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Convergence Time Measurement Method of Active Noise Cancelling Headphones

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Abstract: The aim of this paper is to develop and describe an objective method for measuring the performance of headphones with active noise cancellation (ANC). The focus was on measuring both passive and active sound attenuation and determining the convergence time of the ANC system. A new parameter was introduced—the reaction speed, expressed in dB/ms, allowing an accurate correlation of the active attenuation values with the time needed to achieve them. A series of tests were conducted using three active noise cancelling headphone models of different prices and specifications. The response times were recorded and analyzed. Measurements were performed on two different dummy head models and under two different measurement conditions (reverberation chamber and acoustically adapted room). The results revealed differences between the models, with some headphones consistently providing a better reaction speed. Remarkably, the headphone associated with the lower reaction speed were also the cheapest. This justifies the need for the reaction speed to be a parameter provided by the manufacturer in the datasheet.

Keywords: active noise cancelling headphones; convergence time; active attenuation measurement

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1. Introduction

Headphones with active noise cancellation (ANC) utilize advanced technologies to eliminate unwanted ambient sounds. ANC systems work by generating a sound wave of opposite polarity to the incoming noise, resulting in the mutual cancellation of acoustic waves. This process involves several key stages: recording external noise with microphones, analyzing and processing the signal through electronic circuits, and generating the appropriate corrective signal with transducers. The ANC system must continuously adjust the generated sound to effectively reduce noise that changes over time.

Different types of ANC systems are distinguished in the literature, such as feedforward, feedback, and hybrid systems, which differ in the way they analyze and generate the corrective signal. In feedforward ANC systems, the microphones are placed on the external side of the headphones, and the system analyzes the sound before it reaches the user's ears. In feedback ANC systems, the microphones are placed inside the ear cups, close to the ear, and the system analyzes the sound already reaching the ear. Hybrid ANC systems combine the advantages of both of the aforementioned systems, using microphones both outside and inside the ear cups, allowing for more effective noise reduction over a wide range of frequencies.

Attenuation in headphones can be divided into passive, resulting from the physical properties of the headphone design, and active, resulting from the operation of the ANC systems. Total attenuation is the sum of both these effects, significantly enhancing the comfort of using headphones in various environments.

Articles [1,2] present measurements of the active, passive, and total attenuation of headphones using an acoustic tester. Currently, there is no standard norm for objective measurements of ANC headphones using an acoustic tester. In articles [1,2], measurements were based on the standard [3]: measurements of insertion loss of hearing protectors using an acoustic tester, which recommends performing measurements in a diffuse field or in a free-field plane wave.

Article [4] addressed two significant issues: the use of different ear models for which different results were obtained and the problem with headphone leakage (poor fit to the ear). Therefore, measurements should be performed multiple times, and the measurement procedure should include each independent placement of the headphones. The results should be averaged. The study suggested that the best fit is not necessarily the most realistic usage variant. However, the topic of convergence time measurement was not addressed in the above sources.

Convergence time is the time it takes for the ANC system filters to adjust. Articles [5,6] presented the determination of convergence time through simulations of the created system. The filter tuning time translates to the time it takes for the attenuation values to stabilize. The appropriate modification of ANC algorithms (e.g., FxLMS) can contribute to improving the convergence time [7]. Article [8] conducted studies on signal variability after tuning. Despite the use of algorithms minimizing level variability, the problem still exists. In practical measurement situations of ANC headphone parameters, this can cause a problem related to the difficulty of determining the specific moment at which the tuning (convergence) time should be determined.

In the case of noise attenuation with rapidly changing parameters, it is crucial to adjust the system to the changing conditions as quickly as possible. Momentary detuning can lead to short-term unintended signal amplification. Therefore, minimizing the convergence time is a key criterion in achieving effective noise reduction in dynamically changing acoustic environments, e.g., when changing the direction from which the sound comes, a momentary increase in the signal level was demonstrated [9]. For non-stationary signals, such as speech, improving the ANC algorithm in headphones in terms of the reaction time can contribute to better active attenuation [10] and even increase the frequency range of attenuation [11].

Article [12], which aimed to study ANC algorithms in headphones, presented the measurement of the convergence time for various ANC algorithms in headphones. The measurement was conducted in an anechoic chamber with speakers arranged around the head. However, to measure this, it was necessary to interfere with the construction of the headphones and access the microphone inside the headphones.

Therefore, it has been shown that the convergence time, the time it takes for the ANC system to respond to incoming sounds or changing acoustic conditions, is an important parameter for ANC headphones. Therefore, there is a justified need to develop a method for determining such a parameter, which is not provided by manufacturers. The proposed measurement method for the convergence time presented in this article was created to accurately determine the parameters of the finished product, treating it as a measurement object with limited access to its internal structure. An original method for measuring the convergence time is described, simultaneously introducing the reaction speed parameter when a sound source is activated. This parameter is expressed as the ratio of the achieved attenuation value to the convergence time. Measurements were conducted on over-ear headphones, testing three different headphone models on two different artificial heads, under two different measurement conditions. The results of the attenuation and convergence time measurements were compared. The study also proposed a method for describing the parameters of ANC headphones.

This paper is organized as follows: Section 2 describes the measurement conditions and the active and passive attenuation measurement system, the devices used for measurement, the measurement signal, and the description of the tested headphones. The procedure for determining the attenuation value, convergence time, and reaction speed is also described.

Section 3 presents the measurement results. Section 4 presents the discussion, summary, and conclusions.

2. Materials and Methods

Measurements were performed both in a diffuse field in a reverberation chamber and in an acoustically adapted listening room.

