Active Noise Cancellation Technique using FxLMS for Domestic Noise in Individuals with Autism Spectrum Disorder

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Abstract: - Environmental noise impacts the quality of life and psychological well-being of people with hearing sensitivity or autism spectrum disorder due to the lack of effective noise control strategies. People with this disorder have auditory hypersensitivity and, in many cases, hyperacusis, which increases their vulnerability to loud noises. Previous research describes the use of active noise cancellation algorithms or noise regulatory measures to protect the health and quality of life of people with the disorder. Therefore, we propose the implementation of an active domestic noise cancellation technique based on the adaptive FxLMS algorithm and implemented in in-ear headphones, aimed at reducing sounds such as fireworks, blenders, door slamming, and barking, to protect the hearing health of people with the syndrome. The project consisted of modeling the Primary Path and Secondary Path propagation routes from a database and adapting the system to the Bose QC20 in-ear headphones. The results demonstrated that the adaptive FxLMS algorithm managed to attenuate domestic noise in low and medium frequencies (<4000 Hz), confirming its adaptation capacity, although with critical dependence on the convergence coefficient and limitations associated with the type of noise and database used.

Key-Words: - Hypersensitivity, Hyperacusis, Adaptive algorithm, Least Mean Squares, Adaptive filtering, FxLMS, noise cancellation

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1 Introduction

Nowadays, environmental noise significantly affects the quality of life and can generate psychological discomfort in people exposed continuously, [1], [2]. For this reason, active noise cancellation (ANC) systems are essential for individuals with hearing sensitivity [3] generated in some cases by the human voice [4]. In addition, there is a problem related to noise pollution, with noise being a significant source of health problems. This particularly affects people with Autism Spectrum Disorder (ASD), who, for the most part, have a marked auditory hypersensitivity [5], [6], increasing their sensitivity to noise. Although noise exposure at home can be reduced, there are still sources of domestic noise that cause discomfort, affecting the tranquility of people with ASD, [7]. Furthermore, the lack of effective noise control strategies contributes to the deterioration of the hearing health of people with this condition, [8].

People with ASD have intense sensory experiences that can hurt the ears of those who suffer from it, [9], [10]. One of the main problems is related to the presence of hyperacusis, generating greater sensitivity to sound with a lower tolerance threshold [11], facilitating the perception of intense noises, [12]. Likewise, according to the classification of severity of the disorder in the Peruvian population, a record of 16 thousand people diagnosed with ASD was observed who were entered into the National Registry of People with Disabilities, [13].

From the reviewed research, a large impact of auditory hypersensitivity is observed in stochastic and poorly controlled noises, [14]. Previous studies on noise show that there are few implementations of systems that mitigate noise levels for individuals with ASD or focus on active noise control, [15], [16].

Based on the above, the objective is to design a home noise cancellation system using the FxLMS cancellation algorithm for individuals with ASD in three phases: Determine the noise characteristics; model the noise cancellation technique using the FXLMS algorithm in in-ear headphones; and simulate home noise cancellation. To achieve these objectives, an active noise control system is designed for four types of noise: fireworks, a blender motor, a door slamming, and dog barking.

2 Literature Review

Previous research agrees in demonstrating the effectiveness of the FxLMS algorithm compared to the LMS to improve active noise cancellation, highlighting its ability to handle multiple frequency bands and optimize the system response in real time, [17], [18].

While systems can focus on FPGA implementation for in-ear headphones with a focus on low power consumption [19], [20], another approach addresses industrial applications in motors, achieving attenuation under operating conditions [21], [22]. Together, these contributions show that the FxLMS is an adaptable solution in industrial contexts, which allows considering its potential for sensitive environments such as those for people with ASD.

On the other hand, it has been shown that there is an impact of noise on people, through FxLMS improving its stability in different auditory environments [23], or with passive architectural isolation solutions in educational centers for people with ASD, [24]. Although they differ in the type of approach (technological, architectural, and regulatory), all approaches show that noise mitigation is important for protecting the health and quality of life of people with ASD, suggesting that an integration of active, passive, and legal solutions can generate a more effective impact.

On the other hand, research has found that fireworks and other intense noises generate extreme responses such as fear, anxiety, pain, and even risk situations in people with ASD, making it necessary to have controlled and safe environments, [25], [26]. In addition, regulatory measures such as the restriction or prohibition of fireworks have been proposed to reduce stress and injuries to people, [27]. Likewise, quantitative studies in urban populations have shown that noise pollution from sources such as household appliances, construction, and fireworks significantly affects children with ASD, recommending the implementation of public policies to address this problem, [28].

