The Impact of Microphone Specification on Active Noise Cancellation Performance

White Paper

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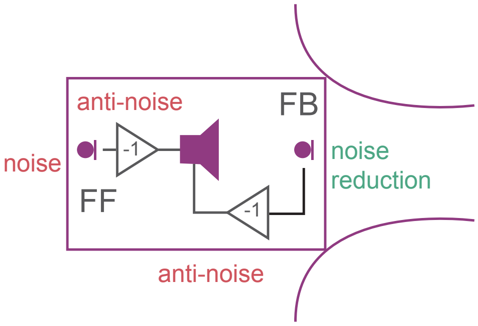
Active noise cancellation (ANC) is a popular feature in consumer electronics headsets. Effective ANC imposes particular specification requirements on audio chain components, including microphones. Knowles portfolio includes microphone models that allow achieving the best noise cancellation possible. This document covers some basics of ANC operation and demonstrates how microphone specs impact ANC performance.

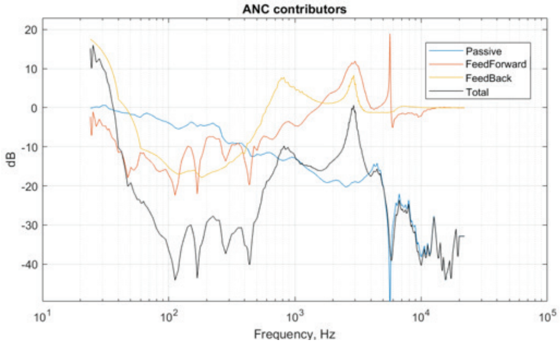
Content

Chapter 1. ANC concept

High-level idea of active noise canceling system is quite simple. The goal is to get rid of unwanted sounds such as airplane noise, highway noise or people's chatter. This is achieved by several techniques. First of all, it is important to recognize passive cancellation. Most common ANC device form-factor is so-called true wireless headset (TWS). Dominant design solution is a rubber ear tip that provides a tight fit in the ear canal. When plugged into the ear the device acts somewhat like an earplug. It provides low-pass acoustic filtering and significantly attenuates high-pitch sounds without any electronics involved. Second is the Feed Forward (FF) ANC path. An external microphone picks up the unwanted environmental sound. The signal is inverted to create anti-noise and played by the speaker. The ambition is to create perfect cancellation inside the ear. FF signal is an exact inverted copy of the sound naturally coupling into the ear from the outside.

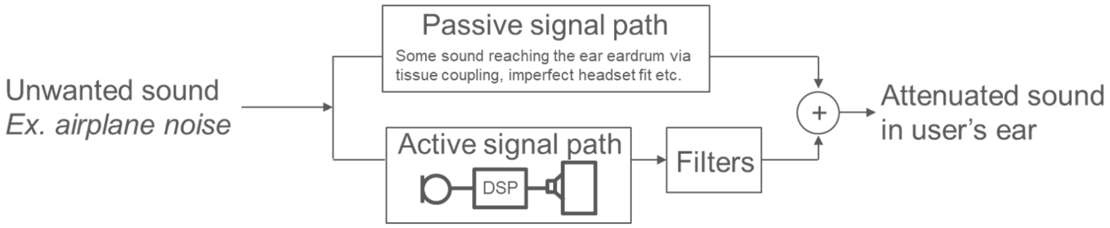
FF ANC is usually effective in low to mid-band range. Finally, the Feed Back (FB) ANC path. The feedback microphone inside the ear is monitoring the sound. Mic's output is inverted and played back through the speaker. This way the noise level inside the ear is reduced. FB ANC cancellation is effective in the low frequency range. See a typical example on the chart below.