2.1. Diffuse Field (Reverberation Chamber)

Measurements were carried out at ARIC (Acoustics Research and Innovation Center) run by KFB Acoustics in Poland. The tests were carried out in a P1 reverberation chamber used to measure the sound absorption coefficient according to EN ISO 354 [13], sound power level according to EN ISO 3741 [14], and sound insulation according to EN ISO 10140-2 [15] and ASTM E90 [16]. The chamber has passed the qualification for use in testing according to the methods listed.

The volume of the chamber V = 293.8 m^3 and the total surface area S = 263.6 m^2. To improve field diffusion inside the chamber, 10 diffusers made of polyurethane with a surface weight of no less than 5 kg/m^2 were installed.

Figure 1 shows the interior view of the chamber. The measurement signal was generated by an omnidirectional sound source. The artificial head was placed at a fixed measurement point. The measurement setup is shown in Figure 2.

Figure 1. Interior view of the reverberation chamber used during measurements.

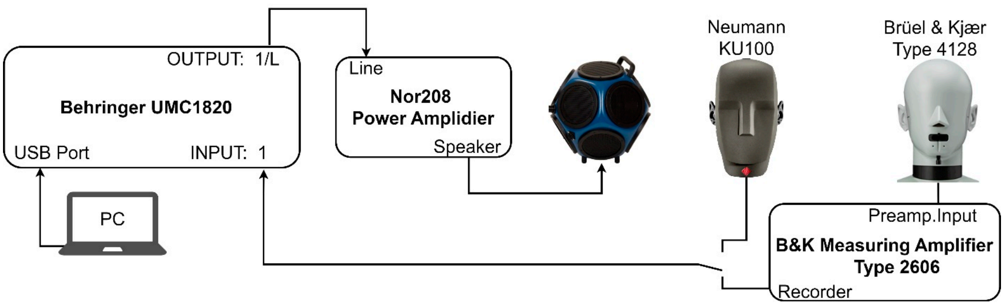


Figure 2. Measurement setup used in the reverberation chamber.

2.2. Plane Wave (Listening Room)

Measurements were also conducted in an acoustically adapted room with a volume of 30 m^3 and a total surface area S = 60 m^2. The signal was generated from a pair of loudspeakers placed on the axis of the tester (located between their left and right ear) at a distance of 1 m from each ear. According to the technical note from Audio Precision [2], this method allows for obtaining reliable results without using a reverberation chamber. Figure 3 shows the measurement setup used for measuring headphone attenuation. Figure 4 shows the actual arrangement of the equipment during the measurements.

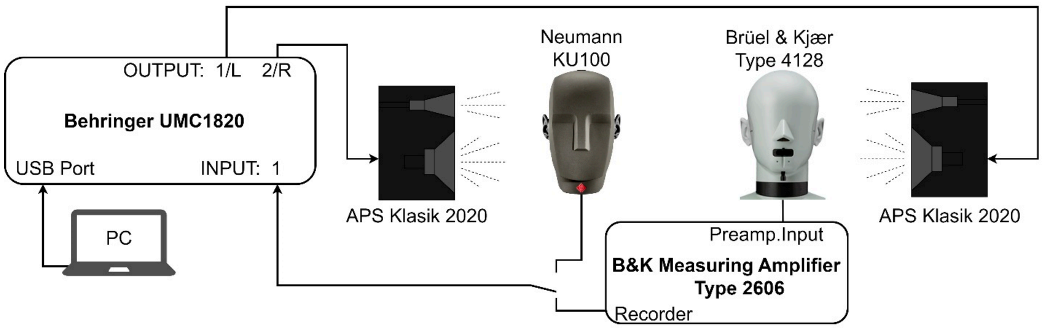


Figure 3. Measurement setup used for measuring headphone attenuation.

Figure 4. Actual measurement setup used for measuring headphone attenuation.

2.3. Ear/Head Models

The first test head model used for measurements was the Neumann KU100 [17] dummy head. This is a type of binaural microphone that mimics the human ear and head, allowing sound to be recorded in a way that is similar to how a listener hears it. According to the manufacturer, the device can be used for various applications, including noise impact analysis (e.g., in industrial plants), speech intelligibility studies, or headphone measurements.

The second test head model was the Head and Torso Simulator (HATS) Type 4128, manufactured by Brüel & Kjær (B&K) [18]. The Head and Torso Simulator (HATS) Type 4128 is a dummy head with built-in ear and mouth simulators that provides a realistic reproduction of the acoustic properties of an average adult human head and torso. It is designed to be used in in-situ electroacoustics tests on, for example, telephone handsets, headsets, audio conference devices, microphones, headphones, hearing aids, and hearing protectors. The HATS we used for the measurements is equipped with a single channel, so measurements were performed for only one channel for both the HATS and Neumann test head models.

2.4. Measurement Signal

The measurement was performed using pink noise. A relatively high signal level (Lp = 85 dB(A)) was used due to the fact that some active noise-canceling headphones may have threshold activation values. Consumer device manufacturers do not provide such information in their documentation. A low input signal level might not meet the activation conditions of the active noise-canceling system.

2.5. Tested Headphones

Three different over-ear headphones with active noise canceling were tested. Each pair of headphones has a phone app for control and varies in price class.

HP1—the price on the Polish market is around EUR 330. The manufacturer does not provide electroacoustic parameters.
HP2—the price on the Polish market is around EUR 305. The frequency range is from 4 Hz to 40 kHz. Sensitivity is 105 dB/mW (when connected by headphone cable and with the device turned on).
HP3—the price on the Polish market is around EUR 90. The frequency range is from 7 Hz to 20 kHz. Sensitivity is 108 dB/mW (when connected by headphone cable and with the device turned on).

Manufacturers do not provide any parameters related to active noise canceling.

2.6. Attenuation Measurement Procedure

To determine the attenuation, it is necessary to perform measurements in four different situations:

$L_{background}(f)$—measurement without headphones with the test signal source turned off,
$L_{signal}(f)$—measurement without headphones with the test signal source turned on,
$L_{withoutANC}(f)$—measurement with headphones on with the test signal source turned on and active noise-canceling turned off,
$L_{withANC}(f)$—measurement with headphones on with the test signal source turned on and active noise-canceling turned on.

