Chapter 2

The use of directional transducers to reduce exposure to noise

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DOI: 10.54215/Noise_Control_2022_A_Digital_Monograph_Makarewicz_G_Morzynski_L_Pleban_D

Abstract
The technological development of sound-emitting and measuring transducers, as well as the increase in the computing power of signal processors, enable the implementation of new methods of reducing noise exposure. They are based on shaping the directivity characteristics of the transducers in such a way that, in the case of actuators, the levels of the produced sound do not exceed the permissible values in places where people are, and in the case of measuring elements, they increase the comfort of work and reduce the noise produced by the employees themselves. The article presents the principles of shaping the directivity characteristics of loudspeakers and microphones in the form of loudspeaker and microphone arrays and describes the principle of operation of a narrowband parametric transducer. The potential danger of exposure to noise generated by parametric matrices is presented. The possibilities of reducing exposure to noise with the use of directional actuating and measuring transducers have been described. The article focuses on noise of a specific nature, as it mainly concerns sounds intentionally generated in the human environment.

Keywords: noise exposure, loudspeaker matrix, line array, parametric loudspeaker, parametric arrays, directional characteristics

1. Introduction

Despite the continuous development of human-friendly technologies, noise is still one of the dominant undesirable physical factors affecting humans. This applies to both the working and living environment. A disturbing trend can be noticed that the nuisance or even harmful factor is more and more often not the noise generated by working equipment or technological processes, but the noise generated by people themselves. Moreover, it is often not noise in the common sense of the word, but acoustic signals carrying a specific information content. It may not be possible to eliminate such signals or at least reduce their sound pressure levels for various reasons such as, for example, their safety relevance.

From the classical point of view, reducing the impact of noise on humans is primarily related to the elimination of the noise source or the separation of the human being from the sound source by means of an obstacle with specific acoustic parameters. This type of approach has been and is still successfully used within the typical relationship between a harmful noise source and man. Unfortunately, such separation from the noise source by means of the so-called collective protection equipment, is often not possible for various reasons. The possible solution is to use, for example, individual noise protection for example hearing protectors equipped with communication systems. In both mentioned cases we are dealing with the so-called passive noise protection methods. After the advent of real-time digital signal processing algorithms, active methods of protection against noise appeared. They consist in the use of an additional sound source generating an acoustic wave to compensate for the noise signal. The second possibility based on digital signal processing, which can be described as improved active methods, concerns the use of emitting and measuring transducers with adjustable directional characteristics. They can be used both to shape the acoustic field in a specific area in order to reduce the exposure to noise of people staying in it and to improve the parameters of active noise reduction systems.

The issues of controlling the direction of wave radiation have their origins in radio technology and research conducted for military purposes, and in these areas they are at a high level [1, 2]. Currently, the technology is mastered to such an extent that it is being successfully used on a large scale in an increasing number of civil solutions. One field of knowledge in which it is more and more commonly used is the control of directivity characteristics of acoustic transducers [3-6]. The development of technology makes it possible to build both sound sources and microphones with variable, controlled directional characteristics [7]. Such a radiated or measured focused and directed sound wave in both sources and microphones is commonly called a beam in the literature [8, 9].

2. Loudspeaker matrix with adjustable directional characteristics

One of the basic parameters of any sound source is its directional characteristics. It is a polar diagram of the directivity index defined as the quotient of the sound pressure in a given direction and the reference sound pressure on the principal axis of the transducer at the same distance from the source. In many cases, it decides that a given source can be used in a specific application. It is then required to find a source with the appropriate directivity characteristics or to apply an appropriate method of adjusting the characteristic. In the case of generating a sound wave, the main problem is the length of the generated acoustic wave and the size of the transducer. One of the first literature reports on the research on beam steering is the article [10], but there were then limitations related to the loudspeaker technology and the possibilities of real-time signal processing. It is worth noting that popular stereo sets also allow to shape the beam to some extent. Such issues were discussed in [11], where musical instruments were adopted as point sources and efforts were made to recreate their directional characteristics. The article [12] uses beam control and tracking of the head movement of the person driving the car in an attempt to make the hands-free system a more private device. The result of the experiment, while proving the thesis, leaves room for many improvements, such as accurate acoustic simulations, thoughtful selection of transducers, accurate measurements, and system calibration.

