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ARCHIVES OF ACOUSTICS
Vol. **38**, No. 2, pp. 185–190 (2013)

DOI: 10.2478/aoa-2013-0021

Active Noise Reduction Algorithm Based on NOTCH Filter and Genetic Algorithm

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(*received October 8, 2012; accepted February 18, 2013*)

Application of active noise reduction (ANR) systems in hearing protectors requires the use of control algorithms to ensure stability of the ANR system and at the same time highly effective active noise reduction. A control algorithm based on NOTCH filters is an example of solutions that meet these criteria. Their disadvantage is operation over a narrow frequency band and a need for prior determination of frequencies to be reduced. This paper presents a solution of the ANR system for hearing protectors which is controlled with the use of modified NOTCH filters with parameters determined by a genetic algorithm. Application of a genetic algorithm allows to change the NOTCH filter reference signal frequency, and thus, adapt the filter to the reduced signal frequency.

Keywords: active noise reduction, hearing protectors.

1. Introduction

The commonly used passive hearing protectors, like most passive noise hearing protection measures, are characterized by low attenuation in the low-frequency band (Bismor, 2012). Increased attenuation in the low frequency range is associated primarily with an increase in the weight and size of the hearing protector, which is limited to a certain extent. For this reason, the use of the passive hearing protectors means that employees are not always adequately protected from low frequency noise (Kotarbińska, Kozłowski, 2009). Additionally, non-uniform frequency attenuation of passive hearing protectors (lower attenuation of low frequency sounds and higher attenuation of high frequency sounds) has an adverse impact on the intelligibility of speech of people using hearing protection (Mejia *et al.*, 2008; Canetto, 2009). Sounds of higher frequencies carrying the main information message of the speech signal are attenuated very well, while low-frequency sounds which are the masking signal for the speech signal are poorly attenuated. These problems can be solved by application of active noise reduction systems which allow for a more effective reduction of low-frequency noise (Oinonen *et al.*, 2006). The use of lighter hearing protectors with poorer attenuation in the high-frequency band additionally provided with active noise reduction systems increasing their attenuation in the higher-frequency band often results in improved intelligibility of speech of individuals using hearing protectors (Prashanth, 2010; Pawełczyk, Latoś, 2010).

Active noise reduction (ANR) has been a dynamically developing branch of science since the '60s. Active noise reduction is based on the phenomenon of mutual compensation of acoustic waves leading to a decrease in the sound pressure level at a given point in space (Engel *et al.*, 2010). A compensating acoustic wave is created by means of an additional sound source. The acoustic compensation wave has to have in the point of space (point of observation) the same amplitude as the acoustic noise wave and opposite phase. The main issue in the application of ANR systems in hearing protectors is ensuring stability of the ANR system operation and at the same time a highly effective active noise reduction (Pawełczyk, 2004). The ANR system should analyze a noise signal and generate adequate compensating signal taking into account transmittances of the electroacoustic path, including phase shift results from different distances between sources and point of observation (Morzyński, Makarewicz, 2003; Krukowicz, 2010). An example of solutions that meet these criteria is an ANR system which is controlled with the use of NOTCH filters (Mojiri, Bakhshai, 2004). Their disadvantage is operation over a narrow band and a need for prior determination of frequencies to be reduced. Despite the narrow-band nature of operation, these systems can be used to reduce noise of a number of specific groups of machines and equipment found in industry. A number of these sources, such as pumps, ventilation systems, turbines, and others, produce narrowband stationary noise (Engel *et al.*, 2010). In the case of such noise, to achieve the required attenuation performance of an active hearing protector it is sufficient to reduce noise in selected frequency bands.

2. Active noise reduction system with modified NOTCH filters

This paper presents a solution of the ANR system for hearing protectors which is controlled with the use of modified NOTCH filters with parameters determined by a genetic algorithm (Goldberg, 1989; Gwiazda, 2007; Makarewicz, 2007). It is assumed that the active noise reduction system will comprise a number of modified NOTCH filters, connected in parallel.