Each measurement was performed for 30 s. The obtained signals were filtered using a bank of 1/3 octave filters in the range from 50 Hz to 5 kHz. The standard for hearing protectors recommends conducting measurements in the frequency range from 63 Hz to 8 kHz. However, due to the bandwidth limitations of the used omnidirectional source, it was decided to limit the analysis range to 5 kHz. Measurements $L_{withoutANC}(f)$ and $L_{withANC}(f)$ were repeated five times, and the obtained results were averaged. The purpose of this process was to average the attenuation values depending on the positioning of the headphone on the ear. The attenuation (passive, active, and total—Equations (1)–(3)) in the individual bands was calculated as the difference between the signal levels measured in each 1/3 octave band from the individual measurements.

$$L_{passive}(f) = L_{signal}(f) - L_{withoutANC}(f) \tag{1}$$

$$L_{active}(f) = L_{withoutANC}(f) - L_{withANC}(f) \tag{2}$$

$$L_{total}(f) = L_{signal}(f) - L_{withANC}(f) \tag{3}$$

The obtained results were compiled graphically for the individual headphone models. The applied method assumes performing the measurement without the need to determine the sound pressure value at each measurement. Measurements were recorded as audio files in wav file format, with a sampling frequency of 48 kHz and a bit resolution of 24 bits. The input signal was driven in such a way that during the measurement without headphones with the test signal source turned on, the peak signal value did not exceed −5 dBFS.

2.7. Convergence Time Measurement Procedure

For convergence time measurement, the same setup was used as for the headphone attenuation measurement. Measurements were performed in two situations:

$L_{withoutANC}$—measurement with headphones on with the test signal source turned on and active noise-canceling turned off,
$L_{withANC}$—measurement with headphones on with the test signal source turned on and active noise-canceling turned on.

The pink noise measurement was performed to observe changes in active attenuation over time when the signal was turned on. After initially analyzing the waveform graphs, it was decided to use a frame length of 256 samples with a window shift of 64 samples (75% overlapping). These settings provide a time resolution of 1.3 ms, which is sufficient for observing changes in attenuation over time when measuring with pink noise. Based on the obtained characteristics, the convergence time was determined as the time from turning on the signal to achieving the active attenuation value in a given 1/3 octave band. This approach was taken due to difficulties in determining the moment of system stabilization. The time from turning on the signal to the arrival of the acoustic wave at the test dummy head was also considered.

A small convergence time value does not always mean better performance. If the active attenuation in a given 1/3 octave band has a small value, the system can reach this value relatively quickly. Therefore, the convergence time value alone is not a sufficient criterion for evaluating the effectiveness of attenuation when the test signal is turned on. The achieved attenuation value after tuning the system is also important. To compare both parameters, a reaction speed (RS) parameter expressed as the ratio of the achieved attenuation value ($L_{active}(f)$) to the convergence time ($T_{convergence}(f)$) (Equation (4)) was introduced.

$$RS = L_{active}(f)/T_{convergence}(f) \tag{4}$$

The method of determining both values (convergence time and reaction speed) is shown in Figure 5. The unit of the parameter is expressed in decibels per millisecond. The value for individual models is presented as an average of 5 measurements. In Figure 5, the linear approximation of the attenuation characteristic from the moment the signal is turned on to achieving the active attenuation value in a given 1/3 octave band is marked with a red dashed line.

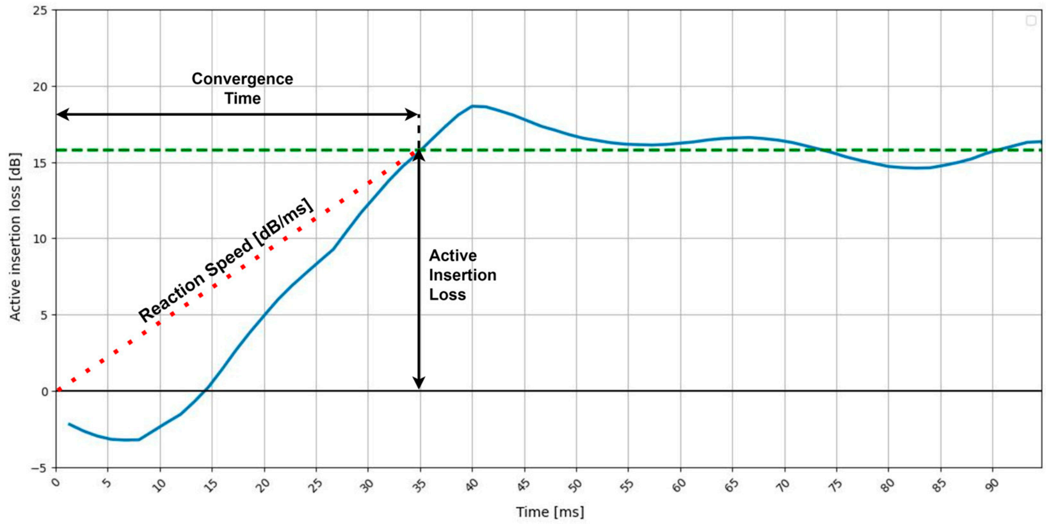


Figure 5. A schematic representation of the method of determining the convergence time and reaction speed; Blue line—graph of attenuation over time. Green dashed line—average value of attenuation. Red dashed line—representation of reaction speed.

