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A development and implementation of a tinnitus treatment method

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Abstract. Tinnitus is a physiological phenomenon where a person listens sounds which have not been generated by any external source. Today, many people suffer this condition. Although, in very few cases therapeutic methods completely eliminate tinnitus, it is possible to apply a variety of techniques to improve the quality of life of people with this condition. One of the most used methods to treat tinnitus consists of masking the tinnitus using an external sound. The main goal of this work is to present the development of a tinnitus treatment method, which optimizes the synthesized sounds in order to improve the life's quality of the user. Subjective tests and experimental results are used to analyze the performance of the method.

1. Introduction

Tinnitus [1] is a condition that affects an important percentage of the Society. It is defined as the condition where a person perceives a sound that has not been issued by any external source. This phenomenon is a hearing condition that can be chronic or not, and affects a large number of people. Tinnitus may be caused either by congenital reasons, stress or trauma of the hearing organ due to louder sounds. Recently, the number of people suffering from this condition has increased considerably due to improper use of portable playback of sounds, for example MP3 players.

While therapeutic methods in very few cases completely eliminate tinnitus, it is possible to apply a variety of techniques to improve the quality of life of people with this condition. In this group of therapies are included medication [2], [3], surgical methods [2] and relaxation sound therapy [4], [5], [6].

The most widely used approach for the treatment of tinnitus is the sound therapy [4], [5], [6]. Such techniques are based on the phenomenon of spectral masking [5], [7],[8]. In this phenomena, the brain in the presence of two spectrally adjacent sounds, can reduce the perception of one of the two sounds, and even eliminates one of them.

There are several types of therapies based on relaxation sounds. Firstly, there are assistive listening devices ([9], [10]) that allow users to amplify the environmental sounds with the aim of masking the tinnitus. This effect reduces the perception of the tinnitus and the individual



is able to improve performance in their daily activities. On the other hand, it is possible to reduce the effect of tinnitus with sounds of interest to the user. This type of therapy consists of playing sounds (either music or sounds that are pleasant) so the brain focuses on them and consequently reduce the perception of tinnitus. This approach is widely used for the rest of the individual.

Finally, there is a group of techniques that have been developed in recent years whose goal is to mask the tinnitus [4], [5], [6]. For this aim, a colored noise generator is used to synthesize the signal which must partially or completely mask the tinnitus. This technique is used in high-end commercial assistive listening devices [9], [10]. While this approach improves the quality of life of individuals who suffer from this disease, there are cases where the noise generated to mask the tinnitus reduces the perception of other sounds. This is undesirable, because it could cause problems such as loss of intelligibility of some words, and also an alert sound could not be perceived. Therefore, it may cause a decrease in the independence of the user.

The first goal of this work is to improve the performance of tinnitus treatment techniques using spectral masking. In this way, a hearing impairment simulator was used [12] to simulate and study tinnitus. Based on obtained data, it is possible to optimize the sound synthesizer in order to mask only the tinnitus and not other sounds of interest for the user.

Algorithms are implemented in MATLAB and a DSP device from Microchip. The chosen device is the dsPIC33EP512MU810 [11].

Section 2 describes several techniques to reduce the perception of a tinnitus. Section 3 depicts the algorithm used to reduce the perception of a tinnitus, while Section 4 presents the most important features of the implemented device. Section 5 presents the experimental measures and subjective experiments carried out in order to validate the proposed algorithm and test the developed device. Finally, Section 6 summarizes the conclusions of the work and provides future research lines.

2. Tinnitus therapy using sounds

Tinnitus is a hearing condition that can be very rarely cured, even using medical treatments and surgical methods. In recent years methods that seek to improve the quality of life of people with tinnitus were developed. The main goal of methods based on sound therapies is to reduce the perception of tinnitus in the individual. There are various types of therapies based on sounds. In the following subsections three types of the most commonly used methods are described.

2.1. Tinnitus treatment using masking sounds

This kind of therapy can be divided into two subgroups: techniques based on zen music, and based on colored noise [4], [5], [6]. In the first subgroup of therapies are included techniques based on natural sounds such as the sound of rain or waterfalls, among others. These sounds can be recorded or, as in the case of some high-end assistive devices[9], also they may be generated using fractal based mathematical algorithms.

The second subgroup includes techniques based on colored noise. These use the spectral masking phenomenon between components[7],[8]. Masking is defined as the process taking place in the auditory system of a person, where a sound of a certain energy can reduce the perception of another sound which is spectrally adjacent to the first.