Loudspeaker arrays can have various geometrical configurations and be constructed from a different number of transducers. The simplest case of a loudspeaker matrix is a set of loudspeakers placed in a line configuration, i.e., elementary point sources placed next to each other along a straight line (Figure 1).

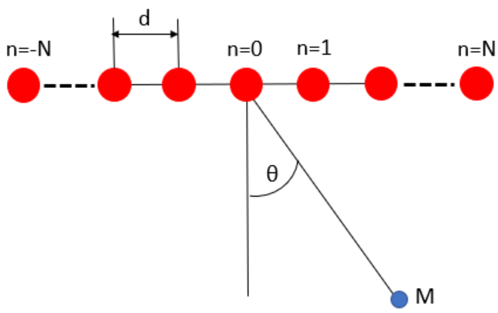

Figure 1. Linear loudspeaker array

The directivity characteristic of the loudspeaker array shown in Figure 1 is determined by the relationship:

$$H(\theta) = \sum_{n=-N}^{N} k_n e^{-jn\omega\tau_0 sin\theta} \tag{1}$$

where:

k_n is the signal gain of the n-th source, τ_0 is the distance between elementary sources divided by the speed of sound.

The linear source allows the directional characteristic to be controlled only in the plane of the source. A very common matrix sound source with controlled directional characteristics is a matrix in the form of a rectangular or square matrix of loudspeakers distributed evenly on a plane (Figure 2a).

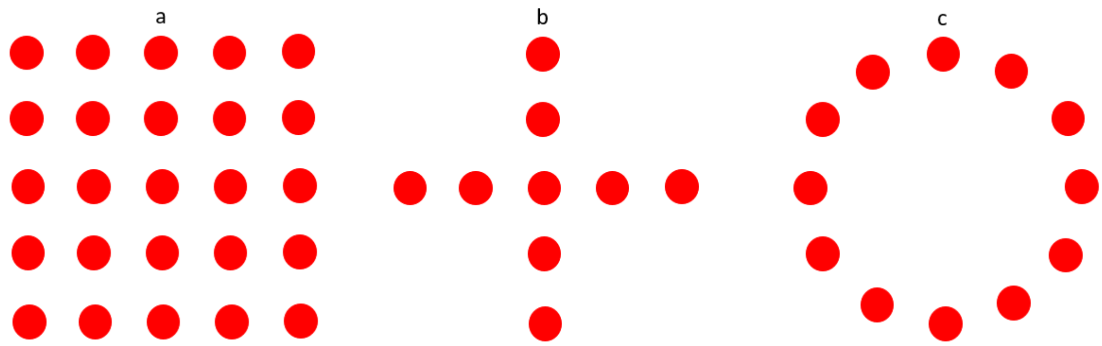

Figure 2. Examples of the geometric configurations of the loudspeakers forming the loudspeaker matrices

Other geometric configurations are also used. Examples of such configurations, shown in the form of a cross and a circle, are shown in Figure 2b and Figure 2c, respectively.

The directivity characteristics of the loudspeaker arrays shown in Figure 1 and Figure 2 can be modified by appropriate processing of the signals fed to the inputs of the transducers. In the simplest case, it may be the introduction of appropriate delays, in more complex cases, the use of individual filters (once analogue and now digital filters).

Due to the envisaged applications, such a source should be made of loudspeakers with the smallest possible dimensions (which translates into a small size of the matrix source and its easier installation) and as wide a frequency range as possible (the possibility of better mapping of noise signals). Loudspeaker arrays contain from several to even several hundred loudspeakers.

3. Parametric arrays with adjustable directional characteristics

Parametric matrices were described for the first time in [10]. They work on a different principle than the loudspeaker arrays. Parametric acoustic loudspeakers with a matrix create highly directional beams of audible sound while transmitting two ultrasonic frequencies [4]. The nonlinearity of the air creates both a summation and a differential frequency as the overlapping ultrasound beams propagate. Since the attenuation is proportional to the square of the frequency, the even higher sum frequency and the original ultrasonic frequencies attenuate very quickly, while the low differential frequency continues to propagate through the air with similar directivity to the original ultrasonic frequencies.