2.8. Data Processing

Data processing and generating attenuation graphs for individual headphones were carried out using a created Python program to automate the analysis of the obtained data. After receiving the path to the folder containing the files, the program generates graphs illustrating the attenuation (passive, active, and total) as a function of frequency for the tested headphone model. Audio data are read from the file and recorded on a scale of −1 to 1. Then, the data are passed through a bank of 1/3 octave band fourth-order filters. In the case of the attenuation measurement, the signal level is calculated in dBFS (Equation (5)).

$$L_{rms} = 20 \log_{10}((\frac{1}{N}\sqrt{\sum_{n=1}^{N} x^2(n)})/(0.707))\ [\text{dBFS}] \quad (5)$$

For the convergence time measurement, data arrays containing the signal are removed until the test signal reaches the receiver (a microphone of dummy head). Then, the RMS value of the signal for each frame is calculated (256 sample frame, 75% overlapping). Active attenuation over time is obtained by subtracting the signal level with the ANC system turned on from the signal obtained with the ANC system turned off. All results are averaged over 5 measurements.

3. Results

3.1. Attenuation Measurement Results

Figure 6 shows the results of the active, passive, and total attenuation measurements for HP2 headphones for one channel. Measurements were made in a reverberation chamber using an artificial HATS head.

The obtained results are consistent with the assumptions. Active attenuation (understood as the attenuation obtained as a result of the operation of the ANC system) dominates up to 500 Hz, above which passive attenuation begins to dominate (understood as the attenuation obtained through the design of the earphone, which acts as a natural sound barrier). Total attenuation, which is a combination of active and passive attenuation, remains high throughout the entire tested range.

To determine the convergence time in accordance with the proposed method and the reaction speed, the active attenuation value is required. The measurement of active attenuation in the 1/3 octave bands was performed under two different measurement conditions (in the reverberation chamber and in the listening room) for two models of artificial heads (Neumann KU100 and B&K Type 4128). The measurements were performed five times and then the results were averaged. The results for HP1, HP2, and HP3 headphones are shown in Figures 7–9, respectively.

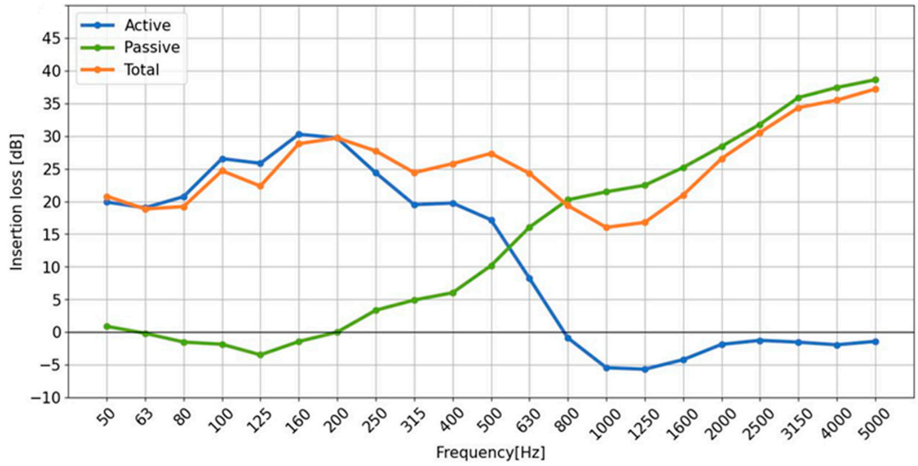


Figure 6. Summary of active, passive, and total attenuation as a function of frequency for one channel of HP2 headphones.

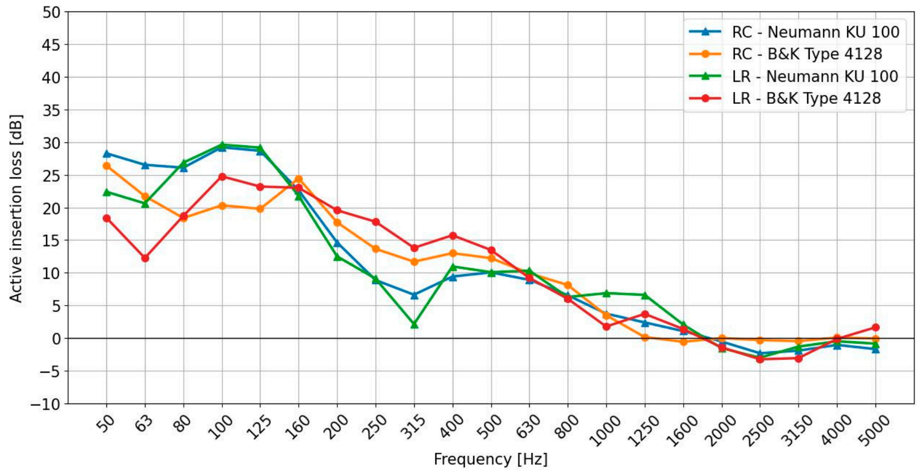


Figure 7. Active attenuation of HP1 headphones measured in the reverberation chamber (RC) and listening room (LR) using Neumann KU100 and B&K Type 4128 test head models.

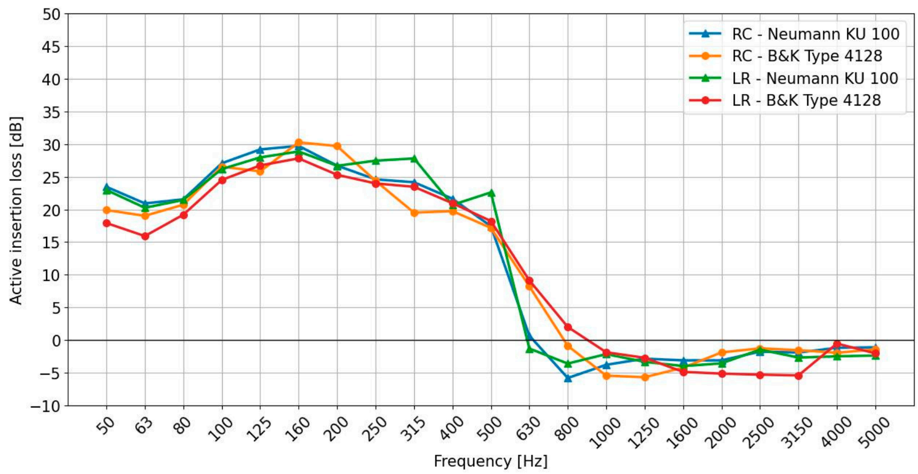


Figure 8. Active attenuation of HP2 headphones measured in the reverberation chamber (RC) and listening room (LR) using Neumann KU100 and B&K Type 4128 test head models.