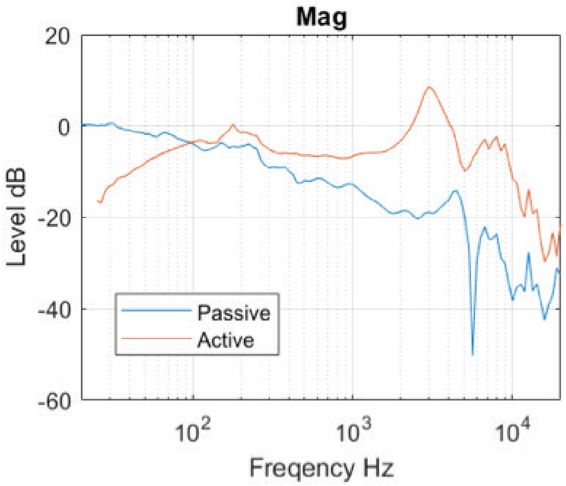


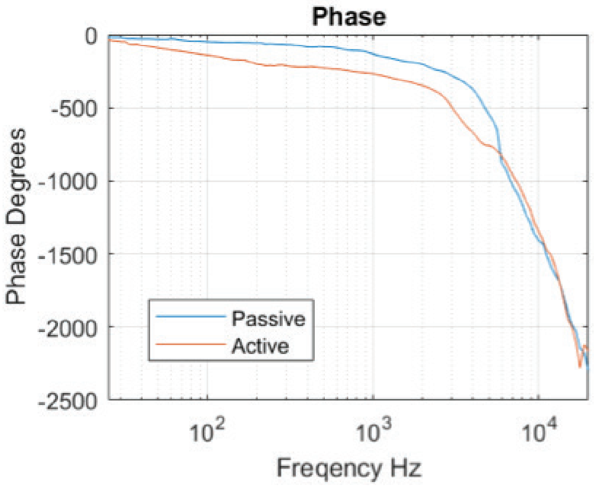


Chapter 2. Feed Forward ANC

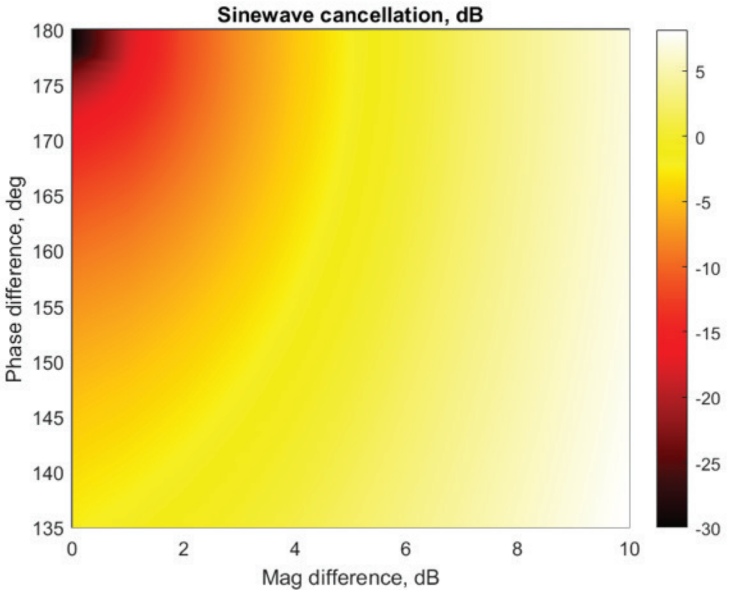
A concept block diagram of feed forward system is given below. The passive transfer function is a low-pass filter, subject to mechanical design of the headset and fit into the ear. Active transfer function includes microphone, digital signal processing, and the transfer function of the speaker generating sound in the ear canal. The shape of active transfer function includes expected features: second order high-pass effect in low end from microphone and speaker LFRO. At higher frequencies there is a pinna resonance from the speaker transfer function. Note that phase response of active path includes linear phase contribution from digital microphone ASIC latency as well as DSP processing latency. The idea is to pick the ANC filters so that at every frequency active and passive signals are equal in magnitude and perfectly out of phase to achieve complete cancellation. In reality ANC filters are part of DSP block but it is convenient to separate those from the fixed components of active transfer function.