The most frequently used equation to assess the parametrically generated acoustic field is the Khokholow-Zablotskaya-Kuznetsov equation (2), which takes into account both the non-linearity of the propagation medium and the diffraction of primary (ultrasonic) waves:

$$\frac{\partial^2 p}{\partial z \partial t'} = \frac{c_0}{2}\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}\right) + \frac{\delta}{2c_0^3}\frac{\partial^3 p}{\partial t'^3} + \frac{\beta}{2\rho_0 c_0^3}\frac{\partial^2 p^2}{\partial t'^2} \tag{2}$$

where:

p is the sound pressure, c_0 is the speed of sound, ρ_0 is the density of the propagation medium, δ is the sound diffusivity associated with sound absorption, β is the nonlinearity coefficient, t' is the delay time associated with propagation along the z axis ($t' = t - z / c_0$), and x and y are the coordinates lying on the plane perpendicular to the radiation axis z.

Parametric arrays allow a compact device to generate narrow beams of sound in the audible frequency range, but problems usually arise due to acoustic scattering by various objects and structures remote from the target area. In addition, when building new-generation parametric loudspeakers, in which new requirements are integrated, such as high quality of the sound produced, electronic control and accurate control of the sound beam, it is necessary to take into account the cost of calculations related to the implementation of various techniques for pre-processing and beam control, the inclusion of technology in personal audio entertainment system and other innovative applications.

Attempts are made to reduce the number of transducers in parametric matrices all the time. It is based both on the analysis of new signal processing algorithms and the design of the transducers themselves. Research is also being carried out on the construction of ultrasonic transducers with two resonance frequencies. Thanks to this, it is possible to develop a parametric transducer based on a single ultrasonic transducer [13].

4. Potential negative effect of the parametric matrices on human

Parametric matrices, i.e. directional transducers using ultrasonic waves, can affect humans as a typical harmful factor occurring in the human work and life environment. The research shows that due to the large impedance mismatch between the air and the skin, almost 99.9% of the energy of the ultrasound wave is reflected from the human skin. Generally speaking, in practice the main effects of exposure to ultrasound are that of the auditory organ [14]. This is especially true when the ultrasound level is extremely high and can cause unpleasant sensations such as headaches, fatigue, and nausea. Moreover, the symptoms vary from person to person. These effects are temporary and in most situations they disappear after the ultrasound has been removed. There are reports that long exposure times may cause the hearing threshold to shift. However, there are no reports describing cause-effect relationships between hearing loss and exposure of the ear to high-frequency ultrasound.

In a parametric loudspeaker, the achieved sound pressure level can reach 120 dB, especially in the near field. Depending on the dimensions of the parametric loudspeaker and its initial sound pressure, a pressure level of 120 dB at a distance of 1 m from the ultrasound emitter can be achieved, although such high pressure is limited to the beam lying on the radiation axis (axial beam). Generally, the pressure level decreases beyond the Rayleigh distance to less than 100 dB per 8 m. However, it is not appropriate to use the pressure limits as a safety guideline when operating parametric loudspeakers because the ultrasonic waves emitted from parametric loudspeakers consist of relatively narrow spectral bands around carrier frequency. This is fundamentally different from ultrasonic devices that emit broadband ultrasound as well as broadband sound heard in space. However, since the specific response to ultrasonic frequencies is still unclear, it is necessary to remember about the maximum permissible levels of 105÷110 dB even for parametric loudspeakers in a short time of operation due to problems with the negative influence of intense ultrasound around carrier frequencies, such as 40 kHz. Some literature reports suggest that from a physiological point of view, the load on the parametric loudspeaker is lower than that of a conventional loudspeaker in short-sentence speech listening tests. Unfortunately, their report does not describe the relationship between ultrasonic pressure levels and the physiological effects of ultrasound on human auditory function.

In conclusion, one of the important considerations in the design and development of a parametric loudspeaker is to investigate how to reduce the ultrasonic carrier component to a safe pressure level without compromising the performance of the parametric matrix.

5. Microphone matrices with adjustable directional characteristics

The laws of physics regarding the microphone and loudspeaker arrays are the same (the principle of reciprocity applies). There are different criteria for the division of microphone arrays. It is common to divide matrices into acoustically transparent and diffractive ones. Transparent matrices are made of a set of microphones with omnidirectional characteristics mounted on a rack made of thin structures. The structure may have constant geometrical parameters or allow the matrix geometry to be changed. They are usually line matrices. The mechanical design of the matrix ensures that in the low and medium frequency range it does not interfere with the acoustic field in which it is placed. Without the use of additional elements including, among others digital processing of the measured signals transparent matrices due to the microphones used and the geometric arrangement do not allow to distinguish whether the acoustic wave arrives from the front or back of the matrix. Therefore, they are not suitable for locating sound sources in confined areas. For this purpose, diffusion arrays are used, in which microphones are placed on a spherical surface.