3 Methodology

The cancellation system consists of a stage for acquiring the domestic noise signal, processing it in Matlab software, analyzing its characteristics based on time and frequency, evaluating its behavior, and determining the predominant noise characteristics.

To model the system, the impulse response of the acoustic paths of an in-ear headphone system (primary and secondary propagation paths) was used to describe the acoustic behavior of the sound propagation paths. Once the acoustic model was defined, the control strategy was selected, and the adaptive FxLMS algorithm was designed. Finally, its performance was evaluated by adjusting the control parameters and the convergence coefficient to improve the system's response, validating the results with noise attenuation measurements (Figure 1).

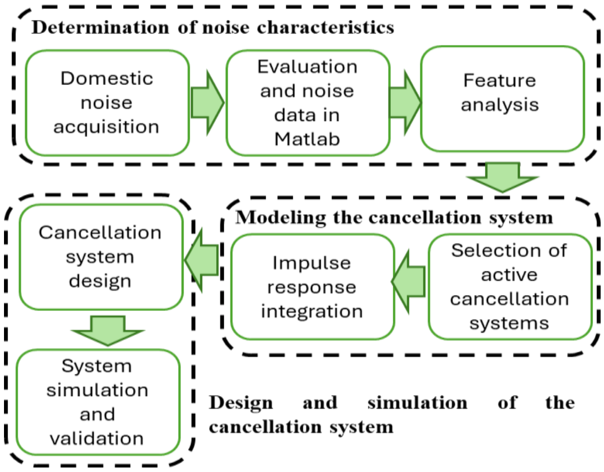

Fig. 1: Stages of development
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3.1 Features of the Noise Cancellation Stage

This section describes the acquisition and analysis of domestic noise signals. The Behringer ECM 8000 transducer was used for noise acquisition. A script was then developed using MATLAB software to evaluate its behavior over time and frequency by analyzing the noise characteristics, determining its type and frequency peaks (Figure 2).

During the noise signal acquisition process, four household noises that affect people with ASD were captured to analyze their characteristics and use them in the design of the cancellation system (Figure 3). These signals were acquired using an analog-to-digital conversion stage with a sampling frequency (fs) of 44.1 kHz, 24 bits, and using Ableton Live Lite software for audio capture.

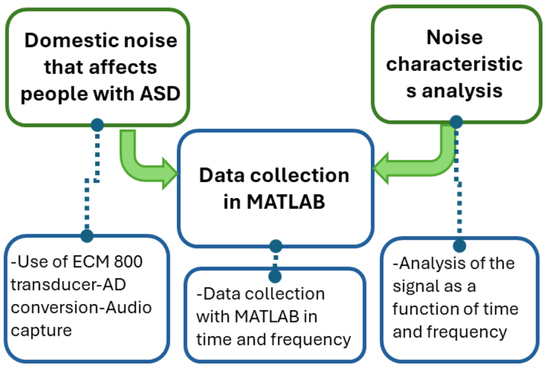

Fig. 2: Acquisition of signal characteristics
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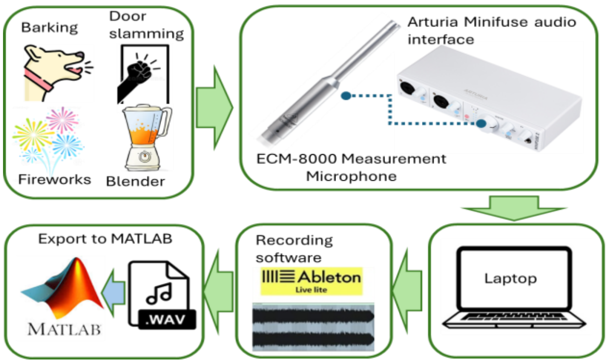

Fig. 3: Domestic noise recording process
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The Matlab script recorded the signals corresponding to the sounds of fireworks, a blender, a door slam, and barking. Temporal characteristics related to signal amplitude, duration, and energy distribution were then considered. Based on the previous characteristics, the noise attributes were defined: Type, maximum frequency amplitude, frequency cancellation, and degree of sensitivity.

3.2 Modeling the Noise Cancellation Stage

Figure 4 presents the flow diagram that describes the ideal cancellation process, based on the characteristics of the previously analyzed noises, and oriented to its application in Bose QC20 in-ear headphones by incorporating the physical and acoustic properties of the hearing aid.

For the selection of the active noise cancellation system, two architectures were considered: Feedforward and Feedback. The choice of these architectures depended on the location of the microphones, the type of noise to be canceled, and the processing hardware capabilities. Furthermore, the cancellation stage was modeled based on the analysis of sound propagation paths in in-ear headphones, as these offer passive and active attenuation that optimizes noise reduction.

