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ACTIVE NOISE CONTROL METHODS IN POLAND

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The article presents the development and selected uses of methods of active noise reduction in Poland: from the first theoretical studies of Prof. Wojciech Rubinowicz to the latest study with the use of neural networks. The article discusses the principles of active compensation of sound. It also presents the results of Polish research centres' work on the use of active systems for reducing noise in ducts, power transformers: noise and to improve hearing protectors parameters.

1. Introduction

The noise is one of the most basic hazards for people's life and work environment. According to the Central Statistical Office data for 2002, about 33% of Polish population is exposed to various noise at levels exceeding standards, and 240 000 of employees are exposed to noise at above > 80 dB. The most difficult noise to control is the low-frequency noise, generated by flow machines, e.g. compressors, fans and blowers. Active methods are the most effective methods for the low-frequency noise control.

The active methods' origin may be found in Christian Huygens (1629–1695) works and is based on well known Huygens–Fresnel interference rule. The first concepts for practical application of active noise control methods emerged in 1930s (Henry Coanda and Paul Lueq patents). The development of different sciences, e.g. electronics, control theory and information science, enabled development of first practical solutions, first in the laboratory and then in the industrial scale. Several technical and scientific centres, dealing with basic research and practical applications for various technical domains, may be found worldwide.

The number of scientific and technical elaborations related to the active noise control proves the active noise control's development.

According to D. Guicking, the Physics Institute of Goetingen, who managed the list of references related to the noise control by the early 1990's, over 3500 publications by authors from 37 countries worldwide were issued by 1992. Guicking gave up managing the list, as the number of publications increased dramatically in the following years. Currently, several thousand publications per year are issued.

The active noise control methods' significance is also proved by the fact that since 1991, ACTIVE scientific symposium is organized in different countries every two years; this symposium is held under auspices of the International Institute of Noise Control Engineering (I-INCE).

The papers are presented on other conferences and scientific conventions, including plenary papers related to the active noise control methods; special scientific sessions are also organized.

In Poland, only some scientific centres deal with the active noise control methods. In spite of the small quantity of the researchers dealing with these methods, it can be assumed that Polish scientists elaborations significantly contributed to the active noise control method development.

The following researchers' works contributed to this development: Władysław Bogusz, Stefan Czarnecki, Roman Gutowski, Zbigniew Engel, Ignacy Malecki, Wojciech Rubinowicz, Stefan Ziemba. The results of their research work became a base for further active noise control research and applications.

Polish active noise control research and application elaborations are presented further in this paper.

2. The first works in Poland

The research related to the active methods in acoustics were started in Poland in 1970's (S. Czarnecki [12–14], Z. Engel). It should be noted that previous elaborations of Polish scientists contributed to the active noise control method's basics development all over the world. The authors of the active noise control method theoretical basics (M. Jesset, G. D. Malużeniec and other) based on elaborations of Prof. Wojciech Rubinowicz (1899–1974), world famous physicist, who dealt with optical phenomena rather than with acoustic ones. In 1917, in *Die Beugungswelle in des Kirchhoffshen Teorie der Beugung* dissertation Rubinowicz described the edge wave theory (called afterwards Rubinowicz's edge wave). He demonstrated an equivalence of Fresnel and Young opinions related to the diffraction phenomena formation, and reviewed T. Young's view to the voltage phenomena matter. Rubinowicz also demonstrated that the wave motion, resulting from Kirchhoff's assumptions, may be decomposed into "the geometrical-optical wave" and the wave of "diffraction". In further elaborations Rubinowicz also demonstrated that for the first approximation, the diffraction wave may be treated as a wave generated by reflection of the wave directed to the diffracting edge. He analyzed the wave motion examined by Kirchhoff which existed in the whole space and was expressed by Helmholtz equation. Without going into details of the mathematical description, the existence of non-transparent bodies (called screens) in the space is assumed. Depending on the boundary conditions, used when solving Helmholtz's equation, "hard" and "soft" screens are distinguished in the acoustics. Rubinowicz concluded that the wave motions on illuminated and shadowed side of the screen differ only by the incident wave. The screen absorbs the incident wave, but is non-transparent for other waves, as it is left unchanged after screen deformation. Kirchhoff specified the screen in his diffraction theory as a "black" screen. This screen absorbs only the incident wave. The motion wave in the system including such a screen is expressed by the Kirchhoff's integral, so this screen is called Kirchhoff's screen. The issues related to the part of the screen which is shadowed on the illuminated side by the wavy shape of the diffracting screen are considered. This screen may be freely deformed, which entails no changes in diffractions phenomena. Such a screen is called Kirchhoff's "wavy screen" or Kirchhoff's "corrugated screen". Rubinowicz also found that a wave "leap" occurs for this screen, and concluded that the screens absorb the incident wave. For a screen created by any surface, the "light rays", i.e. half lines coming out of the light source, cross the screen two or more times. In this case, the incident light behaves in a paradox way on the Kirchhoff's screen. This paradox is called the "Rubinowicz's paradox".

M. Jessel in his active noise control methods theoretical basics says that the "concavity effect has its beginning in Rubinowicz's paradox". When analyzing the acoustic field area, he observed that some part of this area supports the conformity of Huygens' sources, while the other part supports active source reduction. Rubinowicz anticipated such a case for Kirchhoff's corrugated screen. The issues related to Kirchhoff's diffraction theory have been theoretically re-worked in details by W. Rubinowicz. The phenomena of mutual interference of light waves falling onto the screen's edge and effect of the wave compensation in some part of the examined area have been described. The wave falling onto screen's surface (edge) may compensate the wave of the same type, but shifted by π angle, resulting in total light extinguishing. Prof. Rubinowicz, outstanding radiation theory specialist, dealt in his research with the optical issues. Nevertheless, the optical and acoustic wave phenomena may be expressed with the same equations. Therefore, the results of Rubinowicz's research, who introduced a new approach to the wave phenomena, may be considered as theoretical fundament of active noise control methods.

This paper doesn't present active noise control methods in vibration analysis, but please note that the issue of active methods for vibration control appeared ca. fifty years ago. That research concerned mechanical system synchronization and auto-synchronization. R. Gutowski dealt with the vibration control issue, and Cz. Cempel performed the synthesis of the vibration isolation system with compensation in 1973. First elaborations related to active car vibration isolation (E. Kamiński, J. Osiecki) were developed at that time. The research of active hydraulic and pneumatic vibration isolation systems and seat vibration isolation systems (J. Nizioł, J. Kowal) has been conducted. The works of A. Muszyńska and Z. Gosiewski concerned rotor system vibration control. Other elaborations concerned active vibration control in materials (A. Tylikowski).

The research related to active methods in acoustics were started in early 1970's by Stefan Czarnecki and Zbigniew Engel.

Prof. S. Czarnecki dealt mainly with active sound compensation methods. The doctor's thesis which specified the phase compensation conditions in openwork resonance screens has been performed under his direction.

On Prof. Z. Engel initiative, the active method laboratory with special test benches, mainly for active noise control in the waveguides, has been created in Central Institute for Labour Protection – National Research Institute in Warsaw (Centralny Instytut Ochrony Pracy – Państwowy Instytut Badawczy) (CIOP-PIB).

In the following years, another research centres dealing with active methods in acoustics were developed. Apart from the Mechanics and Vibration Acoustics Institute of AGH (University of Science and Technology), the Automation Institute of the Silesia University of Technology, the research is also performed by the University of Rzeszów.

These studies are discussed below.

3. Active sound compensation's conditions

The active compensation phenomenon occurs when appropriate phase and amplitude conditions of the signals involved are met, and the compensation level and its range depend also on the signal type, mainly on their correlation parameters. The compensation principle is presented in Fig. 1.

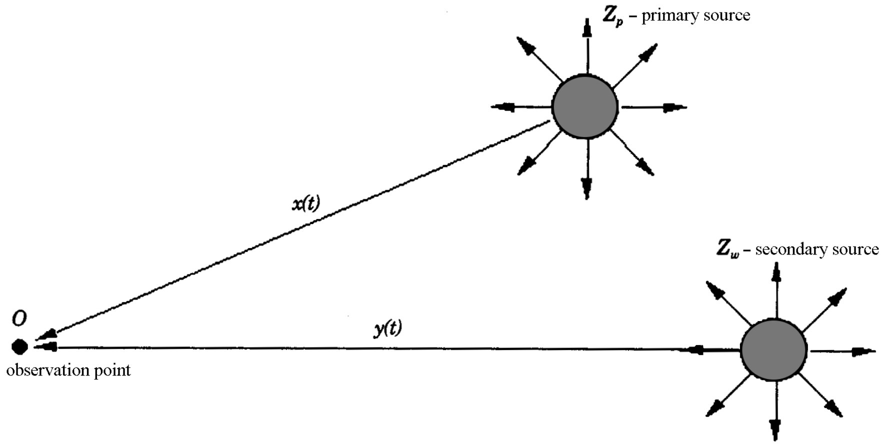

Fig. 1. The compensation circuit diagram.

The primary source Z_p (compensated source) generates the time alternating acoustic signal $x(t)$, and the secondary source Z_w (compensating source) generates the signal $y(t)$. Assuming that the propagation medium is linear, the superposition rule is in effect, so that the resultant signal $Z(t)$ in the observation point O is given below:

$$Z_0(t) = x_0(t) + y_0(t + T), \tag{1}$$

where T – time of delay caused by the difference of the propagation paths from Z_p and Z_w sources.

The phase compensation in the point O occurs, when for average signal powers in this point [137, 139]:

$$Px_0y_0 = Pz_0 \leq Px_0 \, .$$

The compensation level achieved in the O point may be expressed with the compensation coefficient k, which is defined as the compensated signal's acoustic power to the primary signal's power ratio.

$$k = \frac{\langle P_{Skp} \rangle}{\langle P_{Xp} \rangle} = \frac{\langle P_{Xp} \rangle - \langle P_{Zp} \rangle}{\langle P_{Xp} \rangle} = 1 - \frac{\langle P_{Zp} \rangle}{\langle P_{Xp} \rangle}, \tag{2}$$

where $\langle P_{Skp} \rangle$ – an average compensated signal's power.

Since $\langle P_{Skp} \rangle < \langle P_{Xp} \rangle$, so the compensation coefficient k meets the following condition:

$$0 < k < 1. \tag{3}$$

The value of this coefficient depends on the correlation parameters of the signals involved in the compensation process.

By introducing the mutual correlation functions of the signals originated by the sources Z_p and Z_w, and performing proper transformations, the following condition is achieved [137]:

$$\frac{1}{2}\sqrt{a} < -b < \frac{1}{2}\,\frac{1+a}{\sqrt{a}}, \tag{4}$$

where the coefficient a represents the $x(t)$ and $y(t)$ component signal average power ratio, and b is the mutual correlation coefficient for these signals.

These coefficients may be expressed as follows:

$$a = \frac{R_{Tyy}(0)}{R_{Txx}(0)}\,, \tag{5}$$

$$b = \frac{R_{Txy}(0)}{(R_{Txx}(0) R_{Tyy}(0))^{0.5}}\,, \tag{6}$$

where $R_{Txx}(0)$, $R_{Tyy}(0)$ – the auto-correlation functions.