Directional microphone arrays can have different geometrical parameters [3]. Exemplary configurations are shown in Figure 3.

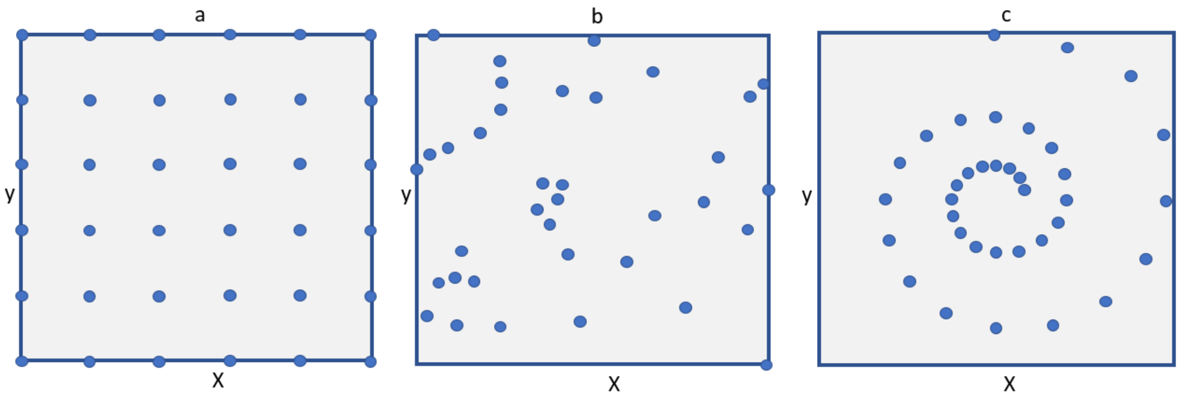

Figure 3. Examples of microphone matrix configurations

Due to the operational parameters, sometimes the use of regular matrix structures (an example structure of this type is shown in Figure 3a) is not advantageous and in such cases matrices are built in which microphones are placed e.g. randomly. The acoustic beam shaping of the microphone array is based on a spatial filtering technique which, based on the direction of the arrival of the acoustic wave, allows the localization of specific sound sources even when there are many other sources in the environment. Two main beamforming algorithms are used: "time domain delay and sum" and "frequency domain delay and sum".

As in the case of loudspeaker arrays, the quality of beam focusing (matrix directivity) depends not only on the algorithm for processing the measured signals and the parameters of the microphones used, but above all on their mutual alignment and calibration.

6. The use of directional transducers to reduce exposure to noise

Noise in the environment is practically everywhere these days. It can be assumed that it is a "natural" element of the environment in which every human being functions. An exemplary division of the sources of this harmful factor is presented in Figure 4.