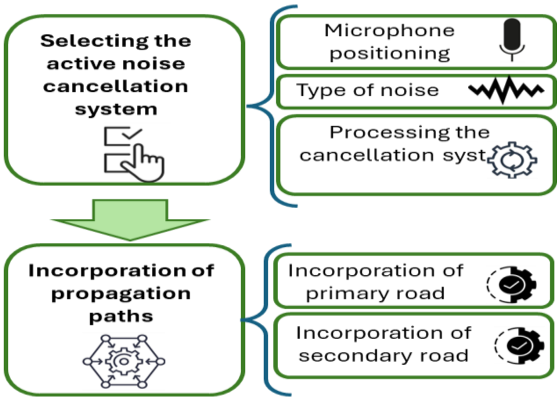

Fig. 4: Flowchart of noise cancellation stage modeling
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The justification for using a direct feed architecture instead of feedback is based on an assessment of the acoustic characteristics of noise and the limitations of in-ear headphones. In homes, broadband impulsive noises are unpredictable over time, which affects feedback. Furthermore, direct feed allows the algorithm to detect the disturbance with the microphone, improving convergence speed. Additionally, the processing requirements of the FxLMS algorithm are lower in direct feed implementations.

The modeling input used was the database by [29], which provided measurements and simulations on Bose QC20 headphones. The acoustic behavior of the database was measured by generating a logarithmic frequency sweep with a sampling rate of 48 kHz and a duration of 4.05 seconds, which allowed obtaining the impulse responses of the propagation paths.

In addition, the secondary propagation path of the cancellation stage was estimated, considering that any modification experienced by the cancellation signal affects the performance. An estimate of the secondary path S'(z) was incorporated, considering the real response of the secondary propagation path S(z) (Figure 5), since an incorrect estimate can generate noise amplification.

The acoustic trajectories were measured indirectly using the database in [29], which provides impulse responses acquired through Bose QC20 headphones. The trajectories were characterized using a logarithmic sweep signal (20 Hz–20 kHz) through the loudspeaker, and a microphone captured the response at the ear canal entrance. This information allowed for the description of the propagation delay, reflection components, and frequency attenuation of the acoustic trajectories. x(n) is the reference signal of the noise source; P(z) represents the acoustic path between the noise and the error microphone; d(n) is the desired signal; W(z) is the adaptive filter that generates the anti-noise signal y(n); S(z) is the secondary path; y′(n) is the filtered anti-noise signal; S′(z) is the estimated model of the secondary path; LMS represents the least squares adaptation block; and e(n) is the residual error signal obtained after noise cancellation.

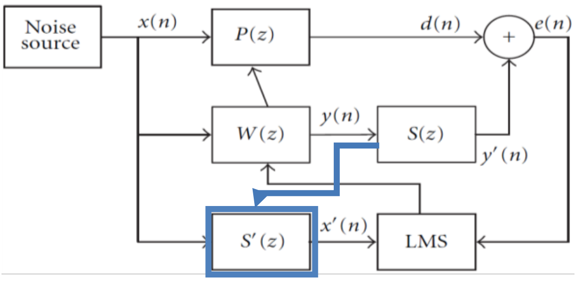

Fig. 5: Block diagram of the FxLMS algorithm with secondary estimation
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3.3 Design and Simulation of the Noise Cancellation System

3.3.1 System Design

The following elements were considered for the design of the noise cancellation system: a) Reference signal of the signal x(k); b) Primary propagation path; c) Estimation of the secondary propagation path; d) Convergence coefficient adjustment.

To do this, it was necessary to initialize the FxLMS algorithm vectors and store the input, error, and adaptive filter coefficient signals. These vectors were updated within a for loop, where equation (1) of the FxLMS algorithm is applied at each iteration to update the filter coefficients and improve noise cancellation. In equation (1), x□(k) represents the reference signal filtered through the secondary path S′(z), which is used to compensate for delay and frequency response. The subscript "s" indicates the compensation of the secondary path on the reference input.

$$w(k+1)= w(k)+ue(k)x_s(k) \qquad (1)$$

where:

- $x_s(k)$: Secondary path that filters the noise signal to model the response from the speaker to the error microphone.
- W(k+1): Represents the vector of adaptive filter coefficients at each iteration k.
- e(K): Error signal obtained as the difference between the signal filtered by the primary path d(k) and the generated anti-noise signal y(k)

This cancellation process runs throughout all iterations, continuously updating the filter coefficients based on the error obtained. This procedure is shown in the flowchart in Figure 6.

