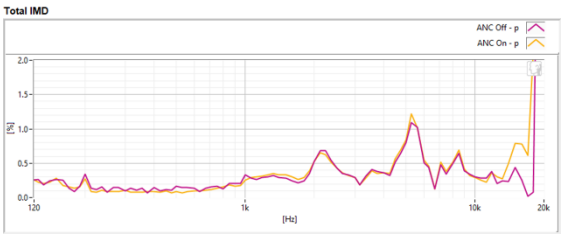

Figure 13. Headphone B Total IMD measured at 90dBA.

Interestingly, for Headphone B (Figure 13), the total IMD is about the same whether ANC is on or off. This indicates that the ANC circuit is not reducing distortion much at the 50Hz fixed tone as previously noted in Figure 10 for Normalized THD.

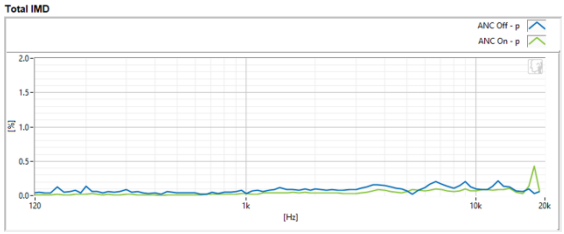

Figure 14. Headphone C Total IMD measured at 90dBA.

Headphone C (Figure 14) also exhibits little difference in IMD between ANC on versus off, and has the least distortion of all the headphones, whether the ANC circuit is on or off. It also has the most noise cancellation of the three headphones. Unfortunately, that doesn't mean it degrades the sound the least of the three headphones when the ANC circuit is activated.

10 Comparison of recordings with ANC On vs. Off

It would appear that the perceived difference in sound quality between ANC on versus off has little to do with any reduction in distortion when ANC is turned on. In an attempt to understand the degradation in quality, music was recorded with ANC on and off, and the signals compared in the time domain.

Recordings of the same music sample were made with both ANC on and off in a quiet office with minimal background noise. The music test signal selected was an excerpt of Jennifer Warnes' Bird on a Wire, a piece of music commonly used for sound quality evaluation due to its high-quality recording using low-noise Brüel & Kjær studio microphones, clear vocals, and wide dynamic range.

The two recordings were precisely time-aligned, then the recording with ANC turned on was subtracted from the recording with ANC off. If the ANC circuit has no effect on the music signal, the resulting subtracted signal should only contain background noise and no music. If the ANC circuit partially removes or changes the music signal, both background noise plus attenuated music should be seen and heard in the resulting subtraction.

When subtracting the recorded music with ANC On from ANC Off for Headphone B (Figure 15), the residual sound (orange line) is mostly background noise. However, some of the music still remains and can be seen and heard, particularly where there are spikes in the difference curve. If the subtracted signal is played back, in addition to a low level of background hiss, fragments of music - enough to identify the song - are heard, with a modest amount of time variation. The attenuated music seems to drift in and out somewhat.

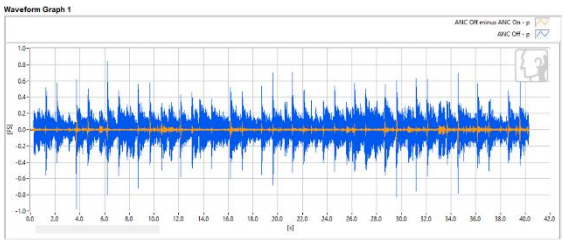

Figure 15. Headphone B Recording of Bird on a Wire with ANC turned off and ANC Off minus ANC On.

The difference curve for Headphone C (Figure 16) displays even more dramatic results, showing significant residual signal throughout the measurement. Subjectively, both the background noise and almost all the music are clearly heard, also with some warbling effects due to time variance.

When listening to the actual recording with ANC turned on, there is very little noise but the music sounds more altered than in Headphone B. This is likely due to the ANC circuit being more aggressive than Headphone B which has less noise attenuation.

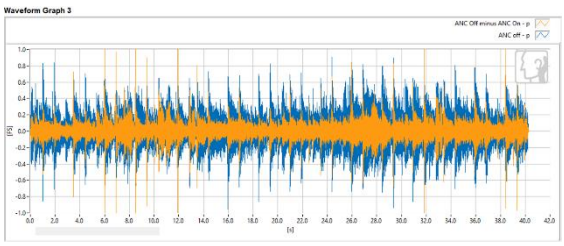

Figure 16. Headphone C Recording of Bird on a Wire with ANC turned off and ANC Off minus ANC On.

Although this measurement correlates well to subjective assessment, it is not clear exactly what the headphone's signal processing is doing to the sound in the time domain. Is the Bluetooth circuit and/or the ANC circuit interfering with the time domain, making this comparison difficult if not impossible? Is there another measurement tool that can compensate for

time alignment, time warping, jitter, packet loss, and variable delay?

11 Perceptual Standards for measuring sound quality

Perceptual standards, specifically PEAQ and POLQA, are widely used in the communications industry for the evaluation of sound quality.