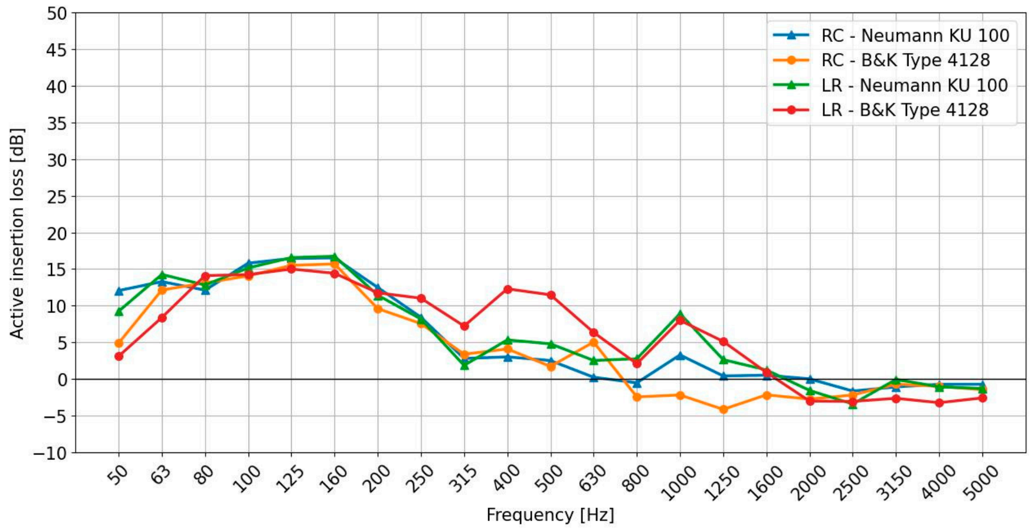


Figure 9. Active attenuation of HP3 headphones measured in the reverberation chamber (RC) and listening room (LR) using Neumann KU100 and B&K Type 4128 test head models.

Analysis of the active attenuation measurement results showed that the highest attenuation values were obtained for the HP2 headphones. For the 1/3 octave bands from 50 Hz to 500 Hz, the active attenuation value exceeded 15 dB, reaching a maximum value of approximately 30 dB for the 160 Hz 1/3 octave band. However, the lowest attenuation values were obtained for the HP3 headphones, where the maximum attenuation was approximately 15 dB in the bands between 100 Hz and 160 Hz. The HP1 headphones were characterized by the highest attenuation in the range from 15 dB to 30 dB, which occurred for the bands from 50 Hz to 160 Hz.

Similar results were obtained for each measurement situation, especially for the HP2 headphones, where the measurement conditions and the head model used slightly influenced the obtained attenuation values. In the case of the HP1 headphones, the greatest differences between measurements were observed; however, the results for the Neumann KU100 test head model in the reverberation chamber and the listening room were very similar to each other, as were the results for the B&K Type 4128 test head model under different conditions. This means that the head model used had a greater impact on the results than the measurement conditions.

Active attenuation greater than 0 dB for the HP1 headphones was observed up to the 1.6 kHz 1/3 octave band, and for the HP2 headphones, this was up to 630 Hz or 800 Hz, depending on the measurement conditions. In the case of the HP3 headphones, the greatest discrepancy between the results was observed, which makes it difficult to determine a clear limit of the effectiveness of active damping in individual frequency bands. For the reference measurement (using the B&K Type 4128 test head model in the reverberation chamber), active attenuation had positive values up to the 630 Hz 1/3 octave band.

3.2. Convergence Time Results

The change in active damping as a function of time as a result of switching on the signal was measured five times. Sample results with an average graph are shown in Figure 10.

The trend of changes in active attenuation is similar for all individual measurements. The differences result from the different fit of the headphones to the ear, which were put on independently for each measurement. You can also observe different starting values of the graphs; sometimes it starts with attenuation and sometimes with amplification of the signal. This depends on the initial conditions of the ANC adaptive filters. For the averaged graph, the damping value is close to zero at the beginning. It can be assumed that the initial value of the averaged graph will tend to zero as the number of measurements increases.

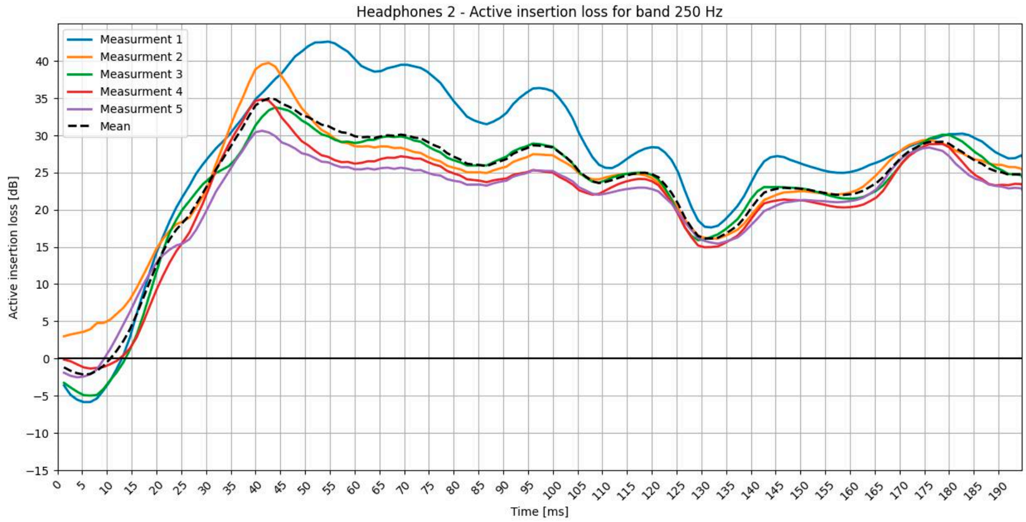


Figure 10. Example measurements of changes in active attenuation as a function of time. HP2 headphones, for 250 Hz 1/3 octave band.