3.3.2 Simulation of the Cancellation System

A 1 kHz signal frequency was used for the validation process. This frequency was selected because it falls within the auditory system's most sensitive band. The literature indicates that frequencies between 1 kHz and 4 kHz represent the range of greatest auditory sensitivity. Therefore, 1 kHz was used as the test tone to evaluate attenuation in the frequency domain, based on validation research reported, [19], [20]. For system validation with FxLMS in in-ear headphones, the following topics were considered:

- Evolution of adaptive filter coefficients
- Mean square error (MSE)
- Attenuation as a function of time and frequency

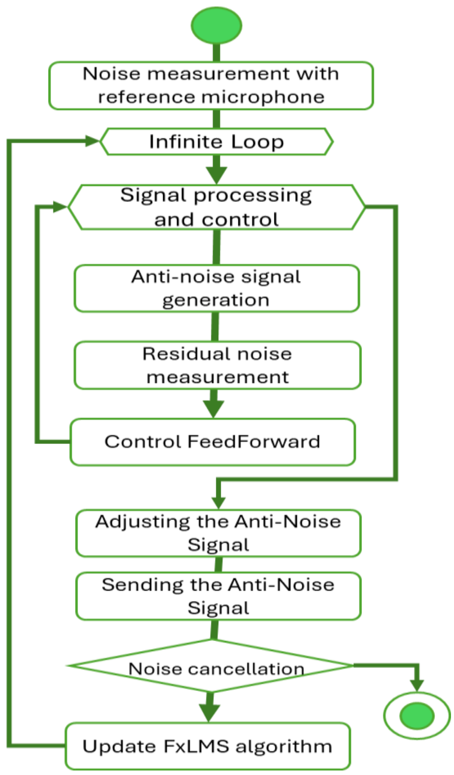

Fig. 6: Active noise cancellation process flowchart.
Source: Created by the authors

The total system latency must be significantly less than the period of the highest frequency to be eliminated. For frequencies up to 4 kHz, this corresponds to a maximum permissible latency of approximately 0.3 ms, as indicated in the scientific literature. In the simulation, the processing includes filtering and adjustment of the FxLM coefficient, both of which were designed to avoid exceeding the permissible latency.

4 Results and Discussion

4.1 Feature Analysis

Using the ECM 8000 recording microphone, the Arturia Minifuse audio interface, and the Ableton Live Lite program, the four noise signals were processed and captured using the MATLAB script for their time-frequency analysis, obtaining the attributes of maximum amplitude, duration, and energy (Figure 7). In the case of the blender noise, it was the only one characterized by a constant and stable signal over time, with a maximum amplitude of 0.8 for 12.2 seconds, while the other signals can be unpredictable (Table 1).

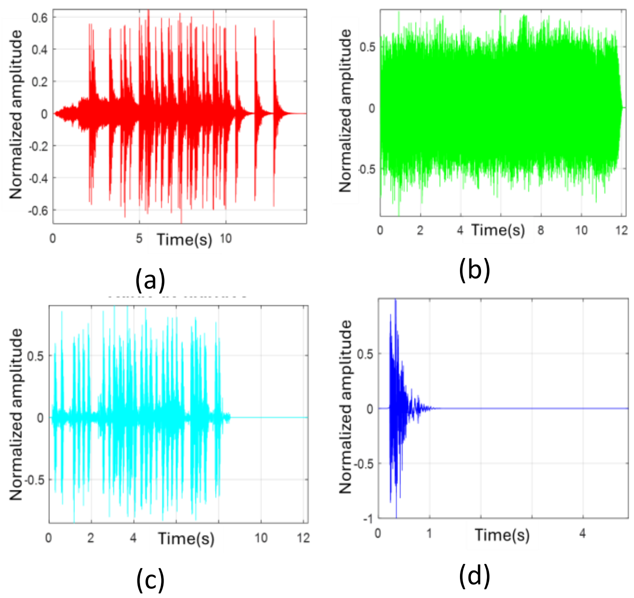

Fig. 7: Noise signals: (a) pyrotechnic, (b) blender, (c) door slam, (d) barking
Source: Created by the authors

After that, the temporal and frequency characteristics of the four collected noises were analyzed to determine the level of expected frequency cancellation, maximum frequency amplitude, and annoyance in people with ASD according to the isophonic curves and the sensitivity of the human ear in the frequency range of 1 kHz to 5 kHz. For example, in the case of pyrotechnic noise, it is observed that the signal presents highly variable temporal characteristics, especially in the highest peaks, which are unpredictable and non-stationary in time. In the frequency domain, it was obtained that during prolonged bursts, low-frequency energy is prevalent, with a maximum peak at 187 Hz (Figure 8).