The condition expressed in (4) combines all the most significant parameters related to the signals $x(t)$ and $y(t)$.

The course of changes $b(a)$ achieved based on this inequality is presented in Fig. 2.

Analyzing the diagrams presented in Fig. 2, and the inequality (4), it is possible to determine for which power ratio the compensation is possible. The right and left side of an inequality (4) are non-negative, so the mutual correlation coefficient b must be negative and fall in the following range:

$$\frac{1}{2}\sqrt{a} < -b < 1. \tag{7}$$

Thus the compensating signal's power to the compensated signal's ratio meets the following condition:

$$0 < a < 4. \tag{8}$$

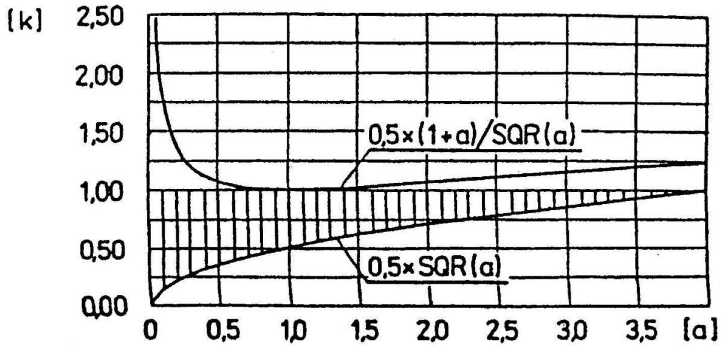

Fig. 2. The conditions for the phase compensation vs. $x(t)$ and $y(t)$ signal parameters.

The inequalities (7) and (8) determine the conditions which have to be met by the compensating and the compensated signal amplitudes for the compensation phenomenon to occur.

The relationships referred to above enable determination of the relation between the compensation coefficient k, the signals power ratio and the mutual correlation coefficient b:

$$k = -2b\sqrt{a} - a. \tag{9}$$

The relation of the compensation coefficient k vs. an average power ratio a for different mutual correlation coefficient b values is presented in Fig. 3.

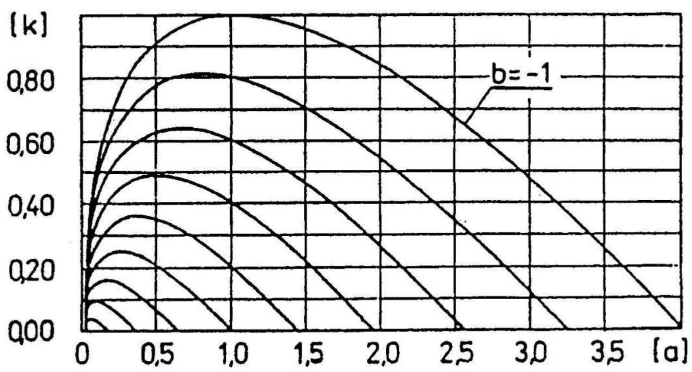

Fig. 3. The relation of the compensation coefficient k vs. parameter a.

The figure shows that maximum compensation occurs for $a = 1$ and $b = 1$.

The curve determined for $b = -1$ shows also the previously determined relation (4), which is related to the parameter a changes. Analyzing the relations referred to above in relation to the signal amplitude ratio, one can state that the compensation coefficient is $k = 1$, when the compensated signal amplitude X and the compensating signal amplitude Y are equal. The extent of changes for the compensation coefficient k vs. the amplitude ratio x/y is presented in Fig. 4.

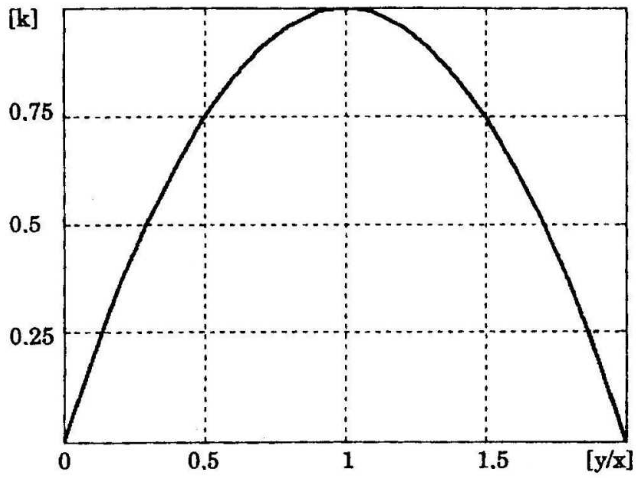

Fig. 4. The extent of changes for the compensation coefficient k.

Another condition for the active compensation to occur, apart from proper compensated signal's amplitude, is to provide proper phase shift angle between the compensated and the compensating signal. We can demonstrate, without reviewing detailed analysis of the phase error significance that when retaining unitary amplitude ratio and increasing the phase deviation, the compensation coefficient k decreases gradually to 0. For sinusoidal signals with identical pulsation, this value is achieved for the phase error of $60°$. Higher phase deviation causes that the compensating signal results in the sound level increase in the observation point O in relation to the sound related only to the compensated source. Please note that the active compensation effect is more sensitive to the phase deviation, if the compensating signal's amplitude is lower or equal than the compensated signal's amplitude. For practice applications, the parameters describing the signal (noise) sources $x(t)$ and $y(t)$ decide on the active system effectiveness and the noise control type (global or local).

Both types of the compensations – for simple sinusoidal signals and more complex periodical signals – are based on the principles referred to above. As the type of the signals involved in the compensation process directly implies the complexity of active noise control system solutions, one of several practically accepted system classifications divides them into single-channel and multi-channel circuits. Considering various classification criteria, general classification of active noise control systems is presented in Fig. 5.

Theoretical work results and simultaneous development of the electronics and IT enabled, in 1970's and 1980's, the development of practical active noise control system solutions. The multi-purpose test bench, developed in CIOP-PIB, may be considered

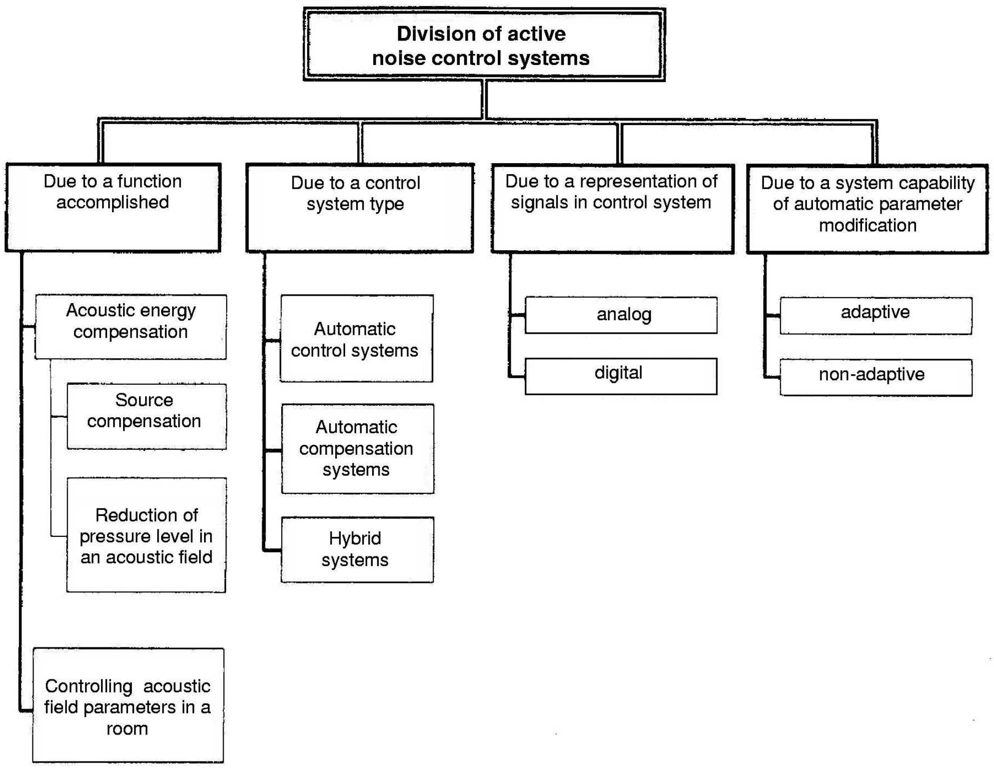

Fig. 5. Active noise control system classification.

one of the forerunning ones; this test bench enables experimental verification of successive active noise control system's synthesis stages. The acoustic waveguide, featuring segmented structure with single compensating and compensated signal source, is a primary test bench's component. The test bench's design enabled both basic examinations necessary to recognize physical features of active noise control, and the research including real noise source simulations. Accepting of high universality of the test bench has been also related to flexible division of hardware & software functions, and capability of stand-alone analysis and synthesis of the following operations:

- gathering necessary set of data related to the acoustic parameters of the compensated field;
- processing the data gathered;
- generating the compensating field.

Basic diagram of the waveguide being a part of the test bench described above is presented in Fig. 6.

This circuit detects, with the microphone M, and processes the sound generated by the compensated source Z_p. The microphone output, properly delayed to compensate the time necessary for the primary wave to pass from the microphone to the compensating source, controls the secondary source Z_w.

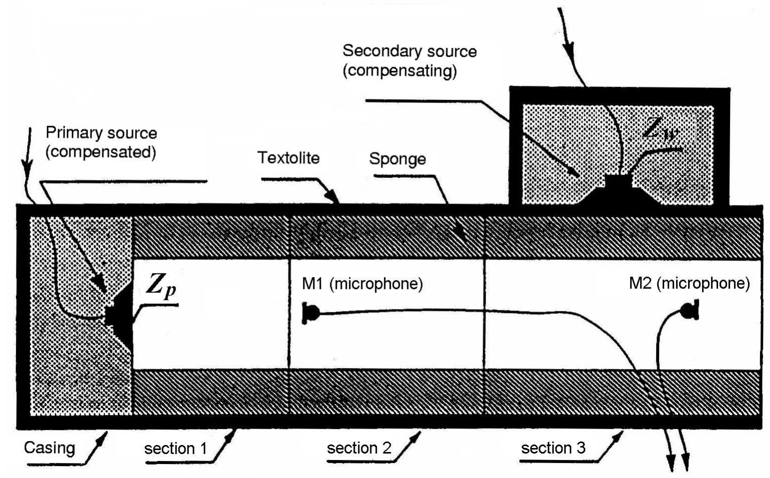

Fig. 6. Basic diagram of active noise control system in the waveguide.

The compensation level is controlled by the microphone M2, located at the waveguide's outlet.

For initial simple experiments, control of the secondary source for sinusoidal signals with fixed amplitude was achieved by relocating of the microphone M1. For successive studies, this system has been enhanced with additional modules: analogue and digital control circuits, measuring circuits, etc.

This test bench, operating successfully up to now, facilitated multiple examinations and research projects, became a basis for development and verification of author's system solutions (mainly control systems), and was also used for three doctor's thesis and didactic courses.