Typical NOTCH filters, in order to operate correctly, need two sinusoidal reference signals, out of a phase 90° (i.e. $\sin(\theta)$ and $\cos(\theta)$), synchronized with the noise signal. The compensating signal $y(n)$, described by use of the Eq. (1), constitutes a sum of component signals $y_1(n)$ and $y_2(n)$

$$y(n) = y_1(n) + y_2(n) = w_1(n)\sin(\omega(n)) + w_2(n)\cos(\omega(n)) = A\sin(\omega(n)+\varphi). \tag{1}$$

The signals $y_1(n)$ and $y_2(n)$ are products of a reference signal and amplification factors called filter coefficient. Usually values of these factors are settled with use of the LMS algorithm (Bismor, 2012), according to the following equations:

$$w_1(n+1) = w_1(n) + \mu e(n)\sin(\omega(n)), \tag{2}$$

$$w_2(n+1) = w_2(n) + \mu e(n)\cos(\omega(n)), \tag{3}$$

where μ is the value of adaptation coefficient, n is the consecutive number of a sample.

The NOTCH filter modification (Górski, Morzyński, 2012) consists in enabling the change in the reference signal frequency (and consequently adaptation to the reduced signal frequency) by introducing an additional coefficient determining the frequency of the generated reference signal, as shown in Fig. 1.

In the modified NOTCH filter, an additional coefficient w_3 is introduced for determining the frequency of the generated reference signal. This modification allows adaptation of the filter to the frequency of the reference signal. In the modified NOTCH filter, the compensating signal $y(n)$, described with use of the

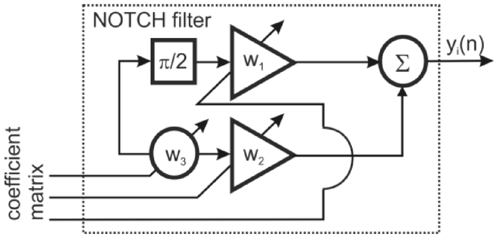

Fig. 1. Block diagram of the modified NOTCH filters.

Eq. (4), constitutes a sum of component signals $y_1(n)$ and $y_2(n)$

$$y(n) = y_1(n) + y_2(n) = w_1\sin(w_3\omega(n)) + w_2\cos(w_3\omega(n)) = A\sin(w_3\omega(n)+\varphi). \tag{4}$$

In this case, it is not possible to apply the LMS algorithm. Figure 2 shows a block diagram of a hearing protector with an active noise reduction system, operating with the use of modified NOTCH filters and a genetic algorithm. The objective of the genetic algorithm is to determine the coefficients of NOTCH filters that allow for achieving the highest possible efficiency of the ANR system and minimize noise reaching the user of the hearing protector; in particular, determining frequencies to be reduced.

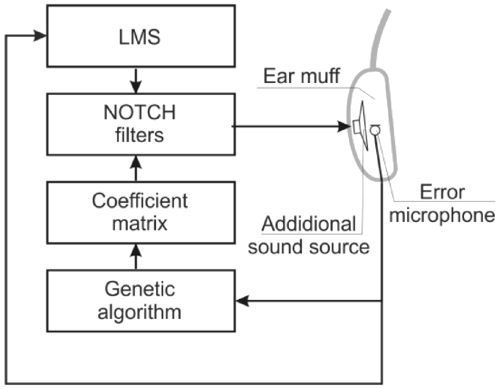

Fig. 2. Active noise reduction system with modified NOTCH filters.

After establishing a set of NOTCH filter coefficients, active noise reduction system switches to the operation mode in which coefficients responsible for frequency change are not changed, and the coefficients w_1 and w_2 are adapted using the LMS algorithm with a very small adaptation step. The user will be able to initiate the process of determination of parameters for the control algorithm using a genetic algorithm whenever such a need arises (e.g. after changing the work room).

Operation of the active noise reduction system control algorithm starts with a genetic algorithm (Fig. 3) creating the initial population of individuals (sets of filter coefficients). Its size is selected experimentally on the basis of numerical simulations. The number of