Because the masked components will not be perceived by the person, there are sound compression algorithms (such as the MPEG-I Audio Layer 3 [14]), which can compress the sound using only the spectral components that are not masked. There are three possible situations defined between the tinnitus and the sound generated for masking it. Firstly, if the sound does not change the perception of tinnitus, it is stated that it is not masking it. Moreover, if the sound level generated a partial alteration of tinnitus is said that the tinnitus is partially masked by the external stimulus. Finally, in the case where tinnitus is not perceived due to the external

stimulus, it is said that it has been completely masked. Note that when applying these therapies, care should be taken that the external stimulus not causes damage to the auditory system of the person.

Therapies based on colored noise attempts to partially or fully mask the tinnitus using synthesized noise. Actually, this technique is included in high-end assistive listening devices[10], where the colored noise is obtained by filtering additive white gaussian noise (AWGN). In these devices, the filtering is done by mean of an equalizer with up to 16 subbands, which are also divided into four bands located between 100Hz-500Hz, 500Hz-1400Hz, 1400Hz-3500Hz and 3500Hz-8000Hz.

2.2. Therapies based on environmental sounds

An interesting option to reduce the effect of tinnitus in daily life of the user is to amplify existing sounds in the environment of the user[4]. This therapy reduces the difference of level between the sounds of the environment and the tinnitus, so it can be viewed as an improvement in the signal to noise ratio (SNR) of the signal perceived by the user. Such therapies should be applied using an assistive listening device that amplifies the signal so that ambient sounds at least partially mask tinnitus. This technique is currently implemented by some assistive listening devices and it is suitable for the user during their everyday activities. The main disadvantage of these techniques is produced when a high level of amplification of the environmental is needed. In this case, additional hearing impairments may appear in the long term.

2.3. Therapies based on sounds of interest for the user

Due to the nature of tinnitus, its perception can be reduced using sounds of interest for the user[4]. This therapy is based on how the brain perceives the tinnitus and generally is used in environments of relaxation of the user. They are very useful in cases where the tinnitus causes sleep disorders in the patient.

3. Proposed technique

3.1. Description of the proposed technique

Methods presented in Section 2 are widely used, but they are not methods exclusively developed for treating tinnitus. Then, these methods often fail due to a poor identification of the nature of the tinnitus that affects a patient. This is evident in the techniques presented in Subsections 2.2 and 2.3. The technique based on relaxation sounds, must take into account the energy of treated tinnitus in order to determine the level of the masker generated noise, in particular if white or colored noise it is used. As was previously described, this technique is widely used in hearing aid devices, and it can be seen that the spectral shape of the generated noise masks the tinnitus afflicting the user, but may mask other spectrally adjacent sounds.

Figure 1 shows the case of tinnitus composed by a pure tone located at $f = 1500\text{Hz}$. Continuous red line depicts the masking threshold of this tone. Continuous green line depicts the absolute threshold of hearing (ATH) of a young person without hearing problems in a quiet environment. Blue line is the spectrum of a composite signal by additive white gaussian noise filtered using a bandpass filter with cutoff frequencies of 1000Hz and 5700Hz. The absolute threshold of hearing of this condition is shown in striped black line. Figure 1 shows that by adding the filtered white noise, the resultant absolute threshold of hearing is elevated and individual components which are below this will not be perceived.

In this paper a method that optimizes generated colored noise is proposed to reduce this effect. In this approach a way to successfully mask the tinnitus and that, moreover, improve the perception of other sounds is presented. The first step of the proposed method consists of determining the ATH of the patient by the presence of tinnitus. Then, based on the phenomenon of masking tones using noise [5], [7],[8], it is possible to determine the minimum level of noise as

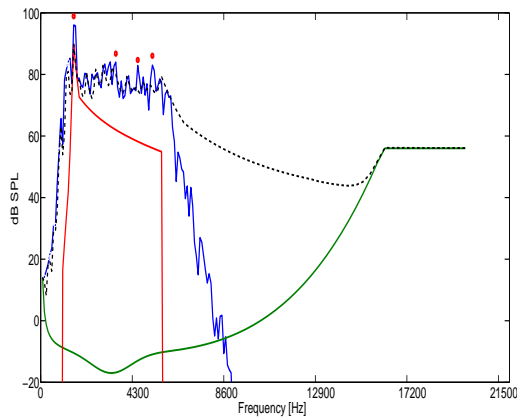


Figure 1. ATH variation generated by the colored noise used to mask tinnitus.