Table 1. Comparison of noise signals over time

Noise	Maximum amplitude	Duration (seconds)	Signal energy
Pyrotechnic	0.65	14.7	Non-uniform and unpredictable amplitude
Blender	0.8	12.2	Continuous and periodic amplitude
slamming noise	1	4.9	Single amplitude
barking	0.9	12.2	Non-uniform and unpredictable amplitude

Source: Created by the authors

Frequency analysis showed that the four household noises exhibit a higher concentration of energy in low and mid-frequencies, although with differences in their characteristic ranges and peaks.

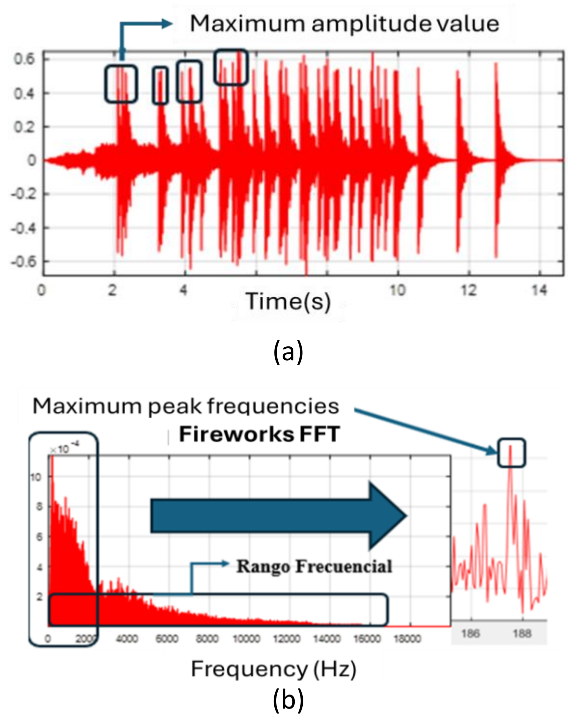

Fig. 8: Visual characteristics of pyrotechnic noise (a) in time and (b) in frequency
Source: Created by the authors

The fireworks noise and the slamming door stand out for their strong presence in the low frequencies, with peaks around 200 Hz and 70 Hz, respectively, while the blender and the barking concentrate their energy between 150 and 1600 Hz.

Overall, it is evident that these noises primarily affected the low and mid-frequency bands, which explains their impact in sensitive environments. Table 2 shows noise values that may affect individuals with ASD, possible frequency cancellation, maximum frequency amplitude, and noise type.

4.2 Modeling Results

As part of the cancellation system design, the secondary propagation path was modeled. This model allowed for the implementation of the FxLMS algorithm using an adaptive NLMS filter for secondary path estimation. To achieve this, the coefficients of the estimated impulse response were adjusted, modeled as S'(z), which were subsequently integrated into the FxLMS algorithm. Furthermore, the length of the coefficients of the adaptive filter S'(z) was defined using equation 2.

$$\text{Filter Length} \geq \text{Ti*Fs} \qquad (2)$$

where:

- Ti is the duration of the secondary path impulse response (s)
- Fs is the sampling frequency (Hz)

Table 2. Comparison of noise signals according to feature analysis

Noise	Type	Max. Amplitude	Output	Discomfort
Pyrotechnic	Broadband	187 Hz	limited	Very high (1 KHz -2 KHz)
Blender	Limited and continuous bandwidth	1248 Hz	expected	Half (1 KHz-1.6 KHz)
slamming noise	Limited and impulsive bandwidth	69 Hz	acceptable	Low (0 Hz-500Hz)
barking	Broadband	808 Hz	limited	High (1 KHz-1.5KHz)

Source: Created by the authors

It was determined that a size of L=960 values was adequate for the length of the adaptive filter. Likewise, the value of the convergence coefficient "μ" is defined, which was found within the range of values between 0 and 1, guaranteeing the stability of the algorithm. Figure 9 presents the comparison between the original signal of the secondary path S(z), the estimated signal of the secondary path, and the adaptation error. It is observed that the algorithm achieves a convergence adjustment in the first 1000 iterations, which demonstrates that the adaptive model is capable of estimating the response of the original secondary path.

The system was not compared to ANC headphones, as the focus of this research was on algorithmic modeling and attenuation simulation. Comparisons with commercial ANC devices require additional configurations and identical hardware architectures, which exceed the available resources. However, it can be inferred that the attenuation obtained (14.8–20.0 dB) is close to that of commercial devices (20–25 dB).

