New techniques and methods for noise and vibration measuring, assessing and reducing

Digital Monograph

Edited by: Dariusz Pleban

Central Institute for Labour Protection – National Research Institute

CIOP PIB

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The monograph "New techniques and methods of noise and vibration measuring, assessing and reducing" contains valuable material with a wide range of applications in the generally understood area of both noise and mechanical vibration reduction. The particular attention was meticulously paid to the impact of noise and vibration on the human body. This in itself stands clearly in line with the European Union's activity in reducing environmental pollution by noise and vibrations.

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Preface

Noise and vibrations are both integral elements of our life. According to the 6th European Working Conditions Survey[1], carried out by Eurofound in 2015, 28% of employees in the 28 (at the time, currently 27) European Union Member States had been exposed at work to noise so loud that they needed to raise their voices to be heard among each other. According to the same data source, 20% of workers in the 28 European Union Member States in 2015 had been exposed at work to vibrations from hand tools, machinery and other sources.

In Poland, on the other hand, according to Statistics Poland data, as many as 265.7 thousand persons were exposed to hazards arising from work environment in 2021 and noise was the most hazardous risk factor arising from work environment among them, affecting 182.2 thousand persons. The impact of vibrations affected 8.9 thousand persons. The most exposures were recorded in manufacturing. Industrial noise and vibration occur primarily during production processes in industrial halls, but they are also audible and felt in office spaces, the natural environment and the living environment.

Due to the prevalence of noise and vibrations (they occur to varying degrees both in the living environment and in the human work environment), it is necessary to strive not only to limit their impact on human beings, but also to ensure adequate vibroacoustic comfort. For decades, techniques and methods have been developed to reduce noise emissions and minimize its impact on humans. These long-known and widely used techniques and methods have already been discussed many times in books and papers. However, the constant progress in the field of technology makes it possible to gradually develop and introduce into practice new techniques and methods in the scope of noise and vibration measurement, assessment and control.

This monograph contains a selection of papers, presented at the Noise Control 2022 Conference[2]. The event in question is the most important international conference on noise control, organized in Poland triennially. The 19th International Noise Control Noise Conference NOISE CONTROL 2022 took place in the Bishops' Castle in Lidzbark Warmiński between 26 and 29 June 2022. The Conference was organized by the Central Institute for Labour Protection – National Research Institute and the Committee on Acoustics of the Polish Academy of Sciences.

[1] Eurofound. Sixth European Working Conditions Survey – Overview report (2017 update). Luxembourg: Publications Office of the European Union; 2017.

[2] The 19th International Conference Noise Control 2022 was organised within the scope of the fifth stage of the National Programme "Improvement of safety and working conditions" partly supported in 2020-2022 – within the scope of state services – by the Ministry of Family and Social Policy. The Central Institute for Labour Protection – National Research Institute is the Programme's main coordinator.

This monograph allows the reader to get acquainted with the subject of the selected and yet the latest techniques and methods in the field of noise and vibration reduction and the improvement of vibroacoustic comfort. The techniques, solutions and results presented in this monograph, due to their interdisciplinary nature, may be interesting and useful to representatives of disciplines and scientific fields other than acoustics. I hope this monograph will be interesting and helpful in studies and work.

Dariusz Pleban

Chapter 1

Acoustic anechoic termination of the waveguide in the measuring system of ducted silencers

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Abstract
The paper presents the assumptions and design of an anechoic termination fulfilling the requirements of the European Standard EN ISO 7235:2009 for systems for measurement of acoustic parameters of ducted silencers. The duct must remain open to ensure the airflow. The attenuation of the reflected wave is ensured by both the absorption of the wave by the sound absorbing material surrounding the duct and an appropriate termination shape to ensure impedance matching. Horn shaped terminations are most used here. Exponential horns are often used, but catenoid horns have better properties. The various types of anechoic termination are described in European Standards EN ISO 5136:2009 and EN ISO 7235:2009. The Standard EN ISO 7235 requires that the standing wave ratio for the acoustic pressure does not exceed the value to 0.3 at the lowest measurement frequency. Three catenoidal anechoic terminations were designed for waveguides with cross-sections 250 × 250 mm, 450 × 450 mm and 800 × 800 mm used in the duct silencer measurement system compliant with EN ISO 7235:2009 standard. The catenoidal part is located on both ends of the anechoic termination. For the duct with a smaller cross-section, it is placed on two sides of the central duct with flow, while for the duct with a larger cross-section it is placed on four sides. The height of the smaller termination is equal to 1060 mm and the height and width of the larger termination is 2024 mm. The length of the termination in both cases is 3900 mm because of geometrical limitation of the measurement room. The measurement of the constructed anechoic termination shows that it meets the conditions of the standard above the 1/3-octave band with a center frequency of 50 Hz.