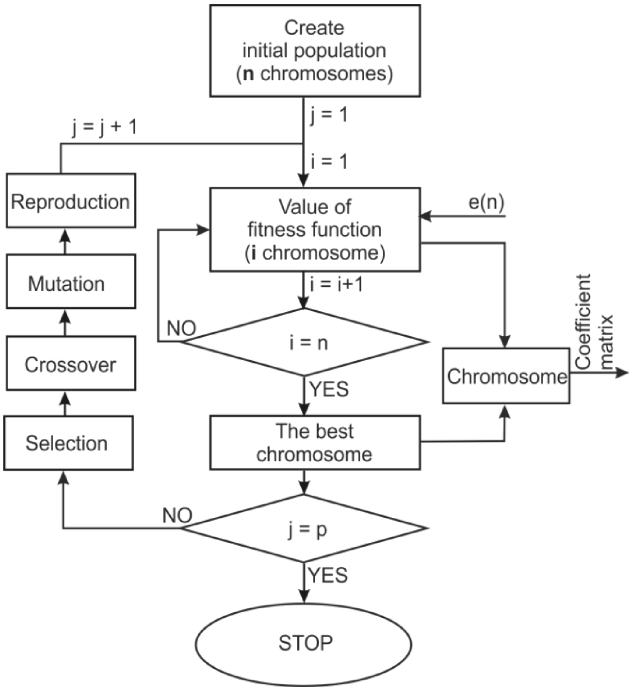

Fig. 3. Block diagram of the genetic algorithm used in an active noise reduction system.

genes in each individual depends on the number of implemented NOTCH filters. Three coefficients will need to be determined for each filter. Their values are real numbers in the range from −1 to 1.

During simulations, calculation of the fitness function involves determination of the simulated error signal vector corresponding to the vector of the sample recorded by the error microphone in a real active noise reduction system. Values of fitness function are calculated for each individual in the population. The same noise signal vector is used to calculate the value of the fitness function for each individual in the population, which is a significant simplification compared to real conditions. In real conditions, the error signal vector is recorded one by one for each individual. For this reason, changes in the (reduced) noise signal cannot be excluded, which can lead to ambiguity in determination of fitness for individuals of a given population.

Selection of the best individual consists in finding an individual with the best fitness. For this individual, the NOTCH filter coefficients are read and assigned to the vector of filter coefficients. After verifying the end condition, which in the algorithm concerned is a certain number of generations, the genetic algorithm ends the operation or enters the stage of the development of new individuals. At the selection stage, a group of individuals with the greatest fitness is selected with the assumed probability. At the stage of crossover of selected individuals in pairs, particular genes are modified in order to obtain individuals with intermediate characteristics. At the stage of mutation of selected individuals, particular genes are modified in order to obtain new values of coefficients which are absent in the selected population. Then, a group of n individuals is selected out of the group of individuals undergoing selection, crossover, and mutation operations to form a new population. After stopping the genetic algorithm and selecting the best individual, the active noise reduction system switches to the operation mode in which it operates using the LMS algorithm. The LMS algorithm is applied due to the fact that the genetic algorithm selects the reduced frequency with a finite accuracy. The genetic algorithm is a stochastic algorithm, the errors of a selected frequency can vary greatly at subsequent runs of the same algorithm. The results of the numerical simulations show that these errors are typically in the range of ±15 Hz.

The effect of the non-ideal determination of the reduced frequency is a generation of two signals with slightly different frequencies, and, consequently, a phenomenon known as beat (Fig. 4).

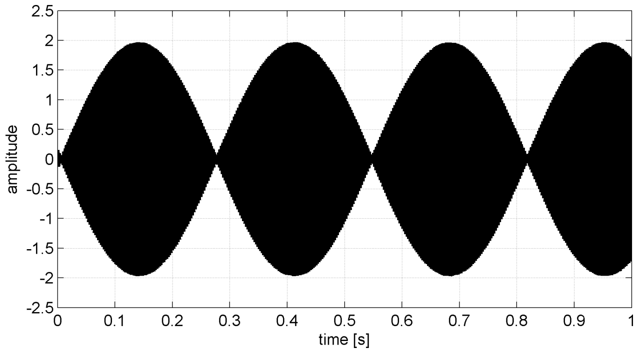

Fig. 4. Sample error signal over time with application of an active noise reduction system with modified NOTCH filters.

3. Numerical simulations

The active noise reduction system presented above was tested using numerical simulations. In order to carry out these tests, the ANR system in the Matlab computing environment was developed. During numerical simulations, analyses were carried out of the impact of modifications in the parameters describing the ANR system. The impact of the size of the initial population, the probability of crossover and mutation and the number of generations was analysed in the group of features describing the genetic algorithm. In the group of describing the ANR system, the number of component frequencies, a change in the frequency of noise signal and the length of the vector of test samples were taken into account.

The main objective of the numerical simulations was to determine the possibility of using the LMS algorithm to reduce the error in determining the reduced signal frequency and estimate the effectiveness of the proposed solution of the ANR system.

Figure 5 shows the waveforms of the noise signal (a tone with a frequency of 400 Hz) before reduction and the reduced signal for the active noise reduction system without the aid of the LMS algorithm. In this case, the genetic algorithm has allowed for signal reduction by about 80%.