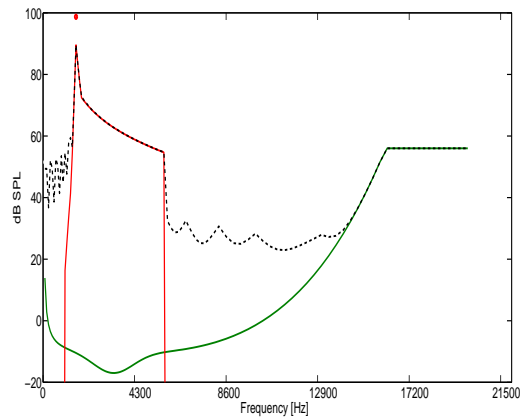


Figure 2. Masking threshold variation induced by tinnitus.

a function of frequency to mask the sound. Then, through this procedure, it is possible to set the noise level necessary to mask the tinnitus. Once obtained these specifications, they are used to process noise, and a bandpass filter is generated. This filter is used to fit the spectrum of white noise to mask the tinnitus. This step of the process is shown in Figure 2, which assumes a tinnitus tone at $f = 1500\text{Hz}$. Continuous red line represents the masked threshold of the tone. This curve indicates that components below it can not be perceived by the person suffering from such condition. In continuous green line, it is shown the ATH for a healthy young person. Finally, in striped black line is shown the curve of the ATH resulting of applying additive white gaussian noise filtered using tinnitus masking curve.

The curves of the resulting absolute thresholds of hearing are compared in Figures 1 and 2. It can be appreciated that the proposed method has a hearing threshold of lowest energy. Therefore, we can say that the proposed method allows the perception of more sounds that the reference method. The proposed system is presented in Figure 3, where it can be seen that in the first stage the diagnosis of the patient is used to estimate the masking threshold caused by tinnitus. Later, a bandpass filter is generated based on the previously obtained information, which is responsible for filtering the additive white gaussian noise. The filtered signal is used as a stimulus to the person who suffers the tinnitus.

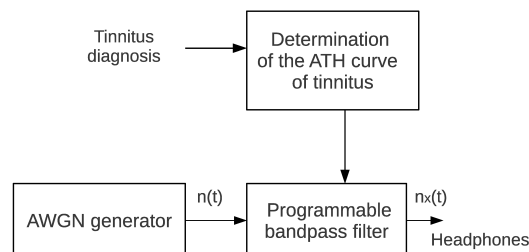


Figure 3. Block diagram of the proposed system.

The result of this method is a therapy optimized to the patient, which is appropriate for most of the cases. Furthermore, this technique has almost direct implementation in sound synthesizers and assistive listening devices. The main disadvantage of this technique is that, the tinnitus afflicting of the user must be known in detail to set the noise level to be synthesized.

3.2. Implementation of the proposed technique

The proposed technique was implemented in a hearing impairment simulator [12]. This tool was developed by the research group to simulate a particular tinnitus. Moreover, the simulator can be used to estimate the masking threshold. Then, by introducing to the system a particular tinnitus, two outputs are obtained: the audible signal which simulates how a person with a particular hearing condition perceives a tinnitus and the masking curve associated with this phenomenon.

The model of the ATH for a young person, in a quiet environment is obtained from expression 1.

$$S(f) = 3.64\left(\frac{f}{1000}\right)^{-0.8} - 6.5e^{-0.6\left(\frac{f}{1000} - 3.3\right)^2} + 10^{-3}\left(\frac{f}{1000}\right)^4 \quad (1)$$

Another advantage of working with this simulator is the possibility to perform experiments with individuals with a healthy auditory system. Thus, it is possible to obtain a greater number of people for the experimental studies, which is critical for validating the results. The first step of the proposed method is to make the diagnosis of tinnitus by a specialist and enter the data into the simulator. In this way, the ATH for the patient is obtained using the simulator. In this way, the masking spectrum caused by each of the spectral components can be obtained. Once the masking produced by tinnitus is established, the level of noise necessary to mask such tonal component is determined. Then, it is used to filter additive gaussian white noise and colored noise is obtained.