Figure 11 shows the active attenuation as a function of time for the 250 Hz band, obtained for HP2 headphones under four measurement conditions: in the reverberation chamber (RC), in the listening room (LR), using two models of artificial heads (Neumann KU100 and B&K Type 4128). The results reveal noticeable differences. Measurements obtained in the listening room demonstrate higher initial values of active attenuation, whereas in the reverberation chamber, the initial active attenuation values are close to zero.

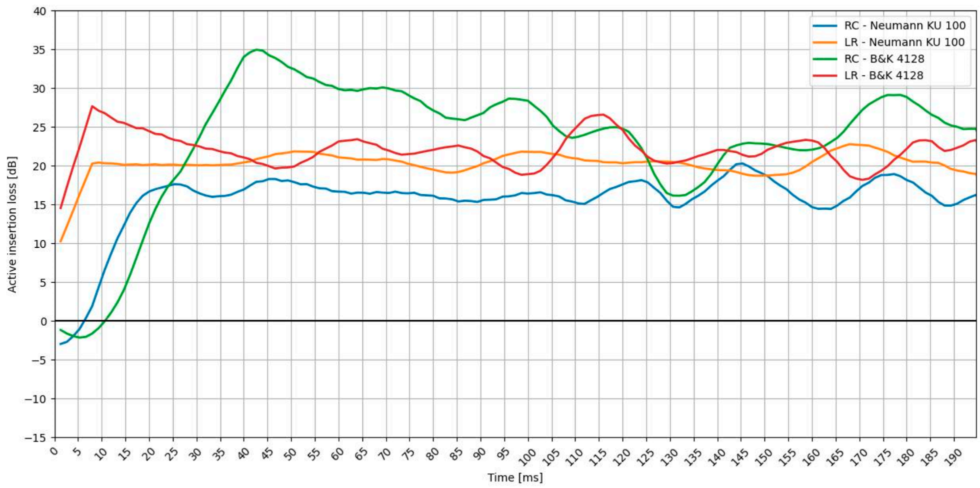
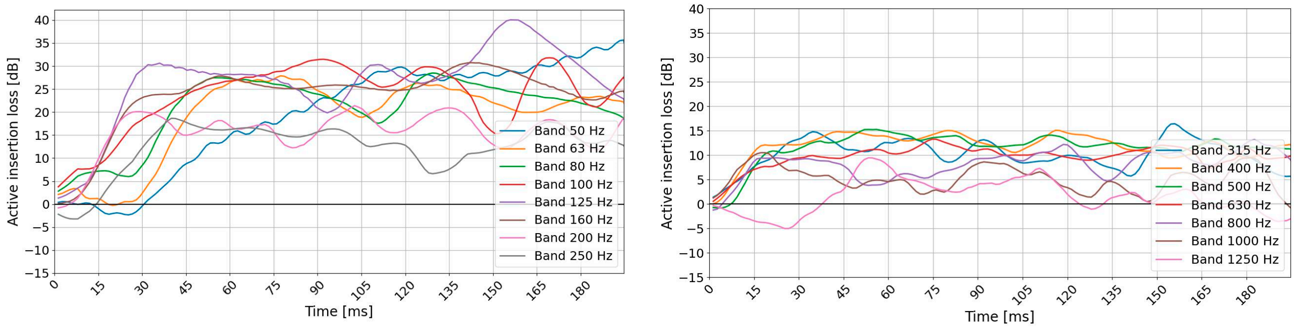


Figure 11. Changes in active attenuation as a function of time. HP2 headphones measured in the reverberation chamber (RC) and listening room (LR) using Neumann KU100 and B&K Type 4128 test head models for 1/3 octave band at 250 Hz.

The measurement performed in the reverberation chamber using the B&K Type 4128 artificial head shows the longest convergence time, although the reaction speed observed for both the B&K and Neumann KU 100 heads appears to be consistent.

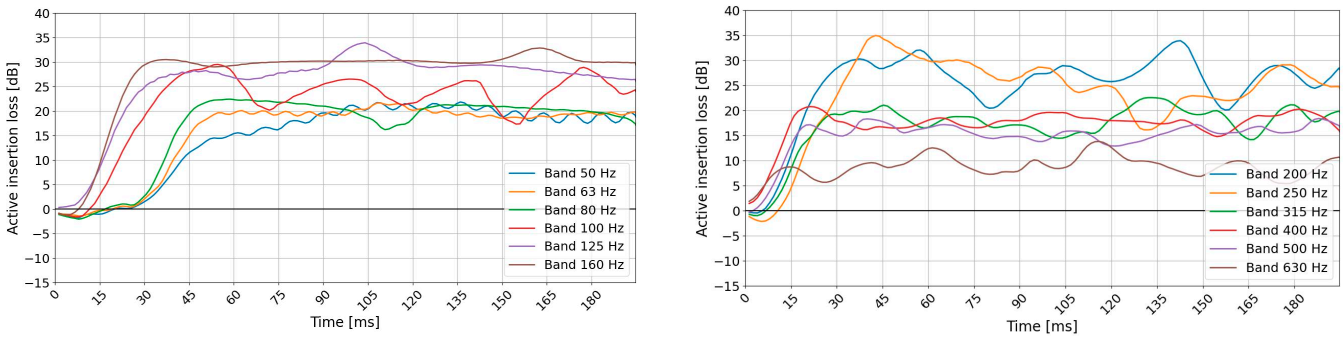
For the remainder of the study, the results obtained in the reverberation chamber with the B&K Type 4128 head were selected for presentation. This choice is justified by the fact that the B&K head is a certified device for this type of measurements, and the reverberation chamber provides a reproducible diffuse field, facilitating measurement standardization and repeatability in future studies.