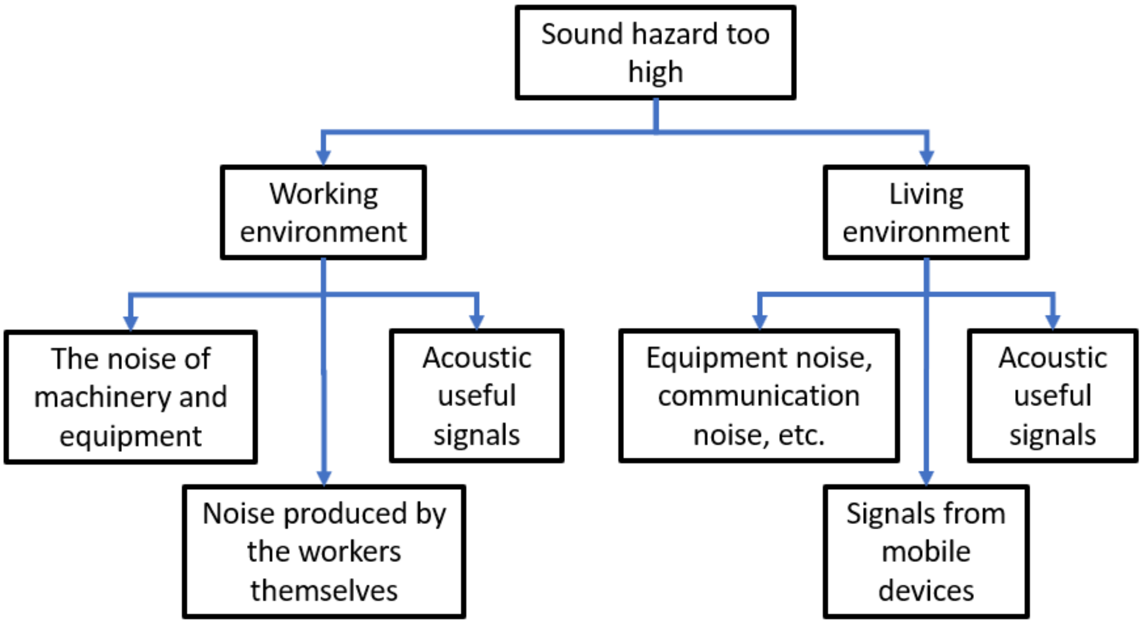

Figure 4. Danger related to sound with too high level of sound pressure in the work and living environment

When people work and live for a long time in a noise area with too high sound pressure levels, there is a great risk to health, mainly due to hearing loss. As people work and live mainly indoors, the application scenarios of noise abatement methods have also been mainly targeted at indoor noise. Now the situation has changed a lot. The most important of them is the fact that harmful or nuisance noise is more and more often generated by people themselves. An example may be stationary or remote customer service stations in "open space" offices. Unfortunately, harmful noise with a high level of acoustic pressure is also more and more often generated at the own request of the exposed person. Examples include making calls or listening to music using mobile devices. Therefore, in the diagram shown in Figure 4, the term "sound hazard" with an excessively high level of acoustic pressure was used on the highest level on purpose, and not the "noise hazard". This takes into account the fact that useful sound with too high sound pressure level has a detrimental effect on hearing as "classic" noise.

To reduce human exposure to the harmful effects of noise of the above-described nature, the possibility of shaping the directivity characteristics of actuating and measuring transducers, i.e. loudspeaker and microphone arrays, can be used (Figure 5).

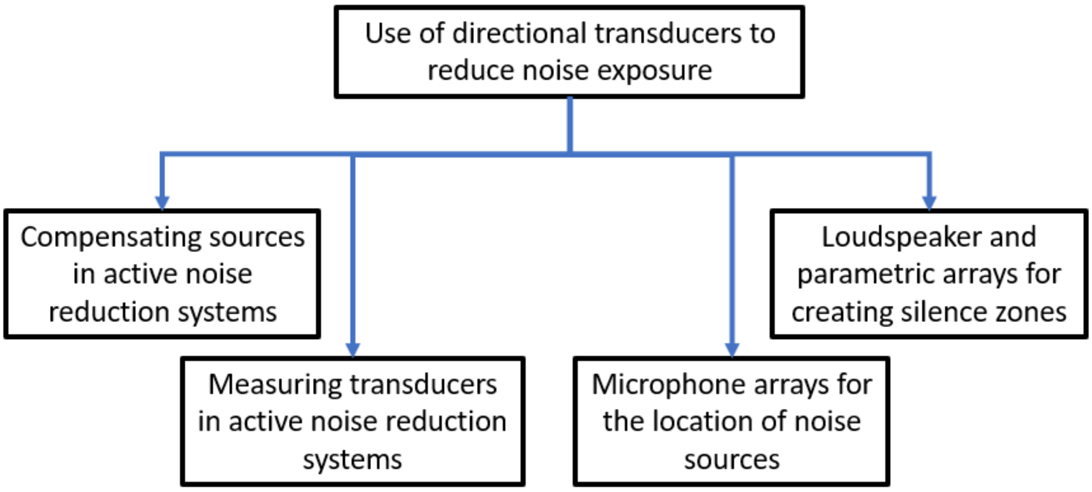

Figure 5. Areas of application of directional transducers in the elimination of exposure to noise