The waveguide acoustic compensation research became a basis for in-house CIOP-PIB designing and developing of the multi-purpose test bench related to active noise control in the ventilation systems.

The diagram of this system is presented in Fig. 7.

The test bench comprises the measuring waveguide, the ventilation system and necessary equipment. The ventilation channel comprises 30 removable elements (segments, T-connections, elbows, flexible pipes, angle reducers, throttles – indicated in the figure as 1–14).

Active noise control system includes the speaker casing and built-in compensating source, and the measuring components, the amplifiers and the controller. The controller features 8 input channels and 2 output channels. Basic system functions are implemented with the software, in-house developed with C++.

This test bench, featuring flexible setup capabilities, enables studying the active noise control system both in laboratory and real environment. The software developed enables simulating of active noise system operation for various controller's configurations and control algorithms. The control algorithms, verified when performing simulation calculations, are implemented in form of the real-time software.

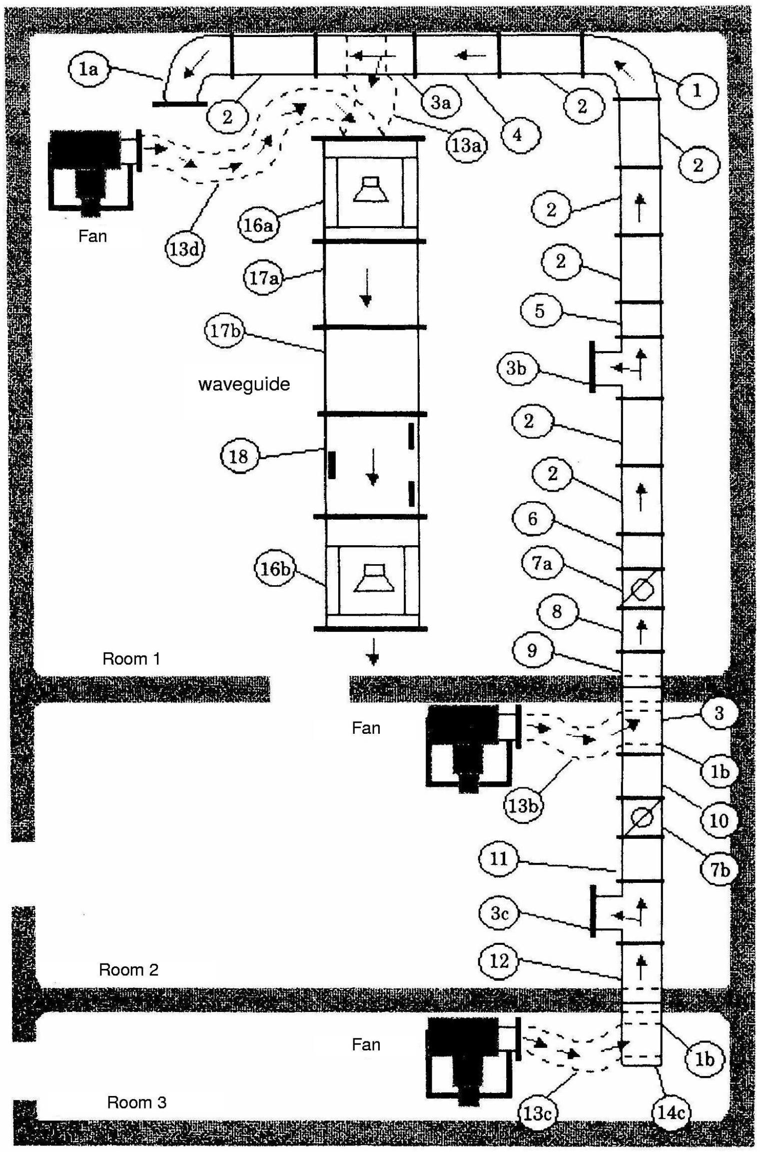

Fig. 7. Test bench diagram.

The block diagram of real-time active noise control system, with an example controller structure, is presented in Fig. 8. This system includes the elements representing the transmittances (transfer functions) measured between the system key points (reference detector, error detector, secondary source) and digital filters. The research performed with this test bench, involving real fans acting as the primary sources, demonstrated that the noise level has been reduced in test room by 5÷25 dB by means of active noise control system.

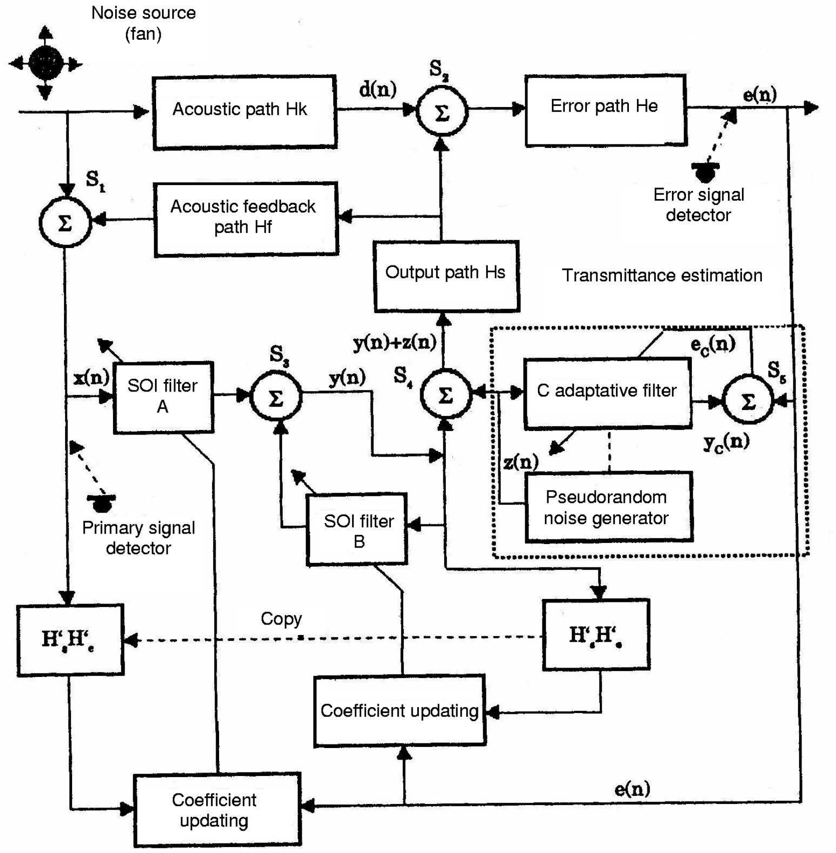

Fig. 8. Controller diagram.

4. Active noise control system's components

In Poland, active noise control system's component research is performed mainly by the Acoustics Institute of the Silesian University of Technology (Instytut Akustyki Politechniki Śląskiej), the Central Institute for Labour Protection – National Research Institute (Centralny Instytut Ochrony Pracy – Państwowy Instytut Badawczy CIOP-PIB) and by AGH University of Science and Technology (Akademia Górniczo-Hutnicza) [References].

The monograph for these problems has been developed, several publications have been published, and the doctor's theses prepared. The active noise control system related research is developed by the CIOP-PIB. That research focused mainly on the controllers for active noise control systems. Such a controller is mainly responsible for secondary source control in order to generate the compensating signal with the parameters necessary for continuous noise reduction.

For many years, the scientific team of Silesian University of Technology, lead by Prof. A. Niederliński, deals with the control theory problems, including the adaptative control problems, i.e. a kind of control, which enables updating of control algorithm based on the object's mathematical model identification.

Since the active noise control is the process influenced by multiple fast transient disturbances, the controller has to react fast enough to provide with high noise reduction performance for rapidly changing operating conditions. For this reason, the adaptative circuits and the effective adaptation algorithms play significant role for active noise control systems. The adaptative circuit research is performed simultaneously in several areas using the state-of-the-art electronic and IT technologies, e.g. the neural networks or the genetic algorithms.

The automated control and compensation circuits are still in use; for applications demanding particularly high stability quality, both circuits are used, constituting the automated control circuit with compensating function for the most relevant interference variables (so called hybrid circuits).

The block diagram of active noise control system with the controller is presented in Fig. 9, and the typical adaptative active noise control system for the acoustic waveguide is presented in Fig. 10.

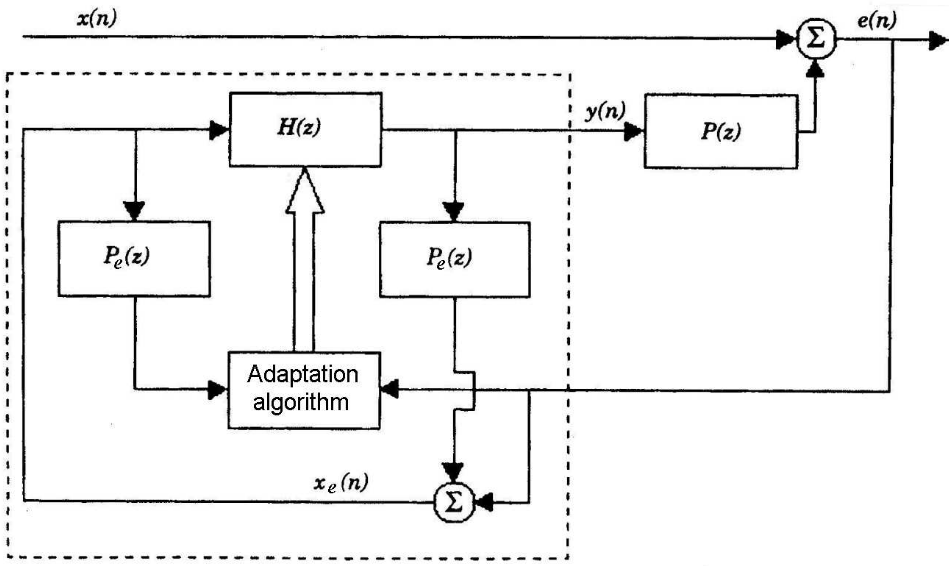

Fig. 9. The block diagram of the active noise control system with the controller and built-in reference model.

LMS algorithm, usually customized, is the most commonly used algorithm for the controllers. This algorithm has been also used for the controllers developed in CIOP-PIB, which assumed as a rule that the role of a controller is performed by the customized software incorporating a specified algorithm.

The block diagrams of several active noise control system versions, developed in CIOP-PIB, with different algorithm and controller versions. Since the error signal for

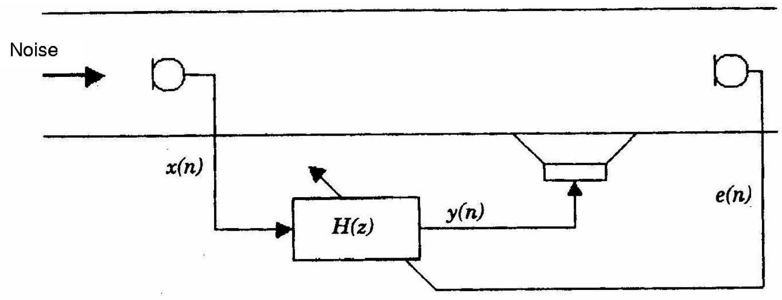

Fig. 10. The block diagram of the active noise control system in the waveguide.

waveguide active noise control systems is not directly available, as assumed in classical LMS algorithm, but is filtered by the acoustic transmittance (transfer function) of the error path, Fig. 11 presents practical solution for transformation of an adaptative LMS filter, which relies on filtering of its input signal by the transmittance $H_w(z)$.

