The Need for Psychoacoustics in Active Noise Cancellation

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Introduction

Active noise canceling (ANC) headphones use destructive interference to eliminate unwanted noise. They are very popular especially with frequent travelers. Some airlines even equip their first and business class seats with ANC headphones to enable a more relaxing flight. There is a huge range of ANC headphones on the market. Various companies offer circumaural, supra-aural and in-ear headphones with different control strategies. They advertise high reductions of ambient noise to improve the sound of the music or make a more pleasant surrounding.

Bose promotes their systems with "Advanced noise reduction across a wide range of frequencies" as "A world of quiet" or to "Create a comfortable escape" to "relax without distractions" [1]. Sony's MDR-NC100D headphones "provide a superb listening experience by reducing up to 98.2% ... of ambient noise" [2]. The ATH-ANC9 of audio-technica "provide a comfortable listening environment in areas with high ambient noise" because of "noise cancellation up to a remarkable 95%" [3]. Sennheiser's NoiseGard™ / digital technologies "reduce ambient noise- allowing the listener to hear subtle nuances in their music, relax and arrive less fatigued" [4].

High noise reductions are supposed to increase the hearing comfort, but what features this comfort is usually not considered in ANC research. Our research project concentrates on the control design for ANC in-ear headphones. From a test person evaluation of different ANC controls it can be concluded that the perceived loudness is not the only important fact that influences the choice of the preferred control. Also the pleasantness is quite important. Because psychoacoustics deals with the perception of sound and for example tries to rate the sensory pleasantness of signals [5], it should be taken into account to design even better ANC controls especially for headphones. Nevertheless the cooperation of both fields is not very common in research. Hence this paper tries to highlight the need for psychoacoustics in ANC.

First some fundamental aspects of psychoacoustic are explained, which may have an influence on the ratings on ANC headphones. Then in respect of these facts properties of different ANC controls are analyzed. Finally the results of the test person evaluation are presented, which illustrate the need for psychoacoustics in active noise cancellation.

Psychoacoustics

In control engineering noise is usually determined by its sound pressure level measured with a microphone, but to design a good control for ANC headphones the human auditory system should be taken into account to better estimate the effect on the user. The difference of the perceived loudness and the measured sound pressure level is illustrated in the equal-loudness graph [5]. It can be seen that the human hearing is most sensitive between 2 kHz and 5 kHz. Higher or lower frequencies are perceived as more silent if they have the same sound pressure level. To take the perceived loudness of a human into account, an A-weighting is often used for sound level measurements. Nevertheless this only compensates the gross behavior of the human auditory system.

First of all ANC headphones want to reduce the loudness to create a more pleasant surrounding. Next to the loudness psychoacoustics tries to define different sensations to rate certain noises such as sensory pleasantness. Even though this is hard to quantify, the dependence on other sensations such as sharpness, loudness, roughness and tonality, is known [5]. Sharpness has the biggest influence on the sensory pleasantness. It decreases with increasing sharpness. Higher frequency bands appear sharper than lower frequencies. Loudness has a negative effect on pleasantness but only if it exceeds the normal level of a communication [5].

Control Theory

Different control structures are analyzed in respect of psychoacoustics and sensory pleasantness. In particular the increase of sharpness is taken into account. First the standard feedback control is considered, because it is the most commonly used control for circumaural and supra-aural ANC headphones. ANC in-ear headphones are usually equipped with a static feedforward control. Hence the adaptive feedforward control is observed, wherein the major research takes place.

Feedback Control

Most ANC-headphones are equipped with a static feedback (FB) [6] control, which needs an error microphone inside the ear or the ear cup. The block diagram of such a FB control can be seen in Figure 1, where $S(z)$ is the acoustic path inside the ear from the output of the FB controller $R(z)$ to the error microphone and includes all necessary signal conversions. The microphone picks up the error $e(n)$ resulting from the superposition of the disturbance $d(n)$ and the anti-noise. This error is filtered

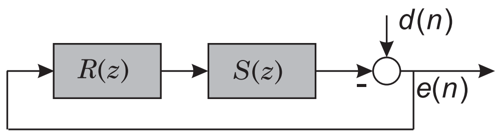

Figure 1: Feedback control loop.

by the controller $R(z)$ to generate the anti-noise. The closed loop transfer function $C(z)$ comes to

$$C(z) = \frac{E(z)}{D(z)} = \frac{1}{1 + R(z) \cdot S(z)}. \quad (1)$$

The attenuation of the feedback control is limited by bode's sensitivity integral [7], also called water-bed effect.

$$\int_0^{\pi} \ln \left| C\left(e^{j\omega}\right) \right| d\omega = 0 \quad (2)$$

Hence it is not possible to achieve an attenuation over the whole frequency range. An attenuation in one frequency range will cause an amplification in another frequency range as depicted in Figure 2.