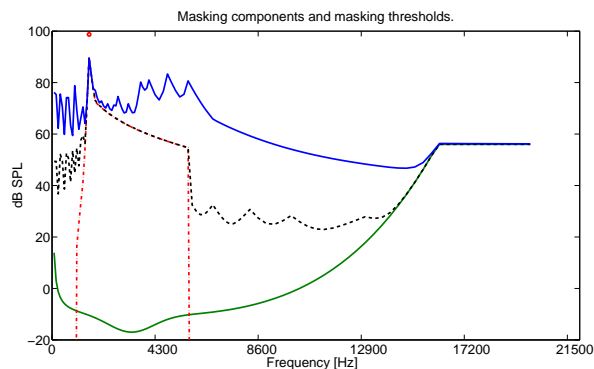


Figure 4. Masking thresholds obtained using noise filtered with a bandpass equal to the ATH of tinnitus and the proposed techniques. The proposed method allows a lower ATH than the reference method.

Once obtained the colored noise, the synthesized sound is used for the treatment of tinnitus. This may be done by a music player or an assistive listening device. The hearing impairment simulator [12] works with a spectral resolution of 32.25 Hz. It is possible to fit the spectrum of the filtered noise to the masking threshold with a precision better than many commercial assistive listening devices, which, as previously mentioned, only have up to 16 bands of equalization. These bands are in the range from 100Hz to 8kHz. Figure 4 shows in continuous blue line the ATH curve of the reference method, and in dashed black line the ATH curve of the proposed method. It can be seen that exists a difference between the ATH curves of the proposed and reference methods. Components placed in this range will be perceived using the proposed method, while they will be masked if a therapy based on the baseline methods would be applied.

Thus, the synthesized sound is adjusted to the desired output, and it masks the tinnitus and reduces the masking of other external spectrally adjacent sounds to the tinnitus. A complete

block diagram of the implemented system is shown in Figure 5, where the implemented system is divided into two stages: training and operation. During the training stage, tinnitus diagnosis data provided by the specialist is loaded to the simulator, which computes the threshold of masking of the tinnitus. Once the system was trained, the ATH obtained is used to reprogram the simulator, which in this case it is used as a bandpass filter. The output of the simulator is used to stimulate the user through headphones.

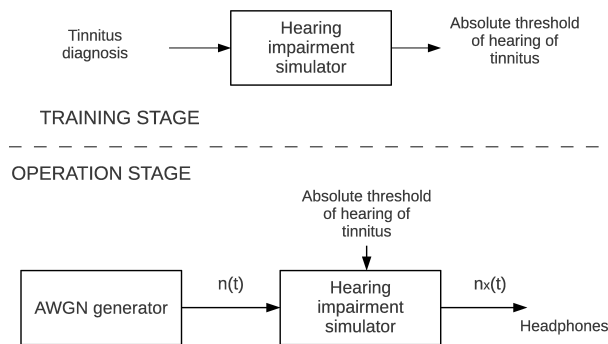


Figure 5. Block diagram of the implemented method.

4. Developed device

The main goal of the developed device is to acquire the sound, and add to this sound the synthesized noise. Thus, the synthesized signal contains the sum of the processed signal and generated noise. Then, the algorithm proposed in the previous section was implemented in a low-cost digital signal processor (DSP). The main goal of the proposed device is to mask the tinnitus using synthesized sounds. In the next subsections, the features of the most important components of the device are described.

4.1. Analog front-end

In order to reduce the size of the device and improve its performance, an audio codec is used for the analog front-end. The chosen codec is the PCM3052A[13] of Texas Instruments. This integrated circuit is a low cost, single-chip stereo audio codec. The most relevant features of this device are listed below:

- Integrated analog-to-digital converter (ADC) and digital-to-analog converter (DAC), with integrated antialiasing filter and output amplifier included, respectively.
- 24 bits data word length.
- Microphone input with preamplifier, stereo line-in input and stereo output.
- Programmable sampling rate between 16KHz and 96KHz.

Among other features, the system has an external line which is used to control the input source between the microphone amplifier and the stereo line input.

4.2. Digital Signal Processor

The chosen DSP is the dsPIC33EP512MU810 [11] from Microchip. This device has 52KB of data memory and 512KB of program memory, thus it is possible to use cross-compilers. Also, the chosen device has an Universal Serial Bus (USB) interface, which allows a communication between the device and other peripherals or a computer.

One of the greatest advantages of the dsPIC33EP512MU810 is its capability to run multiple tasks simultaneously, in this particular case those tasks are the transmission of a data segment and the processing of the previous one. This is accomplished by using the Direct Memory Access (DMA) module of the device [11], which independently operates from the main processor. In the proposed system, the signal is acquired using the codec, which sends the data to the dsPIC. Then, data is processed by the microcontroller and, finally, the processed data is sent back to the codec, which synthesizes the processed signal.