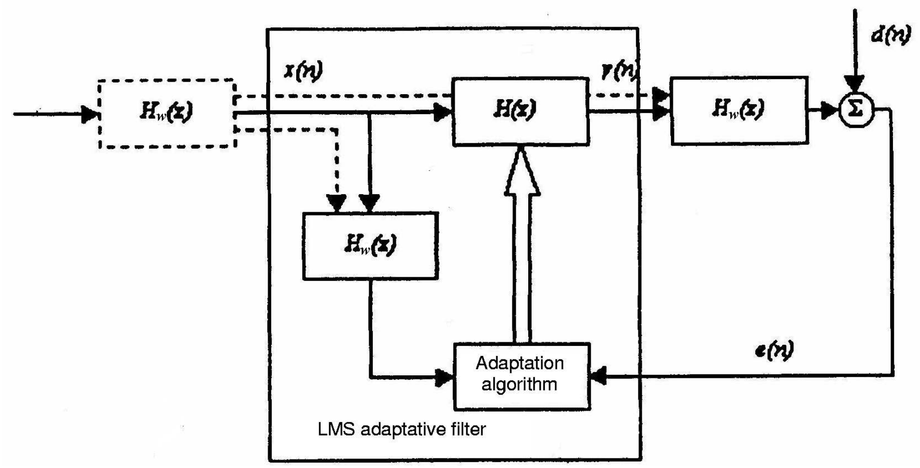

Fig. 11. The block diagram of LMS algorithm with filtered input.

For active noise control systems, which account for the secondary signal path, the effect of this path may be partially eliminated by embedding, within the error signal path, the filter of transmittance being an inversion of the signal path's transmittance. The block diagram of such a system is presented in Fig. 12.

Quite different principle of operation is featured by active noise control systems with reference signal circuits. These systems, also called notch filter systems, are best suited for tonal noise control. However, these systems, by connecting in parallel relevant number of filters, may also be adopted to control the noise incorporating several frequencies (base frequency and their harmonic components). The example structure with two notch filters, tuned to n-th harmonic component, is presented in Fig. 13.

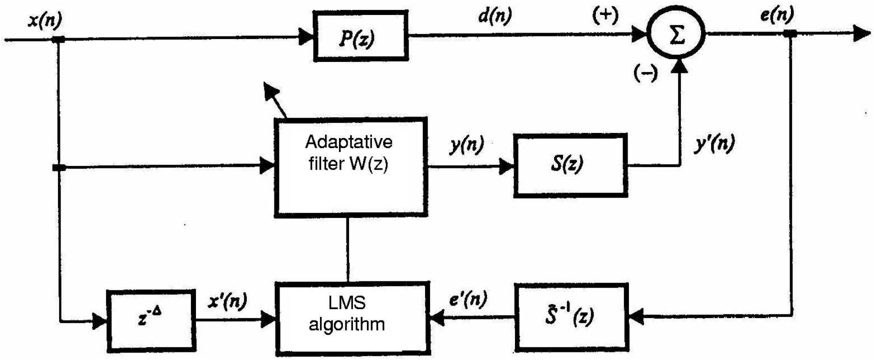

Fig. 12. The block diagram of the active noise control system incorporating the controller, which eliminates the secondary signal path effect.

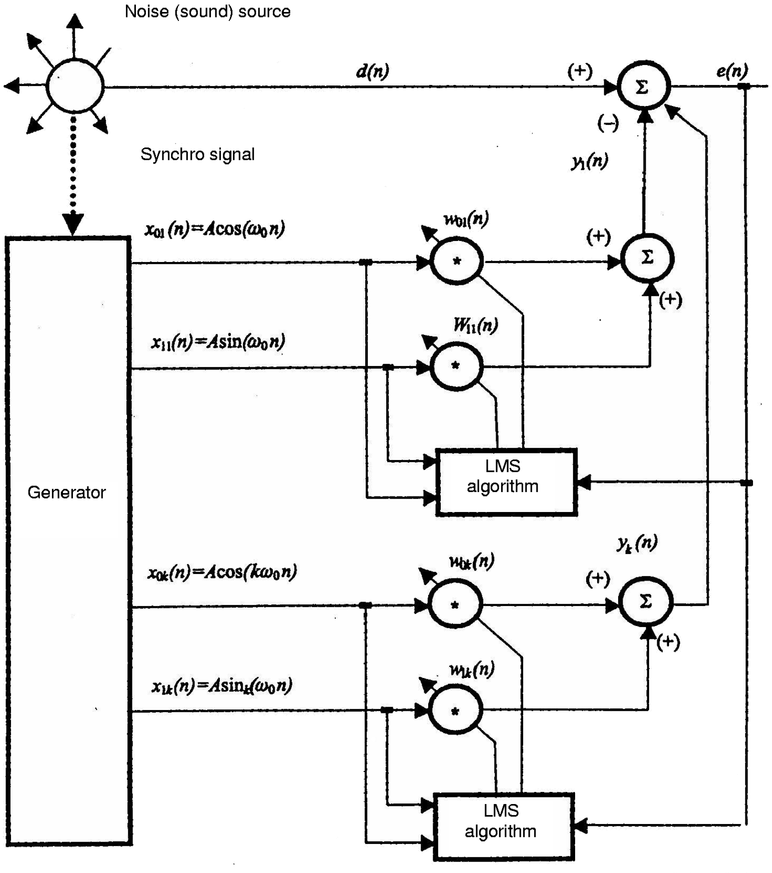

Fig. 13. Active noise control systems with two notch parallel filters.

Only some controllers and control algorithms has been described as above. Most of results and developed solutions has been presented without delay at an international and national scientific conferences, and published in scientific magazines and books. Note also some works related to the optimization of active noise control systems and the stability studies.

5. Active ventilation noise control system

Based on results of the research using acoustic waveguide performed in 1993–1995, the adaptative noise control system for low-frequency noise, generated by the ventilation systems, has been developed and built. This system has been used to eliminate the noise generated by real ventilation fan.

The system's block diagram is presented in Fig. 14.

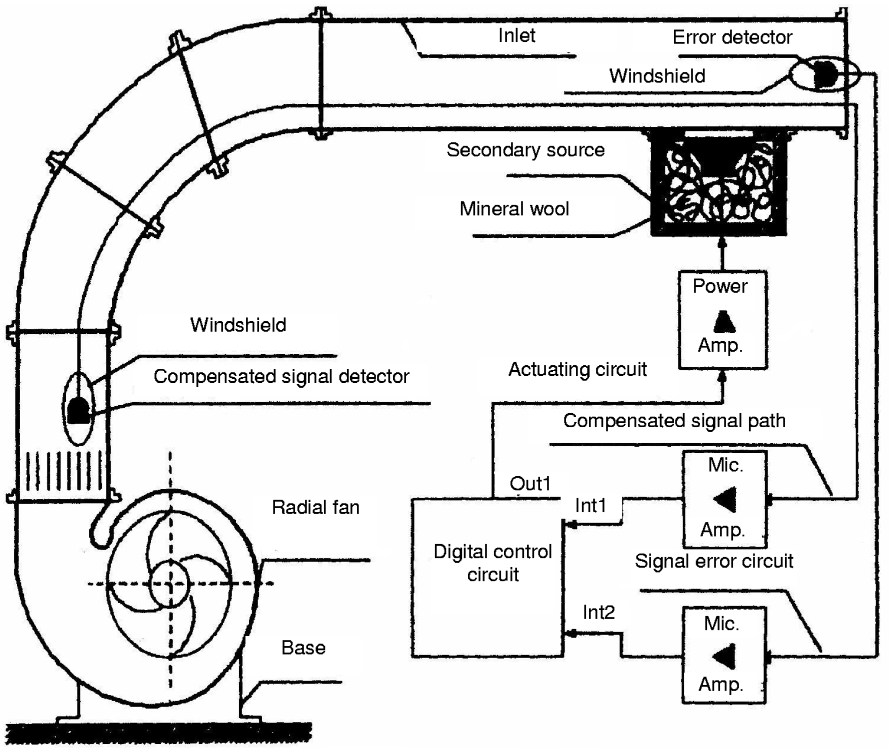

Fig. 14. The block diagram of active noise control system for the ventilation channel, developed and installed in CIOP-PIB.

Proper adaptative algorithm's parameter selection resulted in predominant harmonic elimination by over 20 dB.

6. Active noise control systems for ear protectors

The Central Institute for Labour Protection – National Research Institute (Centralny Instytut Ochrony Pracy – Państwowy Instytut Badawczy CIOP-PIB) and the Automatic Control Institute of Silesian University of Technology (Instytut Automatyki Politechniki Śląskiej) conducted several research works related to active noise control system application for the ear protectors.

As an example, the model ear protector will be described shortly.

The ear protector with active noise control system has been developed and built by the Active Noise Control Unit of CIOP-PIB; the diagram is presented in Fig. 15. The control circuit features surface mounting technology, and that is why this circuit could be placed inside the protector's bowl (each bowl features separate control circuit). The belt or pocket battery pack supplies the power to the control circuit via single cable. The ear protector features the following technical parameters:

Active noise control's frequency range – 20÷500 Hz;

Active noise control level – to 10 dB;

Power supply – 9.6 VDC;

Battery operating duration (minimum) – 8 h;

Weight (incl. cable).

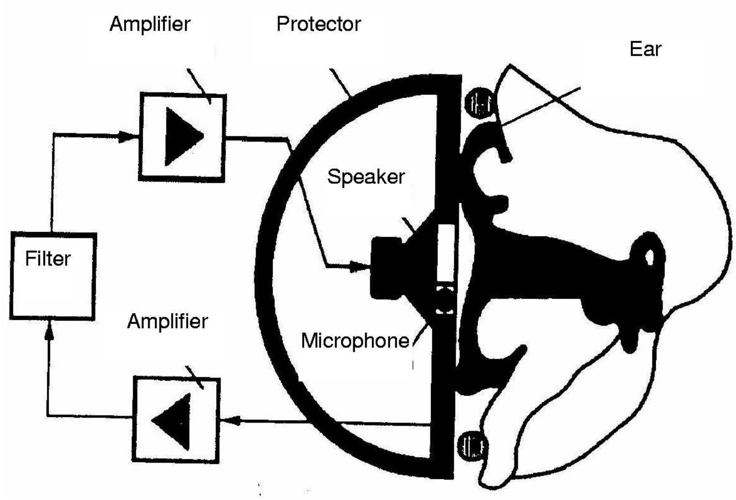

Fig. 15. The diagram of the ear protector with active noise control system.

Figure 16 presents the AOS-2 ear protector developed by CIOP-PIB.

Figure 17 presents the results of active noise control measurement for this ear protector. Active noise attenuation has been defined as a difference of acoustic pressure under a protector's bowl for active noise control system turned ON/OFF.