Figures 12–14 show the results of measuring active attenuation as a function of time for the HP1, HP2, and HP3 headphones for the 1/3 octave bands in which active attenuation was recorded. The results shown were obtained in a reverberation chamber using the B&K Type 4128 test head model.



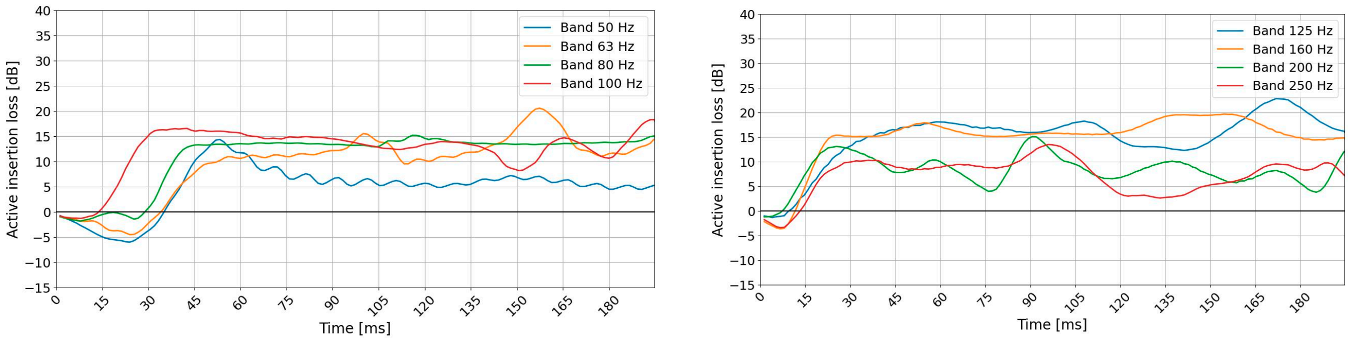
(**a**) (**b**)

Figure 12. Results of measuring active attenuation as a function of time for HP1 headphones for 1/3 octave bands in a reverberation chamber using the B&K Type 4128 test head model; (**a**) 1/3 octave bands from 50 Hz to 250 Hz, (**b**) 1/3 octave bands from 315 Hz do 1250 Hz.



(**a**) (**b**)

Figure 13. Results of measuring active attenuation as a function of time for HP2 headphones for 1/3 octave bands in a reverberation chamber using the B&K Type 4128 test head model; (**a**) 1/3 octave bands from 50 Hz to 160 Hz, (**b**) 1/3 octave bands from 200 Hz do 630 Hz.



(**a**) (**b**)

Figure 14. Results of measuring active attenuation as a function of time for HP3 headphones for 1/3 octave bands in a reverberation chamber using the B&K Type 4128 test head model; (**a**) 1/3 octave bands from 50 Hz to 100 Hz, (**b**) 1/3 octave bands from 125 Hz do 250 Hz.

In many situations, the system after tuning is not stable and the attenuation value changes. This is due to the fact that pink noise is random, so the system must constantly correct its parameters. This causes problems with determining a specific moment when fine-tuning can be considered to have occurred. Therefore, this paper introduces a procedure to determine the moment at which the graph reaches the value of average active attenuation in a given 1/3 octave band. It could be also noticed that a shorter convergence time does not always mean that the system performs better. A longer convergence time often occurs when the attenuation value is larger. For this reason, a new parameter was introduced in this work—reaction speed. This parameter relates the convergence time to the average value of active attenuation in a given frequency band. This parameter is expressed in dB/ms.

3.3. Reaction Speed Results

The reaction speed was determined for those 1/3 octave bands for which the headphones have a significant active attenuation value (greater than 3 dB). The compiled data for the average active attenuation, convergence time, and reaction speed in the 1/3 octave bands for HP1, HP2, and HP3 headphones are presented in Tables 1–3. The data presented concerns measurements in a reverberation chamber using the B&K Type 4128 test head model.

Table 1. Average active attenuation, convergence time, and reaction speed in 1/3 octave bands for HP1 headphones measured in a reverberation chamber using the B&K Type 4128 test head model.

Frequency Band	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1 kHz
Active insertion loss [dB]	26.4	21.7	18.4	20.3	19.8	24.4	17.7	13.7	11.7	13.0	12.2	9.9	8.1	3.5
Convergence time [ms]	94.7	46.7	37.3	34.7	20.0	28.0	18.7	32.0	26.7	13.3	14.7	30.7	9.3	6.7
Reaction speed [dB/ms]	0.28	0.47	0.49	0.59	0.99	0.87	0.95	0.43	0.44	0.98	0.83	0.32	0.87	0.52

Table 2. Average active attenuation, convergence time, and reaction speed in 1/3 octave bands for HP2 headphones measured in a reverberation chamber using the B&K Type 4128 test head model.