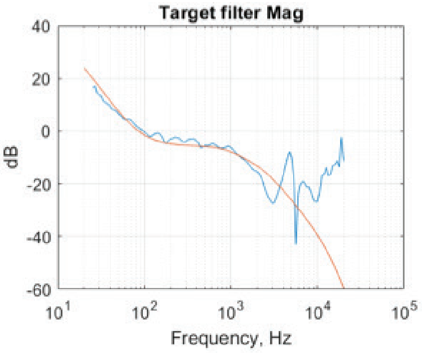


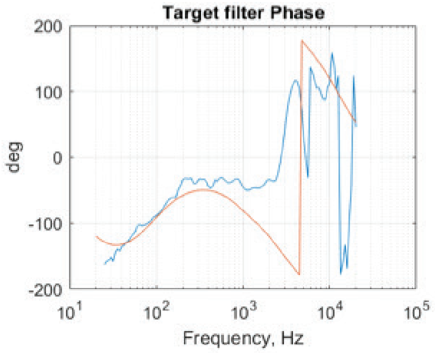


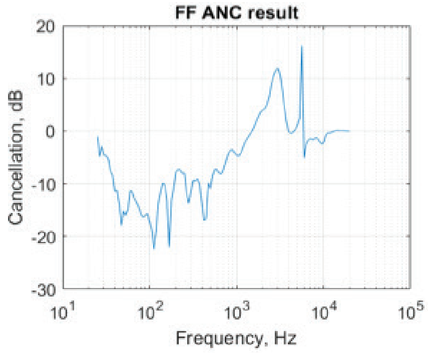
Next step is to set the ANC filters in the active signal path. How accurately do the active and passive paths need to be matched so that ANC is still noticeable by the consumer? In other words, both magnitude and phase difference will lead to less cancellation. The chart below illustrates it. Let's pick -10dB cancellation as a clearly audible target. In ideal case with 0dB magnitude difference and 180 deg phase shift cancellation is perfect. However, -10dB or better noise reduction target is achieved with magnitude mismatch of up to 2dB and phase deviation from ideal 180 degrees of up to 20 degrees. This exercise shows how accurately the ANC filters need to be set.