Above diagram shows that application of active noise control system allowed to improve the passive protector's attenuation by 9 dB within 20÷500 Hz frequency range.

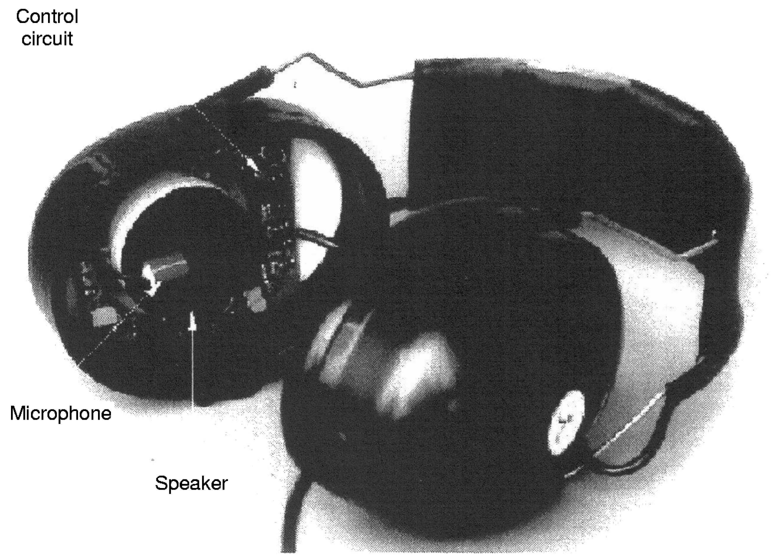

Fig. 16. The AOS-2 ear protector with active noise control system developed by CIOP-PIB.

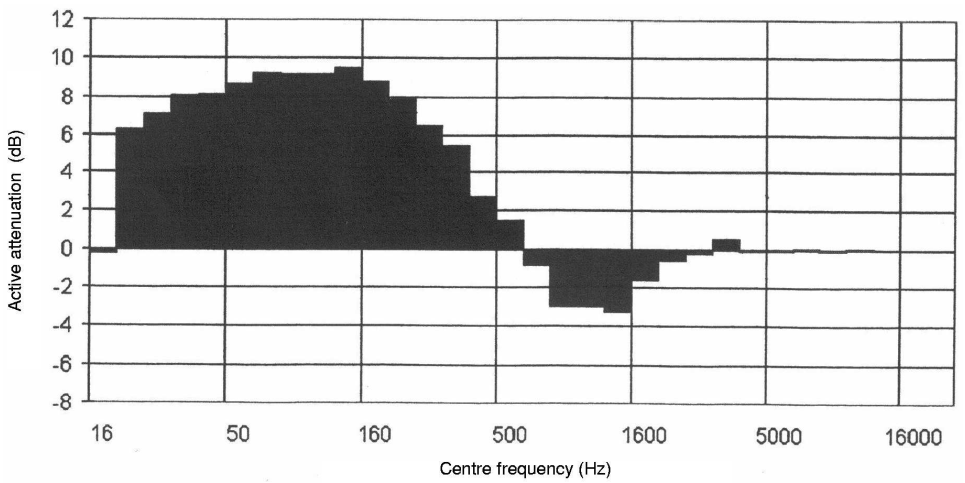

Fig. 17. Active noise attenuation for AOS-2 protector.

7. Active noise control for power transformers

Apart from research and technical works referred to above, several other research works related to active noise control have been conducted in Polish R&D centers. For example, interesting research related to power transformer noise elimination has been conducted by CIOP-PIB. For power transformers, casing panels are basic noise source; these panels generate the vibratory-acoustic energy to an ambient environment.

Radiation of this energy to an ambient environment has been analyzed theoretically, and several experiments have been conducted using intensity and correlation methods. Experiment results have been used to design and to build the system whose operation has been verified in real environment. We can assume, without reviewing detailed analysis of vibratory-acoustic disturbance sources for power transformers that the noise generated by them has predominant frequency components, and the spectrum is almost constant over time (Fig. 18).

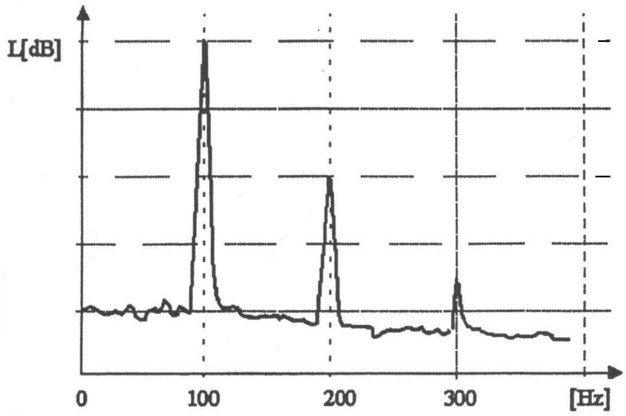

Fig. 18. Course of an acoustic pressure level L vs. frequency for typical power transformer operating at 50 Hz.

The system, presented in Figs. 19 and 20, has been used to compensate the noise generated by selected power transformer.

Application of active noise control systems enables to reduce the noise related to doubling of power line standard frequency to the background noise, and the sound level to 25 dB.

Specific conditions and limitations imply that the piezoelectric elements, apart from speakers, are more frequently used as actuators for active noise control systems. Piezoelectric elements are directly mounted on the transformer's housing or placed in specially designed casings. The former solution actively reduces the transformer's housing vibration amplitude. Such an approach enables reduction of total acoustic energy emitted by the transformer to an ambient environment. In the latter solution, the piezoelectric elements act as typical casing combined with the resonant circuit tuned to predominant noise frequencies generated by the transformer. This element features high efficiency (operating in resonance condition), which enables continuous operation and high noise reduction. Additional advantage is compact size and low weight as compared with the speaker casing, which is very important as the piezoelectric elements may be freely located and mounted in locations normally inaccessible for speaker casings.

Recently performed CIOP-PIB research have been related to the neural network application for active noise system control purposes.

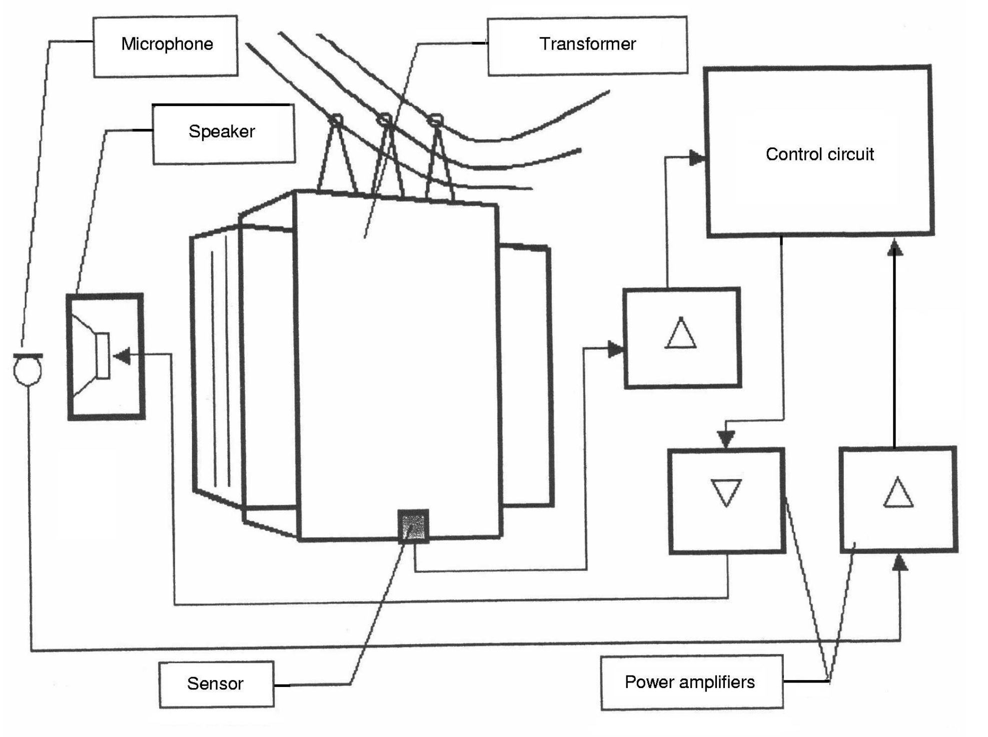

Fig. 19. The active noise control system for the power transformer.

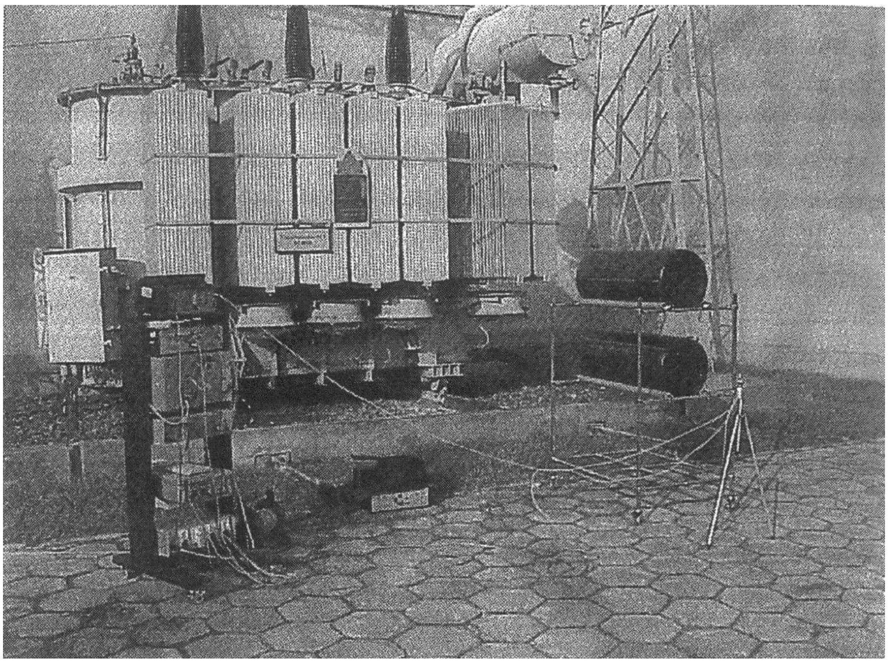

Fig. 20. The power transformer with the active noise control system implemented.

Figure 21 presents a diagram of active noise control system based on the neural network. The doctor's thesis, concerning this issue, has been performed in the CIOP-PIB.