4.3 Simulation Results

The results of the FxLMS feedforward cancellation stage tests are shown in Table 3, obtained by using an adaptive filter with a length of 960 coefficients and varying the convergence coefficient of the FxLMS algorithm. This variation in the convergence rate was applied to the four noise types to identify the optimal coefficient value that provides an efficient response.

The results showed that the selection of the adaptation coefficient of μ=0.007, being optimal to cancel a greater amount of broadband random noise, without compromising the stability of the system due to accelerated convergence.

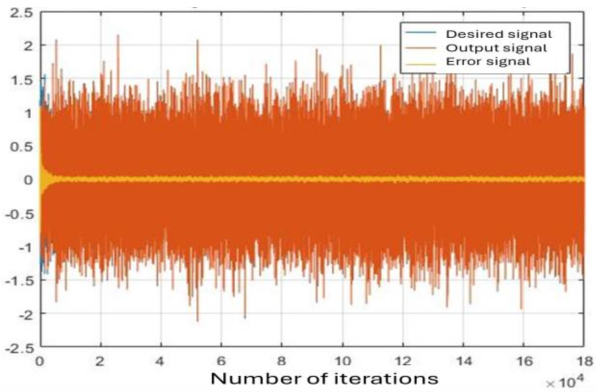

Fig. 9: Iterative estimation of secondary path
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Table 3. Comparison of the stability of the coefficient of convergence

Noise	μ=0.0001	μ=0.001	μ=0.007	μ =0.01	μ =0.1
Pyrotechnic	Stable	Stable	Stable	Unstable	Unstable
Blender	Stable	Stable	Stable	Stable and fast	Unstable
slamming	Stable	Stable	Stable	Stable and fast	Unstable
barking	Stable	Stable	Stable	Unstable	Unstable

Source: Created by the authors

The cancellation system was evaluated considering the adaptive filter coefficients, the time-dependent attenuation, and the mean squared error (MSE). Although the results in Table 3 show convergence with different μ coefficients, the MSE was used as a metric in the validation process. The simulation demonstrated that adapting the FxLMS algorithm coefficients reduced noise energy.

During the simulation and validation tests, 4 results were obtained based on the types of noise described below:

a) Pyrotechnic noise. Figure 10 shows the attenuation in low-frequency regions continuously adapting to the irregular and chaotic variations in the signal. The reduction in maximum amplitude at 187 Hz is notable, demonstrating that when the noise does not maintain periodicity or has a high energy load in low frequencies.

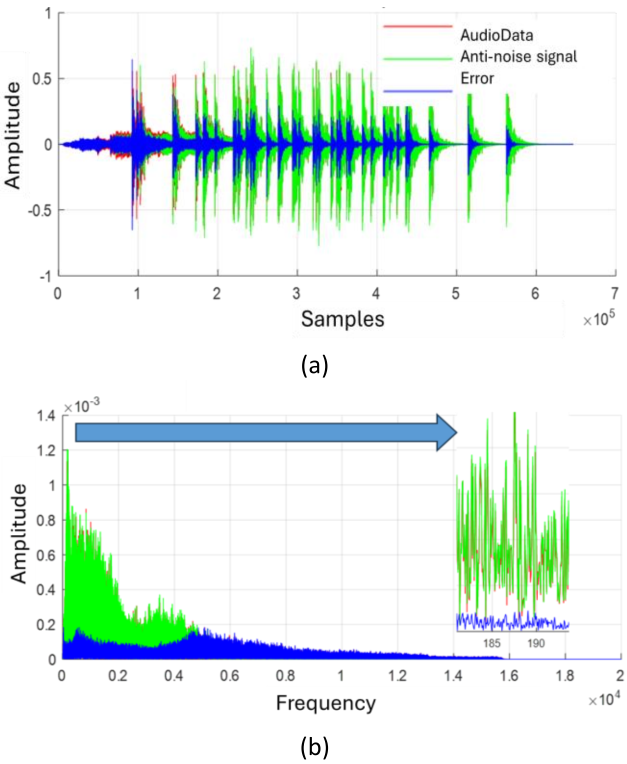


Fig. 10: Cancellation in time (a) and frequency (b) of pyrotechnic noise signal
Source: Created by the authors

b) Blender noise. Significant attenuation is observed in low and mid-frequency regions. Furthermore, the maximum amplitude peak of 1248 Hz is considerably attenuated, as shown in Figure 11. The system exhibits remarkable adaptive capacity over time, achieving an even greater amplitude reduction than that of pyrotechnic noise. Although the algorithm adapts more slowly than that of stochastic noise, the system achieves greater attenuation for noise from household appliance motors such as blender motors.