4.3. Implemented device

Due to the capability of the codec for input selection, the device has one microphone stereo input and a telecoil input. Also, it has a stereo output with a headphone amplifier. With the aim of configuring the hearing aid device with additional parameters, it has an USB interface, which can be connected to a computer. Finally, the implemented hearing aid has a SPI interface which can be used to connect a SD card with external configuration parameters, or to link the device with another hearing aid. Also, due to the amount of data and program memory, a set of very important features in a hearing aid can be implemented simultaneously.

A block diagram of the built system is presented in Figure 6.

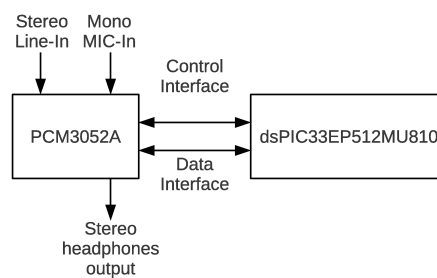


Figure 6. Block diagram of the implemented device.

Due to the packaging of the integrated circuits, the device has reduced dimensions (5cmx7cmx1,5cm) which is important for a portable device. Also, the device requires only one supply of 6V to operate and, current consumption is about 100mA. Figure shows the implemented device. A photography of the device is shown in Figure 7.

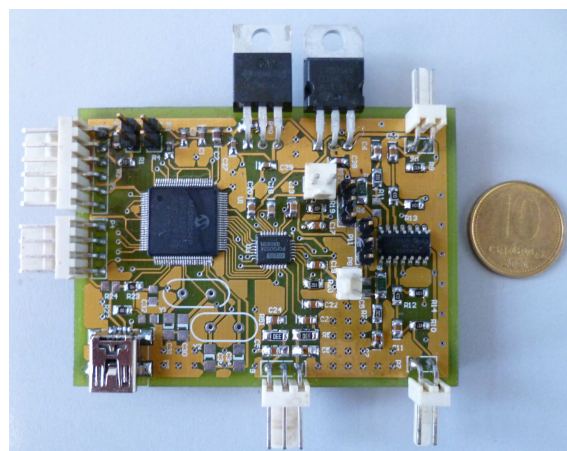


Figure 7. Developed Device.

5. Experiments

With the aim of compare the methods, a set of eight audios with a simulated tinnitus ($f = 1000Hz$) were generated. This frequency was chosen because is the most sensible region of the hearing range. Then, in each audio a tinnitus masking method was generated. The methods under study are listed below:

- 1. Additive white gaussian (AWG) noise.
- 2. AWG noise filtered using a bandpass filter parameterized with the tinnitus masking threshold (proposed method).
- 3. No masking (reference).
- 4. AWG noise filtered using a bandpass filter with $f_C = 1000Hz$ and $B_P = 625Hz$.
- 5. AWG noise filtered using a bandpass filter with $f_C = 1000Hz$ and $B_P = 1750Hz$.
- 6. AWG noise filtered using a bandpass filter with $f_C = 1000Hz$ and $B_P = 312Hz$.

Then, in order to analyze the performance of the methods in operational conditions, the masking methods were evaluated with additional prerecorded words. With this aim, the set of phonetically balanced words of Tato[15] were used. Those words are widely used in Argentina to perform hearing tests. Results of this experiment are shown in Table 1, where volunteers were asked about the intelligibility of each word (MOS-I), degree of tinnitus masking (MOS-M), and transcription of each word. This set of features are analyzed for the simulated configurations.

Subjective experiments were done in order to test the performance of the proposed algorithm. 15 volunteers (which accepted an informed consent) were asked to listen to the synthesized algorithms in random order. Listeners were asked to judge the tinnitus masking level of the sounds using a 5-point scale, from 1 (tinnitus is not masked) to 5 (tinnitus is completely masked). They also evaluated the intelligibility of the synthesized audios. In the same way, volunteers judged the intelligibility of the word contained into the audio using a 5-point scale, from 1 (word is unintelligible) to 5 (word is completely intelligible). Finally, a transcription of each perceived word was required.