In the case of loudspeaker and parametric arrays, they are used to shape the distribution of the acoustic field in such a way that the useful signal reaches only people for whom it is intended. Thus, a kind of dedicated sound zones are created. They give the listener the ability to have their own, separate sound zone without physical isolation or the need to use headphones. There are many ways to use your personal sound zones. For example, patients sitting in a row of hospital beds may watch different TV stations, museum exhibits may have associated soundtracks, or in a living room where the TV sound system raises the frequencies and sound levels in a specific area where hearing-impaired listeners are present. In the above context, modern directional and parametric arrays thanks to the modification of directional characteristics and thus influencing the amount of acoustic energy reaching from the source to a specific area:

- ensure environmentally friendly transmission of audio signals in the selected listening area and maintain silence in other areas,
- enable the coexistence of different sounds in an open space without their mixing and mutual interference,
- they are portable in design, are easy to install and offer many different mounting options,
- they can be used both indoors and outdoors.

Variable directivity transducers are very useful when there are problems with transmitting information. We are then dealing with the so-called Lombard effect. The lack of speech intelligibility of people exchanging information causes them to talk louder and louder, which further worsens the acoustic conditions and causes a further increase in the level of produced sound. The use of traditional methods of protection against noise, e.g. by acoustic separation of the workplace, is often simply not possible due to its basic functionality. On the other hand, the above-described positive feedback can be eliminated by appropriately shaping the acoustic field by means of directional emitters and by receiving information by means of a directional measuring transducer.

As mentioned in the case of prolonged exposure to environmental noise which is dangerous to human health, there is an urgent need to suppress or eliminate environmental noise. Due to the limitations of the surrounding space, preventing the use of passive noise protection measures, active noise reduction / control systems (ANC), i.e. inverted sound waves emitted by the loudspeakers against the noise generated by its source, are increasingly used to reduce noise in both the work and living environment.

Active noise reduction systems in a specific target area use traditional moving coil loudspeakers as actuators (secondary sources). Due to the omnidirectional characteristics of such loudspeakers, apart from the reduction in selected areas in the space, there is also the unfavourable phenomenon of an increase in the sound pressure level in the adjacent areas. In addition, in the case of multi-channel systems, the lack of directivity causes crosstalk between the channels at the location of the error signal microphone, which further increases the requirements and thus the costs related to the calculations within the control process. Due to the omnidirectional radiation characteristics, it is additionally easy to increase the acoustic feedback with the reference signal, i.e., the signal characterizing the noise source. As can be seen, there are still many problems to be solved in connection with the use of traditional loudspeakers as secondary sources in active reduction circuits. Therefore, ANC circuits are emerging that use the online secondary path modelling method using loudspeaker or parametric arrays with adjustable directivity. The results of the experiments show that parametric matrices as a secondary source allow for the same active noise reduction as a traditional loudspeaker and additionally allow for a longer propagation distance, less feedback and a more regular and controllable area in which the active reduction effect occurs. An additional element that allows to reduce the feedback between the detector mixing the noise signal and the acoustic signal generated by the compensating source is the use of a detector in the form of a directional microphone matrix. The detector installation should be such that it measures only the signal from the noise source.

In many studies on the use of parametric loudspeaker arrays as secondary sources, their dimensions and power were constant values. In this case, assuming in the control algorithm that the distance between the secondary source and the observation area is fixed, new problems arise after its change. When the observation area is too close to the secondary source, this can cause distortion and create many areas that interact (superposition and interference) with adjacent sound fields. When the observation area is too far from the secondary source, the effectiveness of active noise reduction decreases. As a result, there are reports of experiments using adjustable parametric loudspeakers. Depending on the distance to the observation area, the size and power of the parametric loudspeaker are adjusted accordingly in order to obtain the active reduction effect.

Along with the progress in the development of active reduction technology, active methods are widely used not only in the work environment such as production halls, but also in offices, cars and, above all, in mobile devices. The more and more widespread application area justifies work on increasing the effectiveness of active systems by using directional transducers and even matrices with adjustable directional characteristics.

Shaping the acoustic beam allowing to obtain a measuring transducer (microphone) with a very narrow directivity characteristic can be used for the remote location not only of noise sources, but in the case of microphone arrays with very narrow directivity characteristics of the components of machines and devices responsible for the generated noise [3, 15]. Microphone arrays make it possible to locate a specific noise source or to separate this source from others based on the direction of the acoustic wave and the time difference between the source and the matrix's measuring elements.