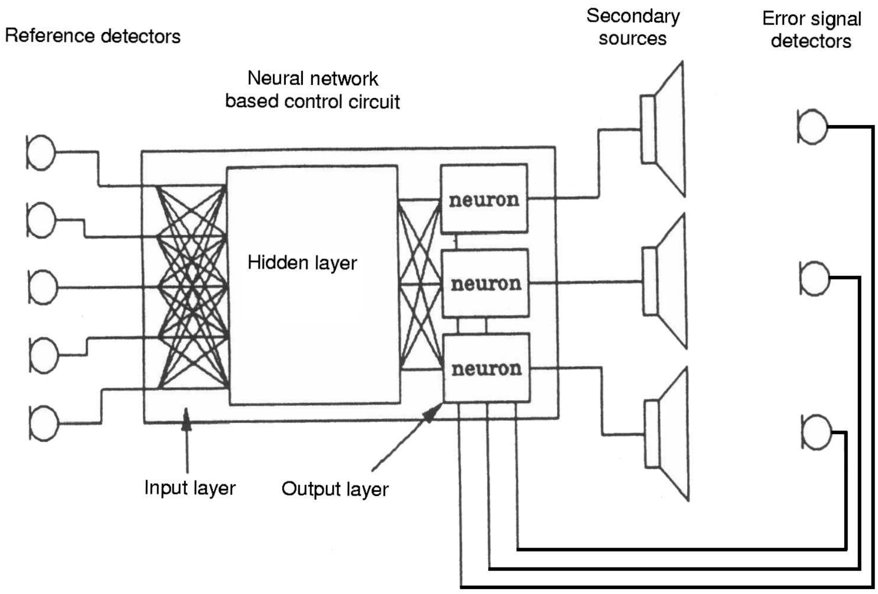

Fig. 21. The multi-channel active noise control system based on the neural network.

8. Conclusions

Active noise control methods are currently developed in Poland in several scientific centers. These issues have been shortly discussed in this paper. Polish scientists greatly contributed to development of active noise control methods, which is proved by multiple publications, doctor's theses and post-PhD dissertations. The seminars and scientific courses of "Active noise control methods" are organized; up to date, five events have been held.

Initial applications of active noise control methods have proved their effectiveness in extent of low-frequency noise reduction. The methods are effective up to 250 Hz. Further research and technical applications improved an effectiveness of active noise control methods for frequency ranges over 250 Hz. Further research should be conducted to cover the frequency range beyond 1000 Hz. The works fulfilled up to date have revealed that extent of current practical applications is very broad, and the future application capabilities are almost unlimited. Unfortunately, the active noise control applications are very expensive despite the cost reduction. Therefore, active noise control methods must be simultaneously cover two important directions: enhancing the application range and reducing the active method costs.

In particular, very broad range of applications becomes probably available due to greater application of the neural networks and the genetic algorithms for active noise control. Currently conducted research demonstrate that the neural networks, in many potential applications, enable achieving much more higher noise control effectiveness than the adaptative digital filter based controllers. It can be assumed that dynamic technology and science development in extent of noise control brings even greater opportunities. Undoubtedly, Polish scientists will use them.

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References

[1] BISMOR D., *Adaptive algorithms for active noise control in an acoustic duct*, Jacek Skalmierski Computer Studio, Gliwice 1999.

[2] BISMOR D., *Porównanie kilku algorytmów tłumienia hałasu w falowodzie akustycznym*, Materiały Otwartego Seminarium z Akustyki OSA'98, pp. 101–106, Poznań–Kiekrz 1998.

[3] BISMOR D., *Zastosowanie technik sterowania adaptacyjnego do aktywnego tłumienia hałasu*, Materiały XXIV Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, s. 25–29, 1996.

[4] BISMOR D., *Zastosowanie technik sterowania adaptacyjnego do aktywnego tłumienia hałasu*, Materiały XXIV Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, Gliwice–Ustroń, 26.02–2.03.1996.

[5] BISMOR D., *Active noise control for an acoustic duct*, Proceedings of the Third International Symposium on Methods and Models in Automation and Robotics. Invited Session, Międzyzdroje, 10–13 September, 1996.

[6] BISMOR D., *Aktywne tłumienie hałasu w dukcie akustycznym*, 19th Seminar on Fundamentals of Electrotechnics and Circuit Theory, Gliwice–Ustroń, 15–18.05.1996.

[7] BISMOR D., *Różnice pomiędzy obiektami automatyki przemysłowej a obiektami akustycznymi w świetle doświadczeń identyfikacyjnych*, Materiały XXV Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, Gliwice–Ustroń, 24.02–1.03.1997.

[8] BISMOR D., *Proving linearity of an acoustic duct*, Proceedings of the Fourth International Symposium on Methods and Models in Automation and Robotics, Międzyzdroje, 26–29 August, 1997.

[9] BISMOR D., *Comparing different structures and algorithms in application to active noise control in an acoustic duct*, The International Workshop on Acoustic Echo and Noise Control, London, 11–12.09.1997.

[10] BISMOR D., *Badania symulacyjne układu adaptacyjnego aktywnego tłumienia hałasu w falowodzie akustycznym*, Materiały XXVI Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, Gliwice–Ustroń, 23–28.02.1998.

[11] BŁAŻEJ M., OGONOWSKI Z., *Adaptacyjne algorytmy aktywnego tłumienia hałasu dla przestrzennych stref ciszy*, Materiały V Szkoły „Metody Aktywne Redukcji Drgań i Hałasu", s. 43–48, Kraków–Krynica 1997.

[12] CZARNECKI S., *Investigations of sound transmission properties of a medium resulting from sound wale compensation caused by other sources*, JoS.V., 11, 225–233 (1970).

[13] CZARNECKI S., VOGT M., GLIŃSKI E., *Optima conditions of cancellation of acoustic waves by using acoustic resonators*, Proc. 8 ICA, Vol. 1, p. 47, London 1974.

[14] CZARNECKI S., VOGT M., *Ażurowe ekrany rezonansowe działające na zasadzie kompensacji fal akustycznych*, Archiwum Akustyki, **5**, 4, 437–459 (1970).

[15] CIESIELKA W., GOŁAŚ A., *An adaptive active noise reduction system in closed space*, Proc. ACTIVE 99, Fort Landerdale, pp. 683–694, 1999..

[16] CIESIELKA W., GOŁAŚ A., *Aktywne tłumienie hałasu przy pomocy cyfrowego korektora fazowego*, Materiały III Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 47–52, 1997.

[17] CIESIELKA W., *Sterowanie dźwiękami przy pomocy cyfrowego korektora fazowego*, Materiały XXV Szkoły zwalczania zagrożeń wibroakustycznych, s. 53–57, Ustroń 1997.

[18] CIESIELKA W., *Aktywne sterowanie dźwięku – systemy jednokanałowe*, Materiały V Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 49–56, Krynica 2001.

[19] ENGEL Z., *Nowe metody zwalczania hałasu i wibracji*, Praca CIOP, z. 144, s. 3–8 (1990).

[20] ENGEL Z., *Rozwój aktywnych metod zwalczania hałasu (rys historyczny, zadania, problemy)*. Materiały I Szkoły Metod Aktywnych, Rabka 1993.

[21] ENGEL Z., *Rozwój metod aktywnych w Polsce*, Materiały III Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 53–58, 1997.

[22] ENGEL Z., *Aktywne sterowanie dźwiękiem i drganiami. Uwagi do terminologii*, Materiały II Szkoły Metody Aktywne Redukcji Drgań i Hałasu, 1997, s. 193–198.

[23] ENGEL Z., *Rozwój aktywnych metod zwalczania hałasu*, Kwartalnik AGH Mechanika, **12**, 1, 9–28 (1993).

[24] ENGEL Z., *Aktywna redukcja drgań i hałasu*, Materiały XI Sympozjum Drgania w układach fizycznych, Poznań 1984, s. 124–125.

[25] ENGEL Z., KOWAL Z., *Sterowanie procesami wibroakustycznymi*, Wyd. AGH, Kraków 1995.

[26] ENGEL Z., MAKAREWICZ G., MORZYŃSKI L., ZAWIESKA W.M., *Metody aktywne redukcji hałasu*, Wyd. CIOP, Warszawa 2001.

[27] ENGEL Z., MAKAREWICZ G., ZAWIESKA W.M., *Metody aktywne redukcji hałasu w monografii Wibroakustyka maszyn i środowiska*, Podstawowe Problemy Współczesnej Techniki, Wiedza i Życie, Warszawa 1995.

[28] ENGEL Z., NIZIOŁ J., *Perspektywy rozwoju aktywnych metod redukcji hałasu i wibracji*, Materiały II Szkoły Metody Aktywne Redukcji Drgań i Hałasu, 1995, s. 11–24.

[29] ENGEL Z., KOWAL Z., *Praktyczne zastosowanie metod aktywnych*, Materiały I Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 131–150, Rabka 1993.

[30] ENGEL Z., *Metody aktywne w akustyce. Marzenia czy rzeczywistość*, Materiały XLII OSA, Białowieża 1995, s. 25–36.

[31] ENGEL Z., *Metody aktywne czy pasywne w redukcji drgań i hałasu*, Zeszyty Naukowe Politechniki Rzeszowskiej Nr 151, Mechanika, z. 48, 53–67 (1996).

[32] ENGEL Z., *Prędkość objętościowa w aktywnych metodach redukcji hałasu*, Materiały IV Szkoły Metody Aktywne Redukcji Drgań i Hałasu, Krynica 1999, s. 41–46.

[33] FALKIEWICZ J., OKOŃSKI M.A., KUSTRA G., *Adaptive ANC system with nonlinear secondary path based on recurrent neural network*, Mechanika, **22**, 3, 263–270 (2003).

[34] FIGWER J., BŁAŻEJ M., *A new look at adaptation in active noise control systems*, Proc. of 6^{th} Conference on Active Noise and Vibration Control Methods, Kraków 2003.

[35] FIGWER J., OGONOWSKI Z., PAWEŁCZYK M., *Stanowiska laboratoryjne do badań algorytmów aktywnego tłumienia hałasu*, Materiały XLIX Otwartego Seminarium z Akustyki, s. 169–174, Stare Jabłonki 9–13.09 2002 r.

[36] FIGWER J., NIEDERLIŃSKI A., *Using the DFT to synthesize multivariate orthogonal white noise series*, Transactions of the Society for Computer Simulation, September 1995, **12**, 3, 261–285 (1995).

[37] FIGWER J., *A new method of multivariate orthogonal random process synthesis*, Poster Book of EUROSIM Simulation Congress EUROSIM'95, ARGESIM Report No. 3, Vienna, p. 89, 1995.

[38] FIGWER J., *Power spectral density defined time-series generation*, XVIII Seminarium SPETO'95, vol. 2, p. 389, 1995.

[39] FIGWER J., *Multisine excitation for process identification*, Archives of Control Sciences, **5** (XLI), 3–4, 279–295 (1996).

[40] FIGWER J., *Random noise synthesis and generation*, Proceedings of the Third International Symposium on Methods and Models in Automation and Robotics, 10–13 September 1996, Międzyzdroje, Poland, Vol. 1, pp. 83–88, 1996.

[41] FIGWER J., OGONOWSKI Z., *Metoda lokowania w aktywnym tłumieniu hałasu*, Materiały XLIII Otwartego Seminarium z Akustyki OSA'96, Gliwice–Ustroń 16–20.09.1996, Vol. 1, pp. 211–216.

[42] FIGWER J., OGONOWSKI Z., *Dobór transmitancji zakłóceniowej w metodzie lokowania zer i biegunów dla aktywnego tłumienia hałasu*, Materiały XLIV Otwartego Seminarium z Akustyki OSA'97, Gdańsk 15–18-09.1997, Vol. 1, pp. 265–270.