Table 1 shows the results of the experiment. In the second column of Table 1 it can be seen that, except for the reference method, all the implemented methods present similar masking scores. In the reference method, because it does not apply any masking method, the score shows that the tinnitus is completely perceived. On the other hand, in the third column of Table 1, it can be seen that the proposed method and the reference method have similar scores of intelligibility, which are also higher than the other implemented methods. A similar conclusion may be obtained from the fourth column of the table. Then, it is possible to conclude that the proposed masking method has a similar performance to other implemented methods, and also, the intelligibility of spectrally adjacent sounds is similar to the reference method, in which no masking method was applied. In words synthesized using the other masking methods listeners had generally problem to distinguish between m and n , and also between v and d sounds, which have components in the range of the generated noise.

In Figures 8 and 9, results of Table 1 are shown using boxplots. In Figure 8, it can be seen that, excluding the reference, all the implemented methods have similar scores in the masking test. On the other hand, Figure 9 shows results of the intelligibility test. It can be seen that the proposed method and the reference have a similar performance.

A set of experimental measurements were also made to test the performance of the system. The sampling frequency used in the experiment is 16.383kHz. In the first test, the processing time of each process and the acquisition time for a frame of 256 samples were measured.

Table 1. Results of masking and intelligibility mean opinion scores, and % of transcription of each method.

Method	MOS-M	MOS-I	Transcription
1- AWGN	3.80	3.45	77%
2- Proposed	3.90	3.85	86%
3- Reference	1.50	3.95	86%
4- AWGN filtered using a BPF ($f_C = 1000Hz$, $B_P = 625Hz$)	3.90	3.35	68%
5- AWGN filtered using a BPF ($f_C = 1000Hz$, $B_P = 1750Hz$)	3.85	3.25	63%
6- AWGN filtered using a BPF ($f_C = 1000Hz$, $B_P = 312Hz$)	4.05	3.30	50%

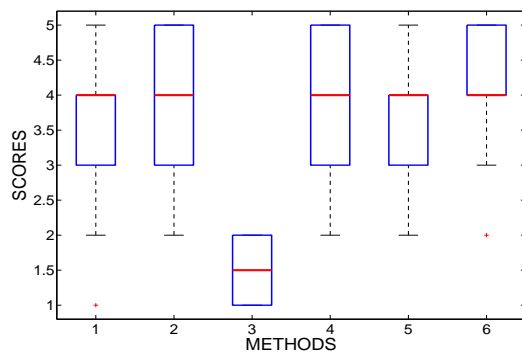


Figure 8. MOS-M boxplots of implemented methods.

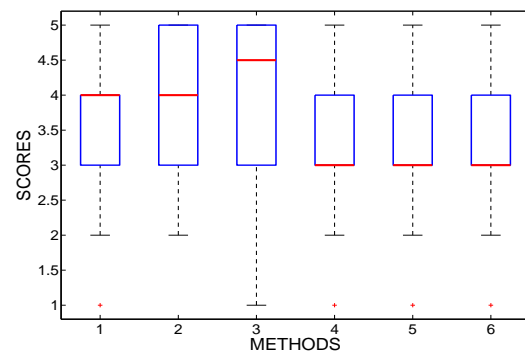


Figure 9. MOS-I boxplots of implemented methods.

The sum of communication ($61\mu s$), the noise synthesizer algorithm ($1.5ms$) and other processing times ($2.07ms$), is lower than the acquisition time ($15.63ms$). Thus, the system operates in real-time.

The available DMA memory is totally used, and only 37% of RAM memory and 4% of ROM memory are used. Thus, there is a good deal of remnant data memory and program memory. Therefore, it is possible to implement additional functions in the device. Also, the proposed algorithm requires less data memory than others noise synthesizers used in hearing aid devices. It is possible to conclude that other tinnitus treatment methods can also be implemented in the device.

6. Conclusions

In this work, a new tinnitus treatment algorithm was presented. It was demonstrated that the proposed method, which masks the tinnitus through filtered noise using a bandpass filter which was set using the absolute threshold of hearing of the tinnitus, at least has the same masking performance of other widely used methods, and also, the proposed technique improves the perception of spectrally adjacent sounds to the tinnitus.

Additionally, a digital assistive listening device which uses digital signal processing techniques to obtain the most important features of a high-end commercial assistive device was presented.

Finally, it was demonstrated that it is possible to successfully implement the tinnitus treatment algorithm in the developed device. This is very important because this type of methods must be applied using a hearing aid device.

The proposed hearing aid system in a low scale of production has a material cost many times lower than the final cost of a commercial high-end hearing aid. Thus, the developed device could satisfy a need of the Society. As a further work, additional features will be implemented.

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