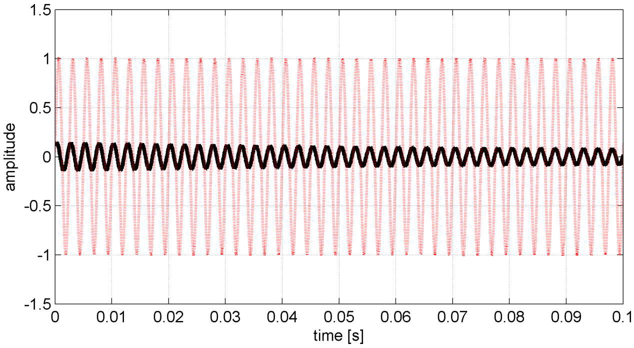

Fig. 5. Waveforms of the noise signal (dotted line) and error signal (solid bold line)with application of an ANR system with modified NOTCH filters.

For the analysed time span, the effectiveness of active noise reduction is about 10 dB (Fig. 6). However, about 0.2% error in determining the reduced signal frequency caused the algorithm to operate correctly only at an early stage (the beat effect).

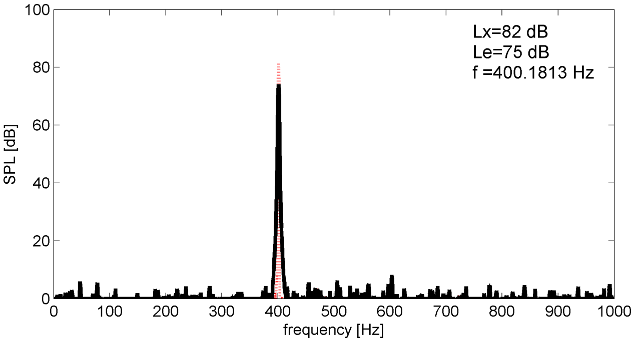

Fig. 6. Spectrum of the noise signal (dotted line) and error signal (solid bold line) with th application of an ANR system with modified NOTCH filters.

Introduction of the LMS algorithm to compensate determination of the reduced frequency error signal by the genetic algorithm eliminated the beat effect and provided a more accurate compensation of the noise signal (Fig. 7). This modification improved the effectiveness of the active noise reduction by up to about 50 dB (Fig. 8).

A similar principle of operation of an active noise reduction system can be applied to multi-tone signals. Figures 9 and 10 show the noise spectrum of a dual-tone signal with the frequencies 400 and 600 Hz, and an error signal. In the first case, the active noise reduction system operated only with the modified NOTCH filters, and in the second case the LMS algorithm was also used.

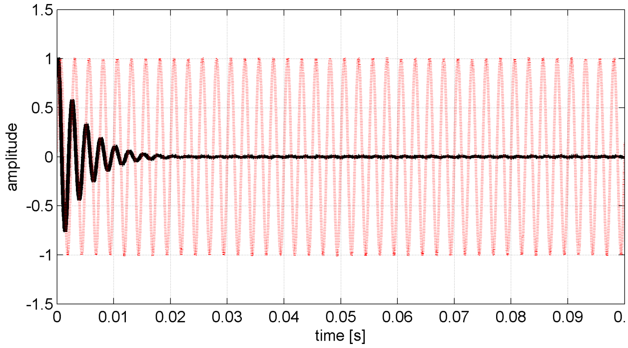

Fig. 7. Waveforms of the noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters and the LMS algorithm.

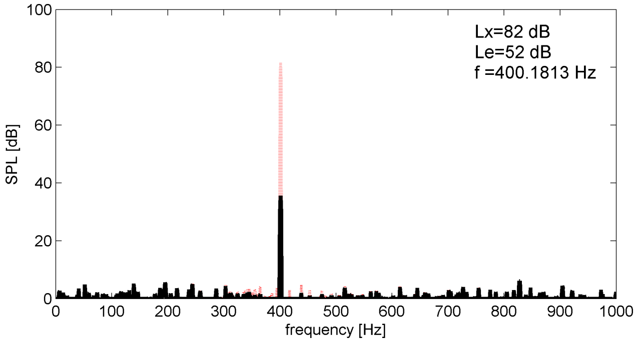

Fig. 8. Spectrum of the noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters and the LMS algorithm.