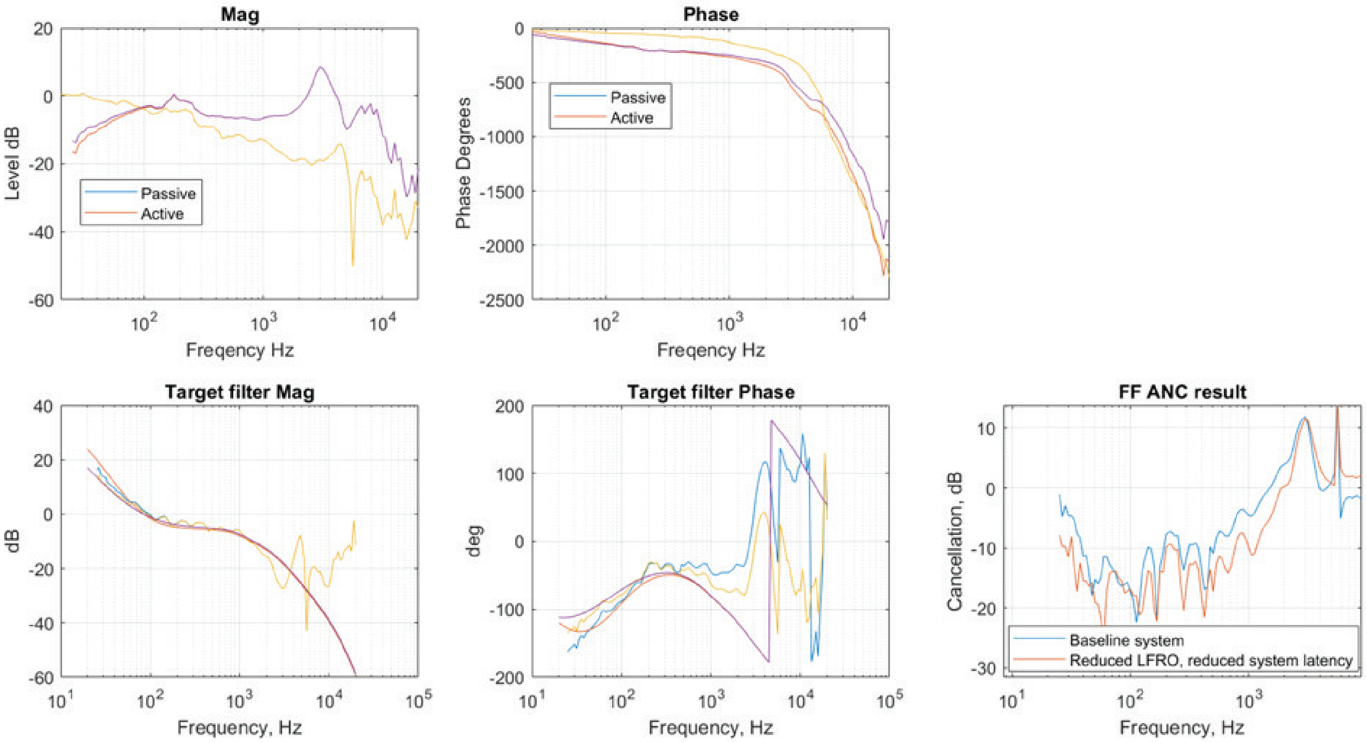
Having measured the passive transfer function and active transfer function without ANC filters (unity filters) it is now possible to compute the target ANC filter curves for magnitude and phase. The curves are shown below in blue. Unfortunately, this exact shape cannot be reproduced with available DSP filters in the ANC chip. Commonly there is a cascade of configurable second-order IIR biquad filters available. Also, there is a fundamental difference – target phase response is rising in the frequency range of interest and a perfect fit in entire frequency range is impossible without violating causality. The best possible fit of DSP filters to the target filter curve is shown below in red. Note that phase match is breaking at 40-50Hz and both magnitude and phase are deviating from target in the frequency region of the pinna resonance (2-3kHz). These exact effects limit the frequency range of effective feed forward active noise cancellation. It is also important to note that FF ANC may not only reduce the sound in the ear but also increase it. At higher frequencies too high of ANC filter gain leads to so-called waterbed effect and final FF ANC effect is above 0dB. This is not desired and solution is to reduce the ANC filter gain at those frequencies. However, this will also make cancellation worse at the frequencies where it is effective. ANC designers have to take this trade off into account. Luckily, passive attenuation is good in high frequencies and helps to mitigate the waterbed effect.







Previous paragraphs explained FF ANC mechanism and sources of its limitations. Now it is possible to analyze effect of microphone characteristics on FF ANC. FF microphone is a part of active transfer function. The shape of its magnitude and phase response adds to other components like the speaker. Simulation below shows a comparison of two FF ANC systems. Baseline solution has 30Hz LFRO mic and 24us mic ASIC digital latency. The modified microphone has 10Hz LFRO and 3us latency as well as assumes 30us lower ANC processing latency. One can observe the change in the shape of active transfer function on the chart below. Target filter curve changes and the fitted FF filter transfer function is updated accordingly. As expected, wider and flatter magnitude and phase response of the mic flattens the active transfer function which makes target filter curves flatter and easier to fit with DSP filters in a wider frequency range. Better fit of ANC filters leads to better ANC cancellation in wider frequency range and pushing the waterbed region to higher frequencies. Specifically, lower microphone LFRO improves the low frequency limit of FF ANC and lower system latency improves the high-frequency limit of FF ANC.