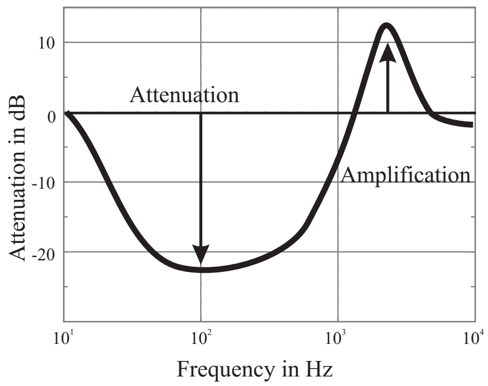

Figure 2: Bode magnitude plot of closed loop transfer function $C(z)$ representing the attenuation of a feedback system.

For headphones FB controllers $R(z)$ are usually designed to achieve maximum attenuation at frequencies between 100 Hz and 400 Hz [8], minimizing the power of most disturbances such as airplanes or trains. This usually leads to an overshoot at around 1000 Hz. Hence the signal might be amplified in the frequency region where the human hearing is most sensitive. Furthermore high frequency amplification combined with attenuation in lower frequencies increases the sharpness of the signal [5]. Hence a general statement about the pleasantness of the residual signal is hard to determine.

Adaptive Feedforward Control

A lot of research projects concentrate on adaptive feed-forward (FF) control. The block diagram of a FF control is shown in Figure 3 [6],[9].

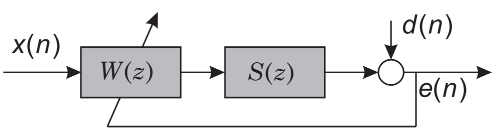

Figure 3: Block diagram of an adaptive feedforward control.

A reference microphone on the outside of the headphone picks up the reference signal $x(n)$, which then gets filtered by the controller $W(z)$. The filter output is played by the loudspeaker, passes the path $S(z)$ and superposes with the disturbance $d(n)$ to the error signal $e(n)$. This error is recorded with an error microphone inside the headphone and used to optimize $W(z)$. Mostly the filter is adapted to minimize the mean square error, hence the power of the error signal. For example this can be done with the least mean square (LMS) algorithm [6].

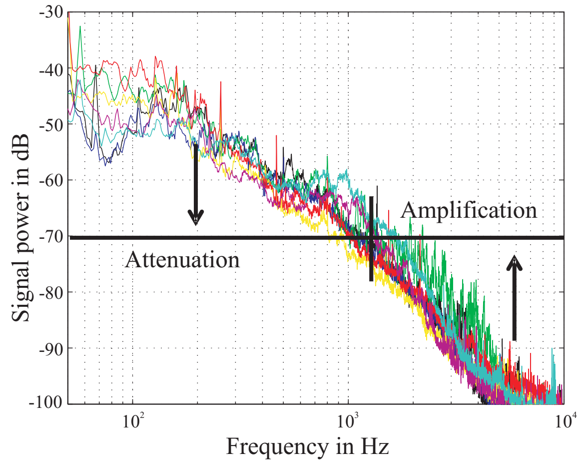

Figure 4: Power spectrum of different airplane interior noises and a possible control result of an adaptive system.

Theoretically it would be possible to calculate an optimal filter $W_{opt}(z)$ to achieve an optimal attenuation with $e(n) = 0$. In real world applications this is usually not possible for example due to dead time in the acoustic plants or a limited number of filter coefficients. Hence an attenuation over the whole frequency range is not possible. Figure 4 shows the signal power spectra of different interior noises of airplanes. Most of the power is in the lower frequency range. For higher frequencies the magnitude decreases. A standard LMS adaptive filter will concentrate on the lower frequencies to get the best possible attenuation. Amplifications of the higher frequencies would be accepted, if in this way a better performance in the lower frequencies can be achieved and thus the overall power is minimized. This amplification may again increase the sharpness of the residual signal.

Some research was done in respect of loudness perception of the human hearing. In [10] an A-weighting was included into the adaptive FF control. The error $e(n)$ is A-weighted and the filter is adapted to minimize this weighted signal.