[43] FIGWER J., *A new method of random time-series simulation*, Simulation Practice and Theory, **5**, 3, 217–234 (1997).

[44] FIGWER J., *Continuous-time cystem identification with multisine excitation*, Proc. 4th International Symposium Methods and Models in Automation and Robotics, Vol. 1, 1997.

[45] FIGWER J., *Multisine approximation of multivariate orthogonal random processes*, Złożone w IEEE Trans. Signal Processing, paper No. SP9953, 1997.

[46] FIGWER J., *Multidimensional random process synthesis and simulation*, Złożone do druku w Multidimensional Systems and Signal Processing.

[47] FIGWER J., *Two-input system identification using bivariate multisine excitation*, Proceedings of the Fifth International Symposium on Methods and Models in Automation and Robotics, 25–29 August 1998, Międzyzdroje, Poland, Vol. 2, pp. 571–576, 1998.

[48] FIGWER J., NIEDERLIŃSKI A., *On the generation of high-quality white noise series*, Applied Stochastic Models and Data Analysis, **8**, 311–326 (1992).

[49] GOŁAŚ A., CIESIELKA W., *Układ adaptacyjny do aktywnego tłumienia hałasu w przestrzeni zamkniętej*, Materiały XLIV Otwartego Seminarium z Akustyki, Jastrzębia Góra, 1997, s. 299–304.

[50] GOŁAŚ A., MELCHAREK P., OLSZEWSKI R., *Aktywna redukcja hałasu – analiza pola akustycznego z zastosowaniem metody elementów skończonych i brzegowych*, Materiały III Szkoły Metody Aktywne Redukcji Drgań i Hałasu, 1997, s. 73–76.

[51] GOŁAŚ A., CIESIELKA W., *Układ aktywny redukcji hałasu w przestrzeni zamkniętej*, Materiały IV Szkoły Metody Aktywne Redukcji Drgań i Hałasu, Krynica 1999, s. 59–64.

[52] GÓRSKI P., MORZYŃSKI L., *Aktywny ochronnik słuchu z zewnętrznym układem zasilania*, Bezpieczeństwo Pracy, 3, 10–12 (2001).

[53] GÓRSKI P., ZAWIESKA W.M., *System aktywnej redukcji dla hałasów o przebiegu okresowym*, Materiały XLIX Otwartego Seminarium z Akustyki, Stare Jabłonki 9–13.09.2002, s. 121–126.

[54] KASPRZYK J., *Model structure determination in parametric model identification*, System Science, **23**, 2 (1997).

[55] KASPRZYK J., *On some aspects of AR and ARX model identification*, Proc. 4th International Symposium Methods and Models in Automation and Robotics, Vol. 1.

[56] LESZNOWSKA L., *Analiza teoretyczna aktywnego tłumienia pola akustycznego drgającej płyty kołowej z uwzględnieniem oddziaływań ośrodka*, Materiały IV Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 155–162, Krynica 1999.

[57] MAKAREWICZ G., *Problemy stabilności w układach aktywnej redukcji dźwięku*, Rozprawa Doktorska, AGH, Kraków 1993.

[58] MAKAREWICZ G., *Wybrane cyfrowe systemy aktywnej redukcji hałasu*, Centralny Instytut Ochrony Pracy – Państwowy Instytut Badawczy, Warszawa 2002.

[59] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., NARKIEWICZ-JODKO J., *Zastosowanie cyfrowego przetwarzania sygnałów w układach redukcji hałasu metodami aktywnymi*, Materiały XI Konferencji Zastosowanie Mikroprocesorów w Automatyce i Pomiarach, s. 191–196, Warszawa 1998.

[60] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *Aktywne metody redukcji hałasu*, rozdział monografii „Ochrona przed hałasem i drganiami w środowisku pracy", D. Augustyńska, W.M. Zawieska [Red.], s. 85–99, CIOP, 1999.

[61] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *An adaptive system for active noise reduction,*, International Journal of Occupational Safety and Ergonomics, Special Issue, pp. 10–12 (2000).

[62] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *Metody redukcji hałasu transformatorów energetycznych*, Bezpieczeństwo Pracy, **12**, 2–6 (1999).

[63] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *Stanowisko do badań nad aktywną redukcją hałasu w systemach wentylacyjnych*, Materiały XLVI Otwartego Seminarium z Akustyki OSA'99, Zakopane, s. 503–508, 1999.

[64] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *Stanowisko do badań układów aktywnej redukcji hałasu w falowodach akustycznych – badania*, Materiały IV Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 171–176, Krynica 1999.

[65] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *Stanowisko do badań układów aktywnej redukcji hałasu w falowodach akustycznych – opis*, Materiały IV Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 177–180, Krynica 1999.

[66] MAKAREWICZ G., MATUSZEWSKI G., MORZYŃSKI L., ZAWIESKA W.M., *Transformator energetyczny jako źródło hałasu niskoczęstotliwościowego*, Materiały XXVIII Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, s. 229–234, Wisła 2000.

[67] MAKAREWICZ G., ZAWIESKA W.M., MORZYŃSKI L., *Zastosowanie programowania obiektowego do symulacji systemów aktywnej redukcji hałasu*, Materiały V Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 195–202, Krynica 2001.

[68] MAKAREWICZ G., ZAWIESKA W.M., *Aktywne tłumienie hałasu układu wentylacyjnego*, Materiały II Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 81–85, Zakopane 1995.

[69] MAKAREWICZ G., ZAWIESKA W.M., *Aktywne metody redukcji drgań w falowodach*, Prace CIOP, z. 140, s. 27–42, Warszawa 1989.

[70] MORZYŃSKI L., *Active noise control system based on neural network*, Proc. of ACTIVE 2002, pp. 729–738, Southampton, United Kingdom, July 15–17, 2002.

[71] MORZYŃSKI L., *Metody aktywne redukcji hałasu*, Serwis BHP, **10**, 5–9 (2000).

[72] MORZYŃSKI L., *Redukcja hałasu w falowodzie akustycznym z zastosowaniem adaptacyjnych sterowników cyfrowych*, Bezpieczeństwo Pracy, **4**, 12–17 (1998).

[73] MORZYŃSKI L., *The use of neural network for active noise control in a duct*, Mechanika, **22**, 3, 361–366 (2003).

[74] MORZYŃSKI L., *Neuronowe układy adaptacyjne w aktywnej kompensacji dźwięku*, Rozprawa Doktorska, CIOP, Warszawa 2003.

[75] MORZYŃSKI L., MAKAREWICZ G., *Aktywna redukcja hałasu w falowodzie akustycznym z zastosowaniem sztucznych sieci neuronowych*, Materiały XLIX Otwartego Seminarium z Akustyki, s. 127–132, Stare Jabłonki, 9–13.09.2002.

[76] MORZYŃSKI L., MAKAREWICZ G., *System aktywnej redukcji hałasu z zastosowaniem sieci neuronowych*, Materiały V Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 219–224, Krynica 2001.

[77] MORZYŃSKI L., GÓRSKI P., *Aktywny ochronnik słuchu z zewnętrznym układem zasilania i baza danych umożliwiająca jego dobór*, Materiały XXIX Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, s. 43–51, Wisła 2001.

[78] MORZYŃSKI L., MATUSZEWSKI G., *Measurements of the effectiveness of the noise reduction of hearing protectors with active sound attenuation*, Proc. Noise-Control'98, pp. 515–518, Krynica 1998.

[79] MOŚCIŃSKI J., *Convergence of direct self-tuning control algorithms in active noise reduction systems*, Proceedings of the Third International Symposium on Methods and Models in Automation and Robotics, Vol. 1, pp. 77–82, 10–13 September 1996, Międzyzdroje, Poland 1996.

[80] NARKIEWICZ-JODKO J., *A sound duct for measurements of secondary sources characteristics and investigation of active sound control systems*, Proc. Noise Control'95, pp. 441–450, 1995.

[81] NIEDERLIŃSKI A., *Systemy cyfrowe automatyki przemysłowej*, WNT, Warszawa 1977.

[82] NIEDERLIŃSKI A., MOŚCIŃSKI J., OGONOWSKI Z., *Regulacja adaptacyjna*, Wydawnictwo Naukowe PWN, Warszawa 1995.

[83] NIEDERLIŃSKI A., *A new look at least-squares dynamic system identification*, Int. J. Control, **40**, 3, 467–478 (1984).

[84] NIEDERLIŃSKI A., *Terror convergence rate for multiple-recursion RLS estimation in linear multistep prediction models*, Archives of Control Sciences, **40**, 3/4, 173–201 (1995).

[85] NIEDERLIŃSKI A., FIGWER J., *Using the DFT to synthesize bivariate orthogonal white noise series*, IEEE Transactions on Signal Processing, **43**, 3, 749–758 (1995).

[86] NIEDERLIŃSKI A., *An upper bund for the recursive least squares estimation terror*, IEEE Transactions on Automatic Control, **40**, 9, 1655–1661 (1995).

[87] NIEDERLIŃSKI A., *Some aspects of recursive least squares and self-tuning*, Proceedings of the Second International Symposium on Methods and Models in Automation and Robotics MMAR'95, Międzyzdroje, Vol. 1, pp. 1–18, Wydawnictwo Uczelniane Politechniki Szczecińskiej, Szczecin 1995.

[88] NIEDERLIŃSKI A., KASPRZYK J., PAWEŁCZYK M., *λ-monitoring for RLS structure identification of MIMO ARX plants*, Proceedings of the Second International Symposium on Methods and Models in Automation and Robotics MMAR'95, Vol. 1, p. 285–290, Międzyzdroje, Wydawnictwo Uczelniane Politechniki Szczecińskiej, Szczecin 1995.

[89] NIEDERLIŃSKI A., KASPRZYK J., FIGWER J., *Inteligentna identyfikacja dynamicznych modeli matematycznych typu ARX-drzewo decyzyjne lub system ekspertowy? Problemy sztucznej inteligencji*, W. Traczyk [Ed.], Wiedza i Życie, s. 157–172, Warszawa 1995.

[90] NIEDERLIŃSKI A., *Convergence rate for RLS-based direct self-tuning minimum-variance control of ARMAX plants*, Proceedings of the Third International Symposium on Methods and Models in Automation and Robotics MMAR'96, Międzyzdroje, Vol. 1, pp. 63–68, Wydawnictwo Uczelniane Politechniki Szczecińskiej, Szczecin 1996.

[91] NIEDERLIŃSKI A., KASPRZYK J., FIGWER J., MULTI-EDIP – *Analizator wielowymiarowych sygnałów i obiektów*, Wydawnictwo Politechniki Śląskiej, s. 1–465, Gliwice 1997.

[92] NIEDERLIŃSKI A., *A new approach to the convergence analysis of RLS-based self-tuning stochastic control*, Appl. Math. and Comp. Sci., **7**, 1, 27–40 (1997).

[93] NIEDERLIŃSKI A., *A bounding approach to convergence analysis of RLS-based self-tuning stochastic control*, Dycomans Workshop IV – Control and Management in Computer Integrated Systems, pp. 35–39, 25–28 September 1997, Zakopane, Preprints.