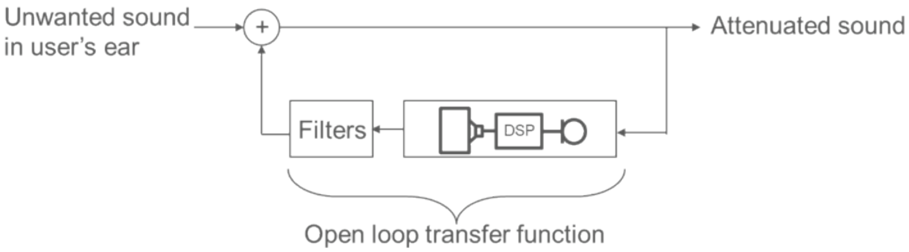


Should it be concluded that FF mic LFRO for TWS ANC headsets should be as low as possible? It will improve ANC but there are other system trade offs that are important to take into account. For example, wind noise mitigation. Having too low mic LFRO makes the system too sensitive to wind noise which is rich in low frequencies.

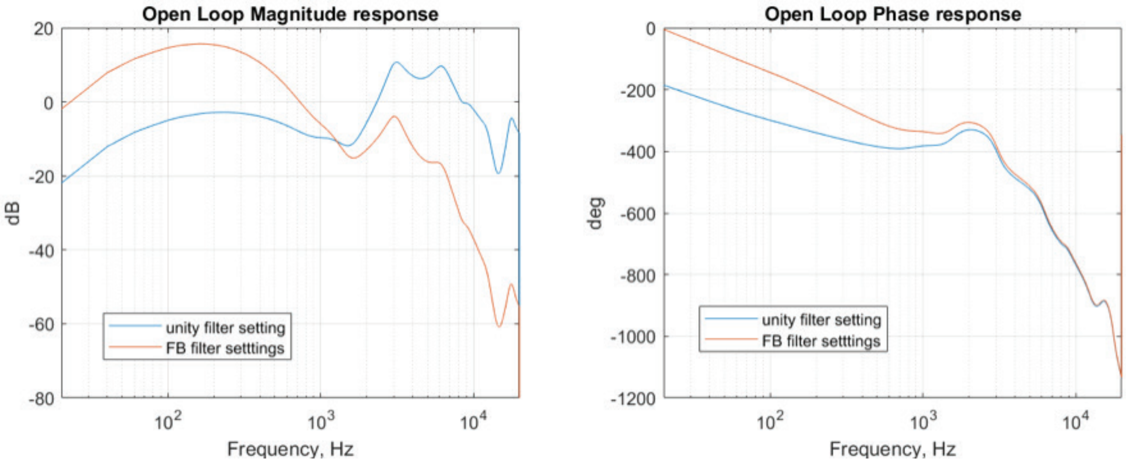
High-frequency FF cancellation improves with lower system latency. Total latency value includes microphone and DSP processing. All components of the system need to be improved for the best results.

Chapter 3. Feed Back ANC

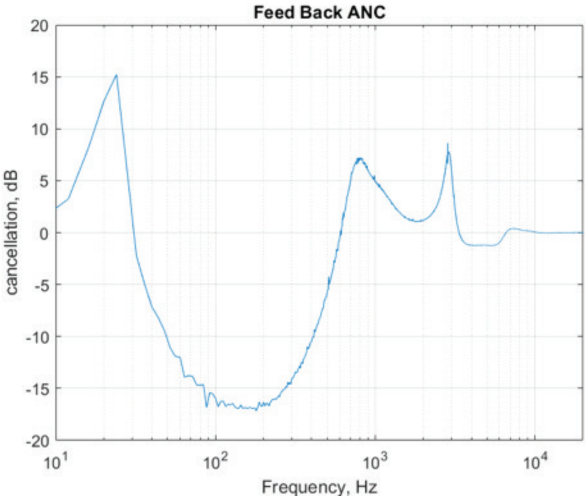
A concept diagram for Feed Back (FB) ANC system is given below. Unlike feed forward ANC, entire system is functioning inside the ear of the user. Input signal into the feedback loop is the residual noise after passive and feed forward cancellation. Sound is captured by the feedback microphone, DSP path applies FB ANC filters and resulting signal is played through the speaker. Open loop transfer function includes all components of the system assuming no coupling from output back to input. Usually it is measured in analog domain by feeding a constant signal to the speaker and measuring output of DAC of the ANC chip.