Thus, as can be seen in cooperation with other measuring devices and with the use of appropriate computational algorithms, microphone arrays allow, apart from acoustic parameters, to determine the distance between noise sources and the distance between the matrix and these sources [15]. In this case, measurements with the use of a microphone array can be treated as an important element used in the broader process of reducing exposure to noise, i.e., within the application of organizational and / or technical solutions.

7. Conclusions

Matrices with adjustable directional characteristics can be divided into emitting and measuring matrices. Performance matrices can, in turn, be divided into loudspeaker matrices and parametric matrices based on ultrasonic transducers. Measurement matrices use traditional microphones. Regardless of the matrix type, the primary parameter used to reduce noise exposure is the directional characteristics of these transducers.

Transducers with adjustable narrow directivity characteristics can be used to reduce exposure to sounds with high sound pressure levels in both work and human living environments. In the work environment, they can be used as elements of active noise reduction systems, and to create silence zones that improve work ergonomics and make it possible to reduce the levels of useful signals and noise generated by employees, e.g., during conversations in a noisy environment. In the living environment, they are increasingly used to create individual zones of silence, target message and in mobile devices. The constant development of the technology of producing loudspeaker, parametric and microphone arrays related to the increase in the computing power of digital signal processors leads to the expansion of the scope of application of directional transducers in the field of noise suppression.

Acknowledgments

Prepared on the basis of research carried out in the years 2021-2023 as part of the statutory activity of the Central Institute for Labour Protection – National Research Institute, financed by the Ministry of Science and Higher Education.

References

[1] Balanis CA, Antenna theory – analysis and design. 3 ed. New Yersey: John Willey & Sons, Inc.; 2005.
[2] Busuioc D, Safavi-Naeini S. Low cost antenna array and phased array architectures – design concepts and prototypes, 2010 IEEE International Symposium on Phased Array Systems and Technology, Waltham, MA, 2010, 965-968.
[3] Chiariotti P, Martarelli M, Castellini P. Acoustic beamforming for noise source localization – Reviews, methodology and applications. Mechanical Systems and Signal Processing 2019; 120:422-448.
[4] Gan WS, Yang J, Kamakura T. A review of parametric acoustic array in air, Applied Acoustics 2012; 73:1211-1219.
[5] Shinagawa K, Takemura H, Mizoguchi H. Sound spot generation and evaluation by a large scale panel loudspeaker array, 2008 IEEE International Conference on Systems, Man and Cybernetics, 2008, p. 1164-1168.
[6] Sugahara A, Lee SS, Takeoka S. Measurements of acoustic impedance of porous materials using a parametric loudspeaker with phononic crystals and phase-cancellation method, Applied Acoustics. 2019; 152:54-62.
[7] Gan WS, Shi Ch. Development of a parametric loudspeaker: a novel directional sound generation technology, IEEE Potentials. 2010; 29(6):20-24.
[8] Parra LC. Steerable frequency-invariant beamforming for arbitrary arrays, The Journal of the Acoustical Society of America, 2006; 119(6):3839-3847.
[9] Yang J, Gan W-S, Tan K-S, et al. Acoustic beamforming of a parametric speaker comprising ultrasonic transducers. Sensors and Actuators. 2005; 125:91-99.
[10] Warusfel O, Derogis P, Causse R. Radiation Synthesis with Digitally Controlled Loudspeakers, Audio Engineering Society; 1997.

[11] Ziemer T. Implementation of the Radiation Characteristics of Musical Instruments in Wave Field Synthesis Applications; 7 July 2016. Available at: https://theses.eurasip.org/theses/669/implementation-of-the-radiation-characteristics/read/
[12] Mizoguchi H, Kanamori T, Kagami S, et al. Implementation of invisible messenger system to whisper in a person's ear remotely by integrating visual face tracking and speaker array. IEEE International Conference on Systems, Man and Cybernetics [Internet]. 6 October 2002. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1175638
[13] Kim ChH, Kim MJ, Ri ChS. Design of ultrasonic transducer for secondary wave generations with high directivity. International Journal of Acoustics and Vibration. 2019; 24(4):744-748.
[14] Pleban D, Smagowska B, Radosz J. Hałas ultradźwiękowy w inżynierii środowiska pracy, Warszawa: CIOP-PIB; 2022.
[15] Baldinelli G, Bianchi F, Costarelli D, et al. Innovative techniques for the improvement of industrial noise sources identification by beamforming. Noise Mapping. 2021; 8:129-137.