Frequency Band	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz	315 Hz	400 Hz	500 Hz	630 Hz
Active insertion loss [dB]	19.9	19.0	20.7	26.5	25.8	30.3	29.7	24.4	19.5	19.7	17.2	8.2
Convergence time [ms]	81.3	48.0	42.7	37.3	28.0	26.7	32.0	32.0	26.7	13.3	17.3	9.3
Reaction speed [dB/ms]	0.24	0.40	0.49	0.71	0.92	1.13	0.93	0.76	0.73	1.48	0.99	0.88

Table 3. Average active attenuation, convergence time, and reaction speed in 1/3 octave bands for HP3 headphones measured in a reverberation chamber using the B&K Type 4128 test head model.

Frequency Band	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz
Active insertion loss [dB]	4.9	12.1	13.1	14.1	15.5	15.7	9.6	7.6
Convergence time [ms]	37.3	50.7	37.3	25.3	32.0	17.3	14.7	18.7
Reaction speed [dB/ms]	0.13	0.24	0.35	0.56	0.48	0.91	0.65	0.40

For the HP1 headphones, the reaction speed could be determined for the largest number of bands, and for the HP3 headphones, for the smallest number of bands. Analyzing the results in individual bands, it can be seen that, in many cases, the HP1 and HP2 headphones achieved higher convergence time values than the HP3 headphones. However, the HP1 and HP2 headphones are characterized by significantly higher active attenuation values. This results in lower reaction speed values for the HP3 headphones. This means that the active reduction system in the HP3 headphones reacts more slowly to appearing noise. This can be seen in more detail in the comparison of reaction speeds for various headphones, which is presented in Figure 15.

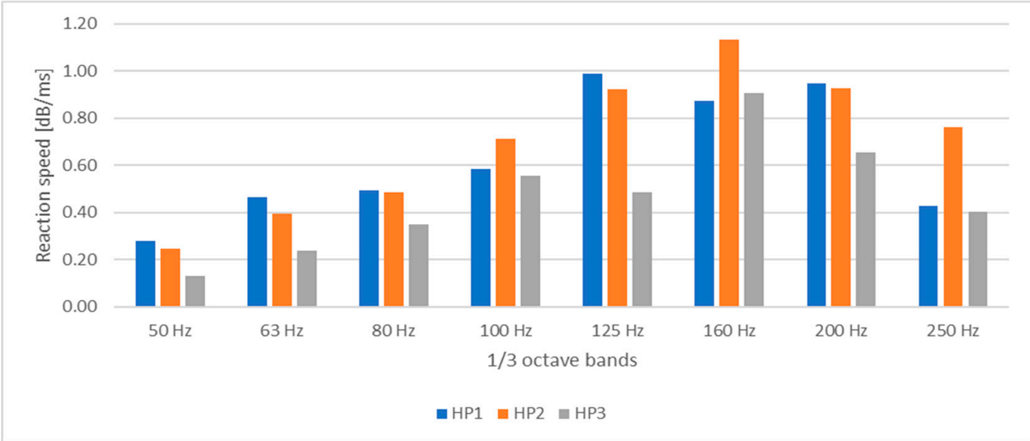


Figure 15. Comparison of reaction speeds for various headphones measured in a reverberation chamber using the B&K Type 4128 test head model.

4. Discussion

This paper presents a methodology for measuring the parameters of headphones with active noise cancellation (ANC), focusing on the assessment of sound attenuation and the convergence time of the ANC system. The results obtained in the research provide new information on the effectiveness of ANC systems in various headphone models and under various measurement conditions.

4.1. Interpretation of the Results in the Context of the Literature

According to the literature, attenuation in headphones with ANC can be divided into passive, resulting from the design of the headphones, and active, resulting from the operation of electronic systems that generate acoustic waves with the opposite phase to external noise. The results obtained in the research confirm these assumptions, showing the dominance of active damping at low frequencies (up to 500 Hz) and passive damping at higher frequencies. This is as expected because low frequencies are more difficult to passively attenuate, and ANC systems are particularly effective in this regard. Moreover, it was confirmed that the convergence time is an important parameter of active noise reduction systems, which may differ for different systems and affects the effectiveness of the system.

4.2. Convergence Time and Reaction Speed

Research on the ANC convergence time is relatively new and the literature on this topic is limited. The results presented in this paper show that the convergence time is an important parameter influencing the effectiveness of the ANC system. Reaction speed, defined as the ratio of the active damping value to the convergence time, has proven to be a useful indicator for assessing the effectiveness of the system. Cheaper and lower quality headphones achieved a worse value for this parameter. A high reaction speed indicates the system's ability to quickly adapt to changing acoustic conditions, which is crucial in dynamic environments such as public transport or offices.

4.3. Conclusions and Future Research Directions

The results of this research suggest several directions for further work. First, it is recommended to perform measurements for other types of signals than pink noise, as suggested in the literature [19,20]. This may help to better understand how ANC systems work in different acoustic conditions.

Second, it may be necessary to increase the number of measurements to minimize errors in averaging the results. As pointed out in [4], headphone leaks can lead to significant deviations in the results, so more representative results can be obtained by a larger number of measurements with independent wearing of the headphones.

One of the next steps will be to try to parameterize attenuation with a single-number indicator. This will help to compare headphones easily and quickly for their users.

From the point of view of the repeatability and reproducibility of the measurements, it seems necessary to assess the influence of the measuring positions on the values of the measured parameters.

4.4. Practical Implications

The methodology presented in this work can be used in the industry where there is a need to objectively measure the parameters of headphones with ANC. Accurate measurements of attenuation and convergence time can help manufacturers optimize their products and provide consumers with reliable information about their performance. Moreover, the developed methods can be used in further scientific research on improving ANC algorithms, which may lead to even more effective solutions in the future.

4.5. Summary

Research on headphones with active noise reduction is a dynamically developing area, and this work makes an important contribution to the development of measurement methods in this field. The results show that the proposed measurement methodology is effective and can be the basis for further research and optimization of commercial products. Future work should focus on varied measurement conditions and different test signals to obtain a more complete picture of the effectiveness of ANC systems.

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