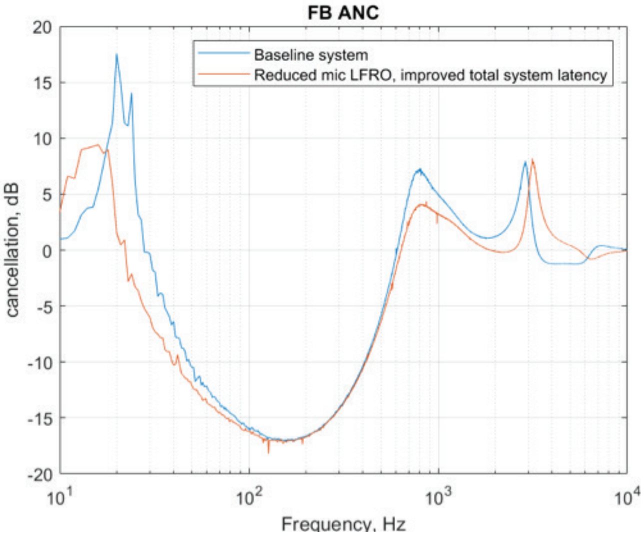
In order to maximize noise cancellation in a feedback system, the open loop transfer function needs to apply as much gain as possible while maintaining stability of the system. There are mathematical techniques to describe this tradeoff. For example, phase and gain margin analysis can be used. The chart below shows open loop transfer function of a feedback ANC system. With filters set to unity one can observe the starting point of algorithm tuning. Next, the filters are picked so that feedback cancellation is maximum while waterbed effect and stability is still acceptable. In this particular example, filters are constructed from 20dB gain, 180 degrees phase inversion as well as second order bandpass filter from 1Hz to 425Hz.



The result of tuned open loop transfer function is given below in a form of feedback ANC cancellation curve. Maximum achievable attenuation is more than -15dB at around 200Hz. Open loop transfer function at that frequency has maximum gain and phase inversion close to 180 degrees. In the low-frequency range and also at 1-3kHz feedback system amplifies the signal. This is unwanted waterbed effect. Phase and gain margins are reduced at those frequencies but the system is still stable. Above 5kHz open loop transfer function is sufficiently attenuated and feedback loop does not impact the signal at all.



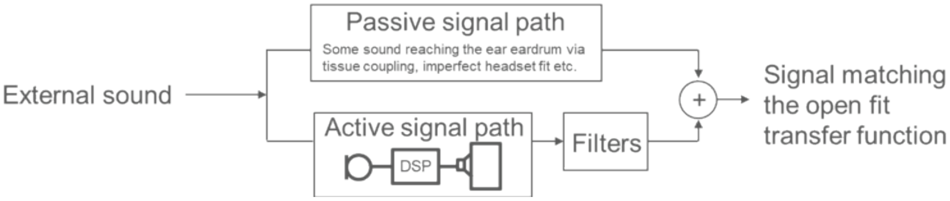
Next step is to evaluate the impact of microphone specification on the operation of feedback ANC loop. Similar to feed forward case, microphone transfer function is one of the components of open loop transfer function. Lower microphone LFRO makes it flatter at low frequencies and thus improves the gain margin. Lower system latency leads to not as steep phase response and allows improving phase margins in high-frequency range. Figure below shows impact of LFRO and latency improvement on feedback active noise cancellation. Effective bandwidth is improved on both sides and waterbed effect is reduced.