Another point to question is the adaptation itself. ANC in-ear headphones require an adaptive control to get the best attenuation for all users because of interpersonal variances [11]. Thus adaptive filters usually achieve a better attenuation than static filters for stationary signals. But the disturbance may be time varying, which may cause the filter to change all the time. The influence on the perceived residual signal has also not been examined yet.

Test Person Evaluation

In the following some results of our project are presented demonstrating the need for psychoacoustics in ANC applications. The project goal is the design of a feedforward control for ANC in-ear headphones. The used prototype headphones are equipped with internal error microphones and external reference microphones. The application concentrates on transport noise like interior noise of airplanes and trains. To compare and rate different controls 20 test persons were asked to fill out a questionnaire while testing these headphones. The goal was to determine the favorite control of an average user and not to perform a complete psychoacoustic study. None of the test persons suffered from major hearing damage and all had no special acoustic training to represent an average user of ANC headphones. The test was performed in an anechoic room and the disturbance was generated by surrounding loudspeakers. The test persons were able to switch freely between three different controls. They were asked to rate these controls at three different disturbing noises, two airplanes and one train, with similar power spectra as presented in Figure 4. Each time the loudness and the pleasantness had to be judged. First the perceived sound had to be compared with and without active control, for that the control had to be turned on and off. Second the controls were directly compared to each other by switching between two different controls. The evaluations had to be marked on a continuum scale line. Thereby some reference points were given, as for example for the loudness: slightly quieter, quieter and significantly quieter. Finally the test persons had to pick the preferred control.

Details of Controls

Two different adaptive feedforward controls were designed and compared to a static FF control which is usually used for ANC in-ear headphones. All filters are designed to minimize the loudness as perceived of the human hearing. The two adaptive FF controls differ by the high frequency influence. Whereby in one control the adaptation in the higher frequencies was unrestricted, in the other control the magnitude response of the adaptive filter was specifically affected to reduce high frequency amplifications of the noise. Figure 5 shows an example of the possible attenuation of the 3 different controls for one test person. The attenuations were simulated based on measurements.

Results

The following analysis shows the results of the 20 test persons, whereby each rated three sounds. Hence each evaluation contains 60 judgments. Figure 6 presents the results of the assessment of the controls itself by turning them on and off in an box-and-whiskers diagram. For each control the perceived loudness and the pleasantness was rated. The blue left ordinate in connection with the blue left box plots show the loudness. The right ordinate and the orange box plots depict the pleasantness. The top and bottom of the box represent the lower and the upper quartiles of all ratings, hence the 25th and 75th percentile. Furthermore the median is marked by a line in the middle of the box. The whiskers indicate the 10th and 90th percentile. Outliers are plotted as a dot. A positive assessment which means a quieter residual noise and a more pleasant signal is indicated by a downward shift. In general all controls achieve a good attenuation, hence the residual noise with control turned on is quieter than without. Also the general trend is that the noise with control turned on is more pleasant. Some test persons mentioned annoying noises especially with control 2, which are possibly caused by high frequency amplifications as can be seen in Figure 5. Others sometimes experienced rather a reshaping of the noise spectrum than an attenuation. This is indicated by outliers in the upper half of the diagram.

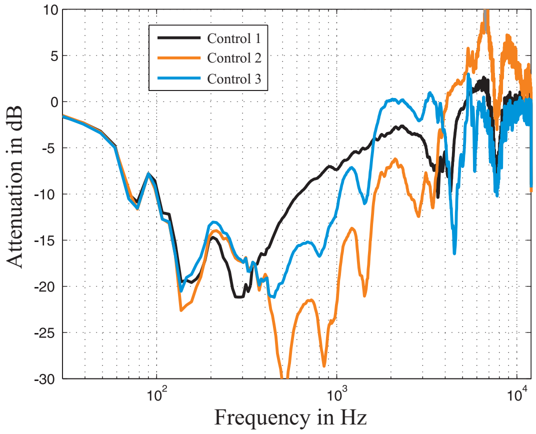

Figure 5: Attenuation of the 3 different controls of one selected test person.