PEAQ (Perceptual Evaluation of Audio Quality) is an ITU standard (ITU-R BS.1387) developed to objectively assess perceived audio quality, particularly for music and broadcast applications. It was introduced in the late 1990s to evaluate audio codecs such as MP3 and AAC. PEAQ compares a reference signal (original) with a processed or degraded version. It uses a psychoacoustic model to simulate how the human ear perceives sound, extracts perceptual features, and calculates signal degradation as an Objective Difference Grade (ODG) ranging from 0 (no degradation) to -4 (very annoying degradation), and signal quality as a "Distortion Index"

POLQA (Perceptual Objective Listening Quality Analysis) is a newer ITU standard (ITU-T P.863) designed to evaluate voice quality in modern telecommunication systems. Like PEAQ, POLQA compares a clean reference signal with a degraded version using a perceptual model. However, POLQA incorporates advanced time-alignment and delay compensation algorithms, making it more robust to time warping, jitter, packet loss, and variable delay—common in real-world communication systems. POLQA provides a MOS-LQO (Mean Opinion Score – Listening Quality Objective) on a scale from 1 (bad) to 5 (excellent), closely matching subjective listening test results.

POLQA was selected over PEAQ to compare Bluetooth ANC headphone quality because it is better designed to handle the time variance potentially added by the Bluetooth and ANC circuitry, which affects the measurements and subjective sound quality of the headphones.

As with the other measurements, the test configuration in figure 2 was used. The POLQA algorithm returns a score of 1-5, with 5 representing excellent quality and 1 being the worst [8]. The same Jennifer Warnes' Bird on a Wire music excerpt was used, and the recording with ANC turned on compared to the recording with ANC off. To try and isolate the impact of the Bluetooth circuitry from the ANC circuitry, both analog and Bluetooth connected performance was measured where both options were available. All MOS-LQO scores are provided in Table 1.

Headphone	ANC Off	ANC On
A with analog input	4.35	3.78
A with BT input	3.62	3.09
B with analog input	4.21	4.16
B with BT input	3.26	3.02
C with BT input	3.21	2.62

Table 1. Headphone POLQA scores when playing music.

Headphone A supports both an analog wired connection and a Bluetooth connection. The best MOS-LQO score is 4.35 out of 5 when the headphone is wired and ANC is turned off. The worst MOS-LQO score is 3.09 when the headphone is using Bluetooth and ANC is turned on. This correlates well with subjective listening tests.

Headphone B's POLQA score is similar with ANC on or off, which indicates less signal processing but maybe also less attenuation of the background noise. Subjectively, the difference in sound quality with the ANC circuit on versus off was less noticeable than in the other two headphones.

Headphone C's POLQA score drops the most of the three when ANC is turned on. This headphone has the most attenuation and sounds very different with ANC turned on versus off. This likely indicates a lot of signal processing going on in the ANC circuit.

12 Conclusions and Future Work

Designing high-quality ANC headphones with effective background noise attenuation and excellent sound quality is very challenging. The added signal processing of the ANC circuit can reduce traditional harmonic distortion but may add other types of noise and distortion both in the frequency and time domains. Trying to quantify the added distortion plus noise is difficult due to the added time variance of the ANC circuit.

Results demonstrate that ANC compensates well for ear leak seals and the resulting low frequency distortion, effectively equalizing it for a very uniform response.

However, ANC headphone designers should be cautious of relying only on traditional frequency domain electroacoustic measurements to evaluate the

effect of active noise cancellation, as these results do not correlate well with subjective assessment and even conceal artifacts that may be perceived negatively by consumers.

Perceptual measurements, such as POLQA, and time domain measurements, however, appear to yield objective information that correlates well with subjective analysis and show promise as valuable analysis tools for the characterization of active noise cancellation.

It would be beneficial to explore this further with a wider range of headphones and more expertly assessing subjective opinions using double-blind listening tests with a panel of trained listeners.

References

[1] GRADO blog, “Earbud Decision: Noise Cancellation vs. Audio Quality.

[2] Stefan Liebich et al, “Acoustic path database for in-ear ANC headphone development”, 23rd International Congress on Acoustics, (Sept 2019).

[3] “Practical Considerations for Implementing Adaptive Acoustic Noise Cancellation in Commercial Earbuds” Agustinus Oey. Journal of Electronic and Information Systems Nov 2023).

[4] Miho Takeuchi et al, “Evaluation of Own Voice Perception while Using In-ear Headsets”, AES 4th International Conference on Audio and Music Induced Hearing Disorders, (May 2024).

[5] Challenges Await In Noise-Cancelling Headset Design, Electronics Design, June 13, 2012).

[6] How to Graph Distortion Measurements, Steve F Temme 94th AES Convention, Berlin, 1993

[7] Application Note: Audio Distortion Measurements. Published by Brüel and Kjær, 1993

[8] POLQA Perceptual Objective Listening Quality Analysis Technical White Paper October 2011