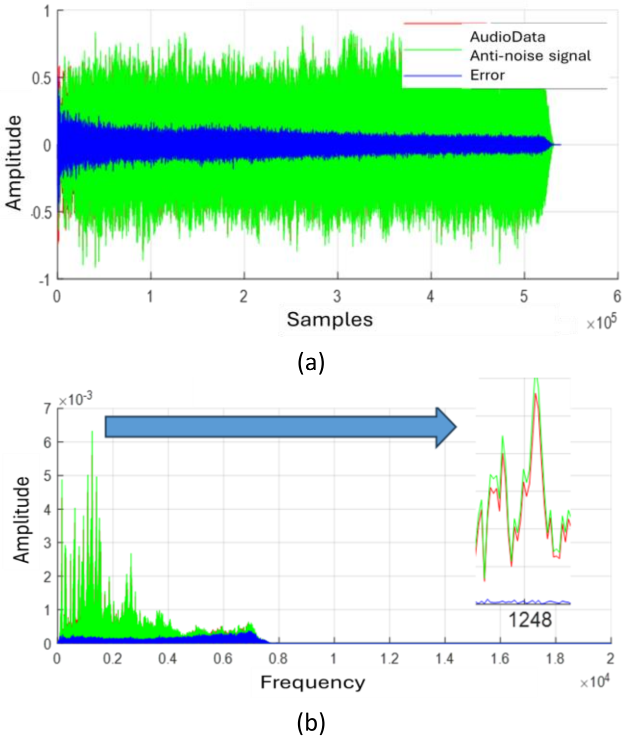
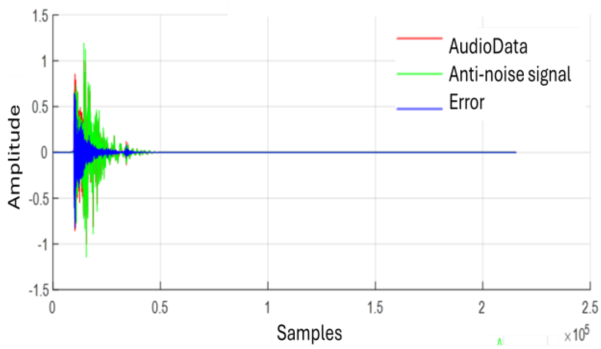
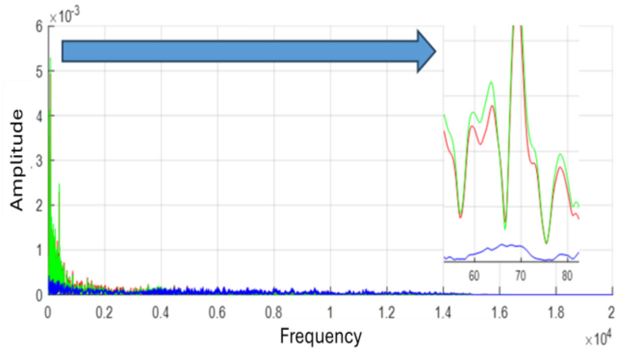


Fig. 11: Cancellation in time (a) and frequency (b) of blender noise signal
Source: Created by the authors

c) Door slamming noise. A significant decrease in low frequencies was obtained. In particular, the maximum amplitude located at 69 Hz showed a considerable reduction in amplitude, from a maximum peak value of 49 x 10 4 to a value of 4 x 10-4, denoting that the noise level is reduced at low frequencies and with a non-periodic impulsive characteristic (Figure 12). This system response demonstrated its effectiveness against noises caused by short-duration impulsive blows, but with high energy, such as hammer blows, falling objects, or any other sound that concentrated the energy for a brief moment in time.



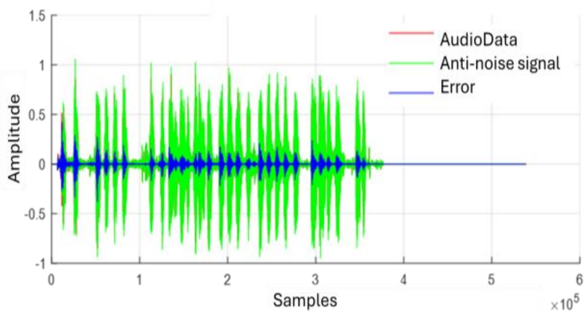
(a)



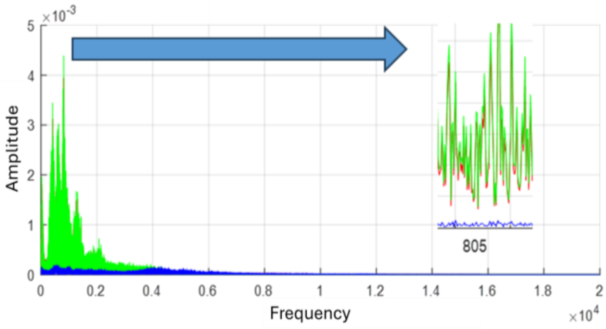
(b)