Keywords: ducted silencer, measurement, anechoic termination, catenoidal horn

1. Introduction

In order to ensure optimum transmission of the acoustic wave power in the waveguide, it is important to prevent the occurrence of wave reflections on discontinuities in the cross-section. Such reflections occur when the waveguide cross-section changes, when the waveguide branches and at the end of the waveguide. Part of the power of an acoustic wave is reflected from a discontinuity, resulting in a standing wave. The standing wave ratio, defined as the ratio of the energy density of the reflected wave to the energy density of the incident wave, is a measure of the reflected power. This coefficient can take values from 0 to 1. A standing wave coefficient of 1 means full internal reflection from a discontinuity, i.e., all energy of the incident wave is reflected. This situation occurs, for example, when a wave is reflected from the rigid end of a waveguide. A standing wave coefficient of 0 means that there is no reflection, and all the wave energy is transmitted. This situation occurs if the acoustic impedance of the waveguide is equal to its acoustic impedance at the end. Then all the wave energy is transmitted to the impedance loading the end of the waveguide. There is no perfect anechoic termination. With any discontinuity there will be reflected waves. The anechoic termination is designed in such a way that these reflections are as small as possible under the given conditions. Two solutions are used. The first is to terminate the waveguide with a sound-absorbing material, e.g., mineral wool or glass wool. The absorption of the wave energy by the sound absorbing material is greater the larger the amount of sound absorbing material is. The constructions made of such material in the form of wedges or pyramids are also used. This solution can be used if there is no air flow in the waveguide. A second solution is to use an impedance matching system at the end of the waveguide in the form of a horn, which is a pipe with a uniformly varying cross-section. The horn matches the impedance at the beginning, causing the wave to be radiated into space through the other end. This solution can be used for a waveguide with flow. Both solutions have their disadvantages, manifesting themselves primarily in the low frequency range. For terminations in the form of sound-absorbing materials or structures, their absorbing properties decrease in this frequency range. For horns, the impedance matching deteriorates with decreasing frequency. Many horns used in practice have a limiting frequency below which there is no wave motion in the horn and then the use of a horn is meaningless. Finally, a mixed solution is possible - using both a horn and a sound-absorbing material.

2. The catenoidal horn

The catenoidal horn belongs to the so-called Salmon horns family. The dependence of the area on the distance from the horn inlet for this family is described by the formula [1]:

$$S(x) = S_1\left(cosh\frac{mx}{2} + Tsinh\frac{mx}{2}\right)^2 \qquad (1)$$

where:

x – distance from the horn inlet (throat), S_1 – throat surface, T – family parameter, m – flare constant. For different parameter values T the following horns are obtained: $T = 0$ – catenoidal horn, $T = 1$ – exponential horn, $T = \infty$ – conical horn.

All horns of Salmon family, except the conical, have a limiting frequency, below of which in the horn the wave motion does not exist, and the horn does not work. The limiting frequencies of all Salmon horns are expressed by the formula:

$$f_{low} = \frac{mc}{4\pi} \tag{2}$$

where:

c – the sound speed in the medium, for air at the temperature 20ºC, c = 343 m/s.

It should be noted, however, that the value of m for each horn with the same geometrical parameters (throat area, mouth area, length) are different and therefore the limiting frequencies are also different.

Above the limiting frequency, the impedance at the horn inlet (throat) changes rapidly to the matching value. A conical horn has a limiting frequency of zero, but the impedance at the throat increases very slowly and reaches the matching value at the highest frequency. For this reason, it pays to use only horns with T values between 0 and 1. For an exponential horn, the matching frequency value is about twice the cut-off frequency, while for a catenoidal horn, the matching is obtained immediately above the cut-off frequency. The catenoidal horn introduces high distortion and is therefore rarely used in systems where the quality of the transmitted sound is important. In noise control solutions, however, it is worth using this horn.

Finally, the dependence the area S on the distance x is given for the catenoidal horn by the formula:

$$S(x) = S_1 cosh^2\left(\frac{mx}{2}\right). \tag{3}$$

The impedance at the throat of the catenoidal horn under ideal matching conditions is:

$$Z_1(f) = \frac{\rho_0 c}{S_1} \cdot \frac{1}{\sqrt{1 - \left(\frac{mc}{4\pi f}\right)^2}} \tag{4}$$

and is pure acoustic resistance. A perfect match is obtained for a horn of infinite length. For a horn of finite length, the impedance has a real and imaginary part and is given by the formula [2]:

$$Z_1 = \frac{\rho_0 c}{S_1} \cdot \frac{jk}{\sqrt{k^2 - \frac{m^2}{4}}} \cdot \frac{jk\frac{\rho_0 c}{S_2 Z_2} tan\left(\sqrt{k^2 - \frac{m^2}{4}}l\right) - \frac{m}{2} tanh\left(\frac{ml}{2}\right) tan\left(\sqrt{k^2 - \frac{m^2}{4}}l\right) + \sqrt{k^2 - \frac{m^2}{4}}}{jk\frac{\rho_0 c}{S_2 Z_2} - \frac{m}{2} tanh\left(\frac{ml}{2}\right) - \sqrt{k^2 - \frac{m^2}{4}} tan\left(\sqrt{k^2 - \frac{m^2}{4}}l\right)} \tag{5}$$

where:

k – the wavenumber, Z_2 – impedance at the outlet (mouth) of the horn. The impedance Z_1 has both the real and imaginary parts.