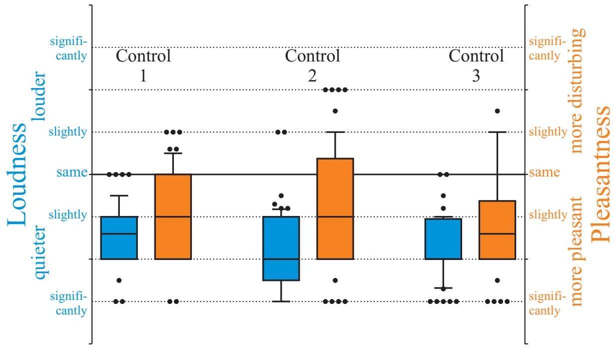

Figure 6: Evaluation of single control.

The difference in the controls can be better evaluated by examining the direct comparison in Figure 7. Again the left and right ordinate in blue and orange represent the loudness and the pleasantness, respectively. The boxes and whiskers represent the same percentiles as before, the 10th, 25th, median, 75th and 90th percentile. The compared controls are named on the left of each pair of box plots. Hence the outer left pair compares control 1 and 2. An upward tendency favors the control 2, as this is labeled in the upper diagram half. Hence control 2 is judged as quieter than control 1, but both controls are similar pleasant because the responses balance. Comparing control 1 and 3 it can be seen that the residual noise of 3 is also quieter than of 1. Hence control 1 is the control with the worst

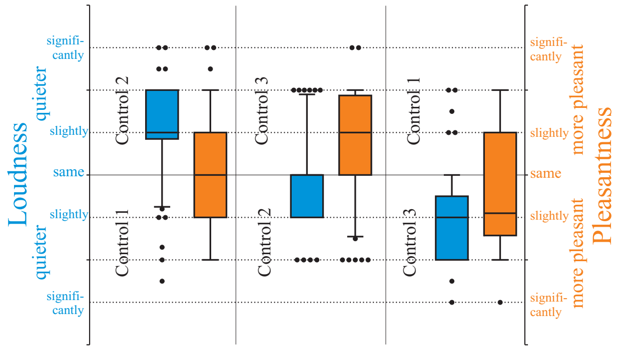

Figure 7: Comparative evaluation of controls.

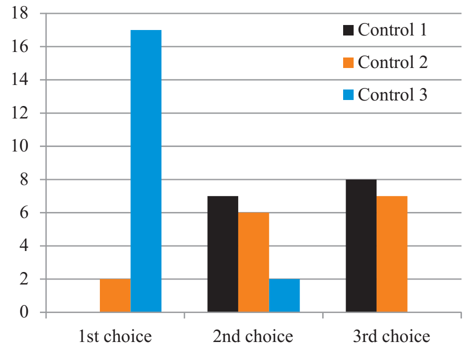

Figure 8: Selection of preferred control

attenuation. Comparing the pleasantness of 1 and 3 shows the tendency, that control 3 is slightly better rated. The most remarkable results can be seen by comparing control 2 and 3. Even though control 2 is judged as slightly quieter, control 3 is evaluated as more pleasant.

The importance of the pleasantness compared to the loudness is reflected in the choice of the preferred controls, which can be seen in Figure 8. The majority of the test persons prefer control 3, even though it is not the quietest one. The preference of control 1 or 2, if 3 would not be available, is well-balanced. In general there was a trade-off between the test persons which preferred the better attenuation of control 2 and accepted some unpleasant noise and the ones which favor less attenuation as long as the noise is less annoying. These unpleasant noises are possibly caused by the high frequency overshoot and the therewith connected increase in sharpness. Analyzing the evaluations in dependence of the used disturbance also showed huge variances even though the average power spectrum of all disturbances was similar.

Summary

ANC headphone producers promote their systems with high noise reductions to increase hearing comfort. To better evaluate this comfort psychoacoustics should be used. Nevertheless loudness is not the only important factor. Until now the cooperation of psychoacoustics and control design is not prevalent in research. Examining different control strategies shows that some characteristics have negative influences on the sensory pleasantness. Especially sharpness of the perceived signal is often increased due to high frequency amplifications.

The presented test person evaluation shows that ANC headphone users can well distinguish between loudness and pleasantness. It imposes that the highest attenuation is not always the most comfortable one. The preferred control in this test is the most pleasant one rather than the most silent one. Hence to rate and compare different ANC controls or control systems it is not sufficient to just ask for loudness. Furthermore the evaluation also depends on the used disturbing noise therefore extensive testing is needed to get significant results.

The question, what does feature a good control in detail, remains. Of course the perceived loudness and not just the measured power spectrum has to be reduced. Also sharpness plays an important role. Other aspects are much harder to determine as for example how other sensations influence the choice of the preferred control. Therefore deeper research connecting psychoacoustics and control engineering is needed.

Acknowledgements

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