Fig. 12: Cancellation in time (a) and frequency (b) of slamming noise signal. Source: Created by the authors

d) Barking noise. Attenuation was achieved in the low frequencies of the signal. In particular, a decrease in the maximum amplitude recorded at 808 Hz was observed, which initially had an amplitude value of 39 x 10 4, reducing its amplitude to a value of 2 x 10-4 (Figure 13). The effectiveness of the system not only covered low frequencies below 500 Hz, but also encompassed mid and low frequencies for aperiodic and stochastic signals.



(a)



(b)

Fig. 13: Cancellation in time (a) and frequency (b) of bark noise signal
Source: Created by the authors

To complement the qualitative graphical results, quantitative attenuation metrics were calculated for each noise type in both the time and frequency domains (Table 4). The average sound pressure level (SPL) reduction within the frequency bands ranged from 14.8 dB for fireworks to 19.3 dB for sources such as the blender, measured between 100 Hz and 1600 Hz. Overall, the system achieved an average noise reduction of 18 ± 2.2 dB. Furthermore, the signal-to-noise ratio (SNR) improved after cancellation, demonstrating that the adaptive filter effectively minimizes low-frequency interference.

Table 4. Results of cancellation behavior

oise Type	Dominant Frequency (Hz)	Mean Attenuation (dB)	SNR Improvement (dB)
Pyrotechnic	187	14.8	9.6
Blender	1248	19.3	12.4
Door slam	69	20.0	11.1
Barking	808	16.7	12.9

Source: Created by the authors

The evaluation focused on simulations under controlled conditions, assuming ideal propagation trajectories. Real-world environments introduce errors related to microphone usage and time-varying trajectories, which affect system stability. These factors were not evaluated, but they are important for future work. Implementing adaptive estimation with a secondary trajectory can compensate for discrepancies in non-stationary acoustic environments. Although the FxLMS system has not been tested with untrained noise sources, it can adapt to different sounds by adjusting the coefficients in real time, which depends on the convergence rate of the algorithm.

5 Conclusion

The system adaptation process using FxLM allowed attenuation of noise signals from pyrotechnics, blenders, door slams, and barking in the low frequencies below 4000 Hz. Additionally, the primary propagation paths and the secondary path were estimated from the headset database, which allowed accurate modeling of its behavior.

The generalizability of the results is limited by the methodology, which focused specifically on adapting the system to Bose QC20 headphones. The propagation path modeling was based on a database specifically designed for the model simulations. The results demonstrate the adaptability of the FxLMS algorithm under the acoustic conditions of this device, but its application to other headphone models was not the design objective.

The cancellation technique is critically dependent on the value of the convergence coefficient "μ," since this parameter presents a critical limit for each type of noise. However, high values of the convergence coefficient can compromise the stability of the algorithm, rendering the system unstable. Furthermore, the results show that the highest amplitude frequencies were attenuated because these peaks were located in the frequency range below 4000 Hz.

The use of pre-recorded impulse responses entails a trade-off for reproducibility and accuracy. Because the use of pre-measured trajectories allows for repeatability in the evaluation of the FxLMS algorithm, controlled acoustic conditions are assumed. However, this does not capture time-dependent effects that alter the transfer function in real environments.

The limitation is the lack of a comparison with other cancellation methods or ANC systems, where the literature review showed that the FxLMS algorithm is superior to the LMS algorithm for cancellation. The system's limitation to frequencies below 4 kHz is due to physical factors, as ANC systems are efficient at certain frequencies. Furthermore, the operating range coincides with the most sensitive hearing band for individuals with ASD, up to 4 kHz. The system does not dynamically adapt to variations in the geometry of each user's ear canal, but in future implementations, personalized trajectory estimation could be integrated. This research is original in the aspect of applying the FxLMS algorithm to noisy environments for people with ASD, integrating context-sensitive psychoacoustic and health criteria, adaptable to assistive devices.

Future research could focus on optimizing the placement and power of transducers, combining active cancellation with passive materials to extend attenuation across the entire frequency range. Furthermore, the real-time response of the FxLMS algorithm could be implemented for further latency testing and evaluation. Another important aspect is the system's energy consumption, since continuous adaptive processing can increase current consumption; therefore, future improvements should analyze the computational cost for use on battery-powered platforms. Although no experimental measurement of energy consumption was performed, its execution is viable on portable platforms due to the reduced processing evaluated in the simulations.

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