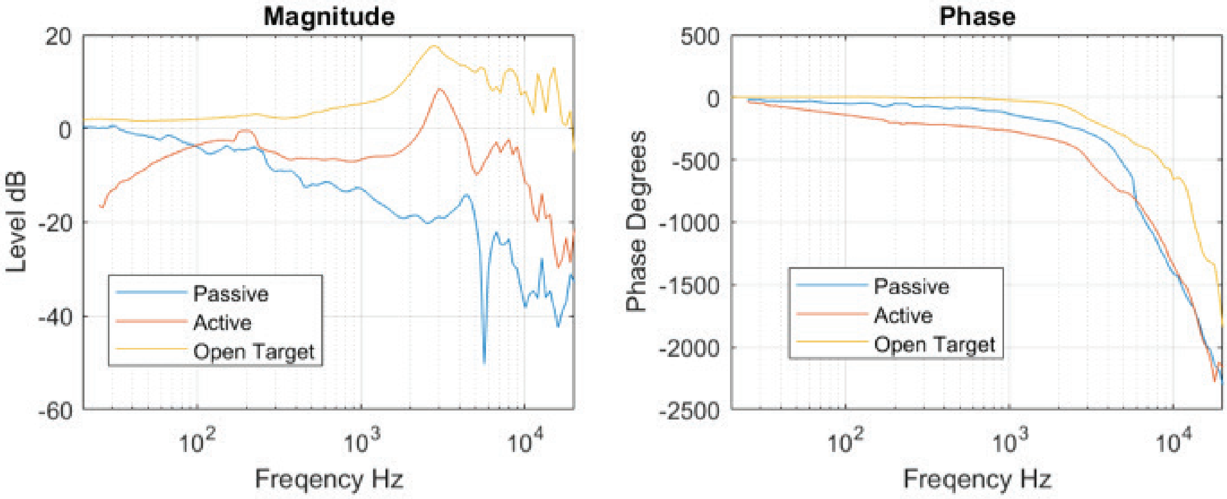
In summary, microphone requirement for the best feedback ANC is having as flat as possible magnitude and phase frequency response. Lower LFRO improved FB ANC in low-frequency range and lower microphone latency improves FB ANC in high-frequency range. It is important to note that lowering mic LFRO too much can have negative consequences. Head or jaw motion, human physical activity can lead to high SPL low-frequency signals generated inside ear canal while wearing TWS headset. Having LFRO sufficiently high protects the system from unwanted overload.

Chapter 4. Transparency mode

Earlier in this paper it was discussed that TWS headset in the ear provides passive attenuation. To put it simply, it acts like an ear plug attenuating high frequency signals. In some use cases it is important to hear the outside world without such passive attenuation. This is achieved in so-called transparency mode. The block diagram for this more is identical to the feed forward system. The difference is the target signal inside the ear. Unlike FF ANC where the goal was to cancel out the sound that couples into the ear, the goal of transparency more is to match the transfer function of the open ear.