[94] NIEDERLIŃSKI A., *Convergence rate for RLS-based direct self-tuning minimum ariance regulation for ARMAX minimum phase plants*, IEEE Transactions on Automatic Control, **42**, 7, 1023–1028 (1997).

[95] NIEDERLIŃSKI A., MOŚCIŃSKI J., OGONOWSKI Z., *Gain-only-adaptive PI and PID control*, Fifth International Symposium on "Methods and Models in Automation and Robotics", Vol. 2, p. 449–454, 25th–29th August 1998, Międzyzdroje, Preprints, Poland 1998.

[96] NIEDERLIŃSKI A., *A new approach to convergence analysis of RLS-based self-tuning stochastic control*, Modelling, Identification and Control, IASTED-ACTA PRESS, Anaheim 1997.

[97] NIEDERLIŃSKI A., MOŚCIŃSKI J., OGONOWSKI Z., *Limited authority adaptive PI control*, IFAC Workshop "Adaptive Systems in Control and Signal Processing", p. 315–320, 26th–28th August 1998, University of Strathclyde, Preprints, Glasgow 1998.

[98] OGONOWSKI Z., *Direct adaptation in predictive control*, Proceedings of the Fourth International Symposium on Methods and Models in Automation and Robotics, Vol. II, p. 471–476, 26–29 August 1997, Międzyzdroje 1997.

[99] OGONOWSKI Z., *Non-linear predictive control*, Proceedings of the Sixteenth IASTED International Conference "Modelling, Identification and Control", p. 305–308, Innsbruck, Austria, 17–19 February, 1997.

[100] OGONOWSKI Z., *Application of artificial neural networks in assessment of sulfuric acid plant states*, Proceedings of the Fourth International Symposium on Methods and Models in Automation and Robotics, Vol. II, p. 797–802, 26–29 August, Międzyzdroje 1997.

[101] OGONOWSKI Z., *Robust pole placement using predictive control*, Prep. of the 4th DYCOMANS Workshop on Control and anagement in computer integrated systems, p. 105–110, Zakopane, Poland 1997.

[102] OGONOWSKI Z., *Niekonwencjonalne algorytmy sterowania. Potencjalne możliwości i ograniczenia praktyczne*, Materiały 7 Seminarium nt. Doświadczenia i perspektywy modernizacji kotłów energetycznych dla obniżenia emisji Nox – technologie, automatyka procesu spalania, s. 159–164, Szczyrk 1997.

[103] OGONOWSKI Z., *Influence of the observer polynomial on pole placement control properties*, Proc. of the 3rd Scientific – Technical Conference, Process Control'98, p. 291–294, Kouty nad Desnou, Czech Republic 1998.

[104] OGONOWSKI Z., *Pole placement using predictive convolution control*, Proc. of the 3rd Portuguese Conference on Automatic Control, Controlo'98, p. 75–80, Coimbara, Portugal 1998.

[105] OGONOWSKI Z., *Adaptation in convolution predictive control*, Proc. of an IFAC Workshop on Adaptive Systems in Control and Signal Processing, p. 261–266, Glasgow, Scotland 1998.

[106] OGONOWSKI Z., *Badania aktywnego ochronnika słuchu*, Materiały XXIII Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, s. 72–78, Wisła 1995.

[107] OGONOWSKI Z., *Struktury układów aktywnego tłumienia dla ochronnika słuchu*, Materiały II Szkoły Metody aktywne redukcji drgań i hałasu, s. 111–116, Zakopane 1995.

[108] OGONOWSKI Z., *Predictive control with permanent gain linearization*, 10th Conference on Process Control'95, p. 5–9, Taranske Matliare, Slovakia 1995.

[109] OGONOWSKI Z., *Adaptive zone of quiet in 3-D reverberant enclosures*, Third International Symposium on Methods and Models in Automation and Robotics MMAR'96, p. 95–100, Międzyzdroje, Poland 1996.

[110] OGONOWSKI Z., *Struktury układów aktywnego tłumienia dla ochronnika słuchu*, Materiały II Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 111–116, Kraków–Zakopane 1995.

[111] OGONOWSKI Z., *Aktywne tłumienie hałasu z wykorzystaniem metod bezpośrednich*, Materiały XXII Szkoły Zwalczania Zagrożeń Wibroakustycznych, Wisła 1994.

[112] OGONOWSKI Z., *Badanie aktywnego ochronnika słuchu*, Materiały XXIII Szkoły Zwalczania Zagrożeń Wibroakustycznych, Wisła 1995.

[113] OGONOWSKI Z., *Aktywne tłumienie zakłóceń okresowych z wykorzystaniem wielomianu generującego*, Materiały IV Szkoły Metody Aktywne Redukcji Drgań i Hałasu, s. 197–204, Krynica 1999.

[114] PAWEŁCZYK M., *Aktywny ochronnik słuchu*, Materiały XXIV Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, str. 161–166, Polskie Towarzystwo Akustyczne – Oddział Górnośląski, Gliwice–Ustroń 1996.

[115] PAWEŁCZYK M., *Adaptive noise cancellation algorithms for Active Ear Defender*, Materiały Seminarium Podstaw Elektrotechniki i Teorii Obwodów, t. 2, str. 261–264, Politechnika Śląska w Gliwicach, Ustroń 1996.

[116] PAWEŁCZYK M., *Noise cancellation in active ear defender – Original modifications of some known adaptive algorithms*, Proceedings of Second World Automation Congress, t. 4, s. 551–556, TSI Press Series, Montpellier, Francja 1996.

[117] PAWEŁCZYK M., *Multirate signal processing for broadband noise cancellation in active ear defender*, Proceedings of the Third International Symposium on Methods and Models in Automation and Robotics, t. 1, s. 11–114, Szczecin Technical University Press, Międzyzdroje 1996.

[118] PAWEŁCZYK M., *Algorytmy kompensacji w aktywnym tłumieniu hałasu*, Materiały XXV Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, s. 161–165, Polskie Towarzystwo Akustyczne – Oddział Górnośląski, Gliwice–Ustroń 1997.

[119] PAWEŁCZYK M., *A New adaptive approach to narrowband noise cancellation*, Proceedings of Fourth International Symposium on Methods and Models in Automation and Robotics, Vol. 2, p. 551–554, Szczecin Technical University Press, Międzyzdroje 1997.

[120] PAWEŁCZYK M., *Feedforward algorithms in active noise control*, [in:] Proaceedings of International Workshop on Acoustic Echo and Noise Control, Vol. 1, p. 65–68, Imperial College of Science, Technology and Medicine, London, UK 1997.

[121] PAWEŁCZYK M., *New Approaches to active noise control – Theory and experimental results*, Proceedings of 5th International Congress on Sound and Vibration, Vol. 1, p. 335–342, The International Institute of Acoustics and Vibration, Adelaide, Australia 1997.

[122] PAWEŁCZYK M., ELLIOTT S.J., RAFAELY B., *Active noise control using feedback. Fixed and adaptive controllers*, Technical Memorandum No. 822, Institute of Sound and Vibration Research, Southampton University, p. 1–68, Southampton, UK 1997.

[123] PAWEŁCZYK M., *Tłumienie i stabilność w układach ze sprzężeniem zwrotnym*, Materiały XXV Zimowej Szkoły Zwalczania Zagrożeń Wibroakustycznych, s. 159–167, Polskie Towarzystwo Akustyczne – Oddział Górnośląski, Gliwice-Ustroń 1998.

[124] PAWEŁCZYK M., *Aktywne tłumienie hałasu w obiektach akustycznych o małych gabarytach*, Materiały Otwartego Seminarium Akustyki – OSA'98, Poznań–Kiekrz 1998.

[125] PAWEŁCZYK M., *Active noise control for compact acoustic plants*, Jacek Skalmierski Computer Studio, Gliwice 1999.

[126] PAWEŁCZYK M., *A double input – quadruple output adaptive controller for the active headrest system*, Mechanika, **22**, 3, 367–374 (2003).

[127] PAWEŁCZYK M., *Analogue active noise control*, Applied Acoustics, **63**, 11, 1193–1213 (2002).

[128] PAWEŁCZYK M., *Analogue-digital control for active headsets*, Proc. of ACTIVE'2002, pp. 1219–1230, Southampton, UK 2002.

[129] PAWEŁCZYK M., *A double input – quadruple output adaptive controller of the active headrest system*, Mechanika, kwartalnik AGH, **23**, 3, 267–274 (2003).

[130] RUTKOWSKI L., *Filtry adaptacyjne i adaptacyjne przetwarzanie sygnałów*, WNT, Warszawa 1994.

[131] RDZANEK W., ENGEL Z., RDZANEK W., Jr., *Kompensacja fazowa ciśnienia akustycznego płaskiej płyty pierścieniowej*, Materiały V Szkoły Metody Aktywnej Redukcji Drgań i Hałasu, s. 249–256, Krynica 2001.

[132] RDZANEK W.J., RDZANEK W.P. Jr., ENGEL Z., *The total sound power radiated by a circular plate with a whole in its center*, Mechanika, kwartalnik AGH, **23**, 3, 395–404 (2003).

[133] RDZANEK W.P., Jr., ZAWIESKA W.M., *Theoretical analysis of the total sound power radiated by a simply supported rectangular plate*, Mechanika, kwartalnik AGH, **23**, 3, 405–410 (2003).

[134] RUBINOWICZ W., *Teoria dyfrakcji Kirchhoffa i jej interpretacja na podstawie poglądów Younga*, Ossolineum, Wrocław 1972.

[135] RUBINOWICZ W., *Die Bengungswelle in der Kirchhoffschen Teorie der Bengung*, Physik, (4), 53, 257–278 (1917).

[136] TYLIKOWSKI A., *Stabilization of beam parametric vibrations*, Mechanika Teoretyczna i Stosowana – Journal of Theoretical and Applied Mechanics, **3**, 656–670 (1993).

[137] VOGT M., *Ogólne warunki kompensacji fazowej sygnałów w polu akustycznym*, Archiwum Akustyki, **11**, 141–157 (1976).

[138] VOGT M., *Correlation analysis of phase cancellation in an acoustic field*, Proc. NOISE CONTROL'76, pp. 403–407, Warszawa 1976.

[139] VOGT M., CZARNECKI S., *Analysis of sound source phase cancellation conditions*, Proc. NOISE CONTROL'76, pp. 409–413, Warszawa 1976.

[140] ZAWIESKA W.M., *Aktywne tłumienie hałasu w falowodach*, Praca CIOP, z. 144, s. 25–43, Warszawa 1990.

[141] ZAWIESKA W.M., *System aktywnego tłumienia hałasu w falowodzie – laboratoryjne stanowisko badawcze*, Materiały XXXVII OSA, 1990.

[142] ZAWIESKA W.M., *Analiza i synteza układu aktywnej redukcji hałasu*, Rozprawa Doktorska, AGH, Kraków 1991.

[143] ZAWIESKA W.M., *Laboratoryjne stanowisko do aktywnej redukcji hałasu w falowodach*, Prace CIOP, z. 144, s. 45–57, Warszawa 1990.