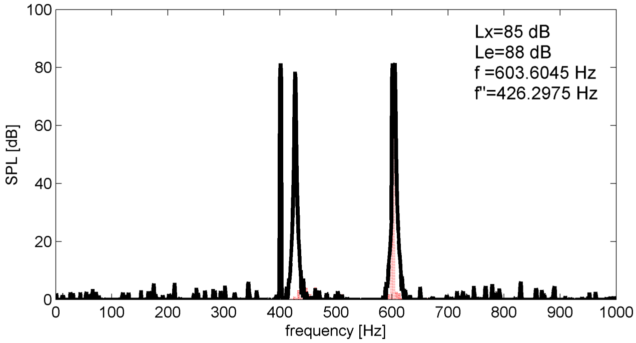

Fig. 9. Spectrum of the two-tone noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters.

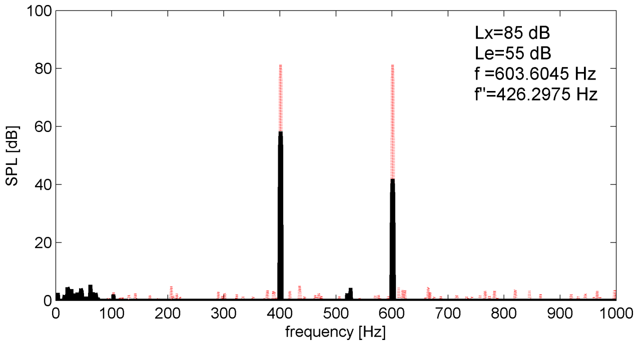

Fig. 10. Spectrum of the two-tone noise signal (dotted line) and error signal (solid bold line) with the application of an ANR system with modified NOTCH filters and the LMS algorithm.

The effectiveness of the active noise reduction with the use of only modified NOTCH filter is about −2 dB (Fig. 9). The genetic algorithm error in determining the reduced signal frequency is about 15–20 Hz. Introduction of the LMS algorithm to compensate the determination error of the reduced frequency signal by a genetic algorithm improved the effectiveness of active noise reduction by up to about 30 dB (Fig. 10).

Figure 11 shows the waveforms of the noise signal (a two-tone with a frequency of 400 and 600 Hz) before reduction and the reduced signal for the ANR system with the application of the modified NOTCH filters and the LMS algorithm. In this case, the genetic algorithm has allowed for signal reduction by about 90%.

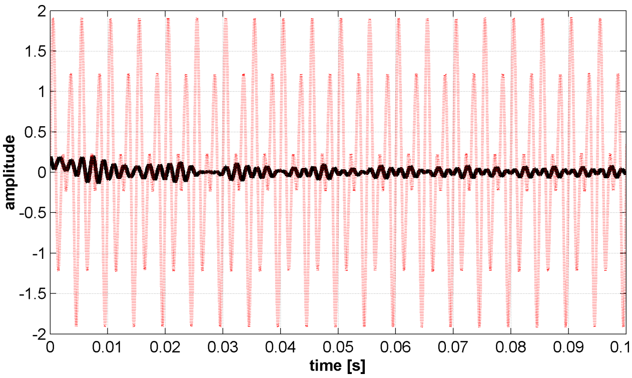

Fig. 11. Waveforms of the two-tone noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters and the LMS algorithm.

4. Summary

A solution of the ANR system for hearing protectors has been presented. In this solution, modified NOTCH filters with parameters determined by a genetic algorithm were used. The ANR system was tested using numerical simulations. The main objective of the numerical simulations was to determine the possibility of using the LMS algorithm to reduce the determination error of the reduced frequency signal and estimate the effectiveness of the proposed solution of the ANR system.

Application of the LMS algorithm to compensate the error in determining the reduced signal frequency by the genetic algorithm can significantly reduce the operation time of the genetic algorithm and considerably improve the efficiency of the entire system. Numerical simulations have shown that for errors in determination of a frequency signal to be reduced by the genetic algorithm of 5 Hz, the maximum design efficiency of active noise reduction is about 55 dB. Lower maximum effectiveness of active noise reduction is achieved for multi-tone signals (about 40 dB). The problem in this case is the appropriate selection of the adaptation step, which has a significant effect on the activation of the ANR system.

Acknowledgments

This paper has been based on the results of a research task carried out within the scope of the second stage of the National Programme "Improvement of safety and working conditions" partly supported in 2011–2013 – within the scope of research and development – by the Ministry of Science and Higher Education/National Centre for Research and Development. The Central Institute for Labour Protection – National Research Institute is the Programme's main coordinator.

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