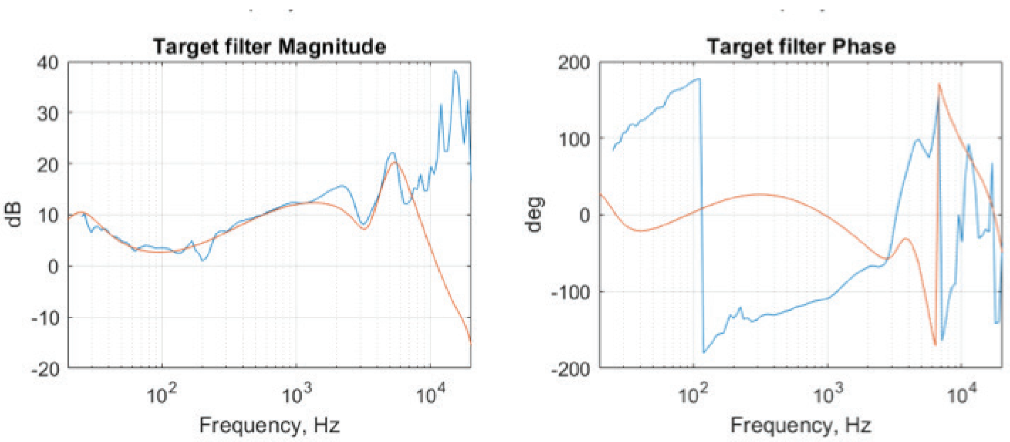
The target open fit transfer function is shown on the charts below alongside with active and passive signal path transfer function discussed in the feed forward chapter. The curve is generally flat with high-frequency resonances in the ear as expected. Active signal path multiplied by the transparency mode filters combined with passive signal path need to match the open target curve. At this point it is already clear that transparency mode will require lots of gain applied to microphone signal.



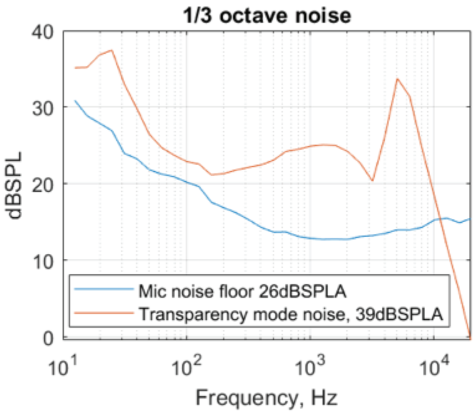
Target transparency mode filter coefficients can be derived by solving a simple equation described above.

$$TargetFilter = \frac{OpenFit - PassivePath}{ActivePath}$$

Similar to feed forward ANC, target curves are fitted with available filters in DSP chip. Example is given below. Note that filter magnitude is above 0dB, lots of gain is applied to the microphone. Matching perceived loudness will be the most noticeable effect in transparency mode. Of course the shape of phase response curve can be audible due to temporal distortions. Given the flexibility of DSP filters available, the match of magnitude filter curve is considered more important in this case for audible experience of the user in transparency mode.



As a result of this algorithm the user of TWS headset will hear the sounds that closely resemble experience with open ear. However, it is critical to recognize that microphone by itself is a noise source. Mic noise will be amplified by the DSP coefficients and played through the speaker. Resulting noise floor in the ear will increase. If the environment around the user is sufficiently loud microphone noise will be negligible and the system will operate as intended. However, in a quiet environment in-ear noise floor will be dominated by the microphone and not the environment. Sometime this effect is described as transparency mode hiss. The cart below compares microphone input-referred third octave noise spectrum and the same characteristic of transparency mode system. Integrated A-weighted noise difference is 13dB. In this example, user might start hearing the transparency mode hiss if environment is below 39 dBSPLA.



The level of transparency mode hiss drives the requirement to use microphones with as high as possible SNR. Higher SNR and thus lower microphone noise expands the range of use cases for transparency mode where the user will not experience the hiss.

Chapter 5. Conclusions

This white paper describes the operation of feed forward and feedback Active Noise Cancellation as well as transparency mode. Critical microphone specifications identified that lead to improved user experience.

Microphone latency needs to be reduced as much as possible. With proper algorithm tuning, this allows better cancellation for feed forward and feedback ANC in high frequency range. It also reduces unwanted high-frequency amplification known as the waterbed effect.

Microphone low frequency roll-off (LFRO) needs to be set optimally. With proper algorithm tuning, lower LFRO allows achieving better cancellation in low frequencies for both feed forward and feedback ANC. However, LFRO cannot be set too low in order to avoid wind noise issues with feed forward microphone and infrasonic overload issues with feedback microphone.

Microphone SNR needs to be as high as possible. This way audible hiss is reduced and transparency mode can be used in wider range of use cases.