3. Measurement of ducted silencers: standard EN ISO 7235:2009

The procedures for measuring the acoustic performance of duct silencers are described in the European Standard EN ISO 7235:2009. Acoustics – Laboratory measurement procedures for ducted silencers and air-terminal units – Insertion loss, flow noise and total pressure loss [3]. The procedures described in this standard include measurements under airflow and no-airflow conditions. The basic measurand with which the indicated acoustic parameters are determined is the sound power. Methods are described for measuring sound power under diffuse field conditions in reverberation chambers, and for travelling wave conditions. Measurements can be carried out without air flow and with air flow. This paper describes the anechoic termination of a waveguide, used for traveling wave measurements with the possibility of measurements with airflow. The measurement installation works in an airflow looped circuit. It consists of a sound source, a waveguide connecting the source to the silencer under test together with adapters, a measurement waveguide and an anechoic termination, behind which is a fan generating the flow with silencers at the input and output to suppress its noise and instruments to measure pressure and flow velocity. The pipe after the fan is connected to the sound source. The standard [3] requires that the standing wave ratio of the sound pressure, defined as the ratio of the amplitudes of the reflected and incident waves at the anechoic termination from the measuring waveguide, should not exceed the value $r_p = 0.3$, i.e., the energy absorption coefficient α should meet the condition:

$$\alpha = 1 - r_p^2 \geq 0.91 \tag{6}$$

in the frequency range between 50 Hz and the limiting frequency above which a wave in a waveguide cannot be considered as plane due to the formation of higher-order modes. In the case described, the waveguide has a square shape, for which the upper limiting frequency is [3]:

$$f_H = \frac{0.5\ c}{a} \tag{7}$$

where:

a – side of the square.

Standard [3] shows an example of an anechoic termination consisting of a double-sided catenoid part and a tubular connector. In the center of the termination there is a waveguide with a connecting pipe cross-section, and on the sides, there is an attenuator with a stepped catenoid shape, and a pipe part filled with sound-absorbing material. Other anechoic termination solutions can be found in the European Standard [4].

4. Design of catenoidal anechoic termination

This chapter presents the design of a double-sided catenoidal anechoic termination used in an installation for the measurement of acoustic silencers according to EN ISO 7235:2009. This installation is carried out at BH-RES company in Rzeszow. In this design, the catenoid shape is composed of conical segments connecting to each other. The cross-sectional area of the anechoic termination consists of two parts: a square waveguide of side a, through which the medium can flow, and a catenoidal part, placed along two or four sides of the waveguide. The side of the waveguide to which the catenoidal part adjoins is perforated with a perforation ratio of 60%. The interior of the catenoid part is filled with a sound absorbing material: mineral wool with a density of 40 kg/m^3. The side walls of the catenoidal part are an extension of the corresponding side of the waveguide. The cross-sectional area of the waveguide containing the waveguide part and n catenoid parts is expressed by the formula:

$$S(x) = a^2 + n \cdot a \cdot \mathrm{h}(x) \tag{8}$$

where:

n = 2 or 4, $h(x)$ – external profile of the catenoid part. The shape of the catenoid profile is given by the formula (9):

$$h(x) = \frac{a}{n}\left[cosh^2\left(\frac{mx}{2}\right) - 1\right]. \tag{9}$$

Calculations were performed for a limiting frequency of 50 Hz and for three sides of the cross-section: $a = 0.25$ m, 0.45 m and 0.8 m. For a horn with side $a = 0.25$ m, $n = 2$ was assumed (the catenoid part is placed on two opposite walls of the waveguide), while for a waveguide with side $a = 0.8$ $n = 4$ was assumed (the catenoid part is placed on all four walls of the waveguide). For the intermediate case $a = 0.45$ m calculations were performed for two variants: $n = 2$ and $n = 4$. Based on formulas (2) and (3) the flare constant $m = 1.8$ m^{-1} was determined. The upper limited frequencies according to formula (7) are: for the channel with $a = 0.25$ m, $f_h = 688$ Hz, for $a = 0.45$ m, $f_h = 382$ Hz and for $a = 0.8$ m, $f_h = 215$ Hz. Calculations of $h(x)$ were performed every 30 cm in the range from $x = 0$ to 1.5 m, then the cross-section is constant up to the value of $x = 2.4$ m, after which it decreases symmetrically to $x = 3.9$ m.

The results of the calculations are given in Table below.

Table. Profile of the catenoid section of a single side of an anechoic termination

Channel	0.25 x 0.25 m	0.45 x 0.45 m	0.45 x 0.45 m	0.8 x 0.8 m
Variant	***N = 2***	***N = 2***	***N = 4***	***N = 4***
***x* [m]**	***h(x)* [m]**	***h(x)* [m]**	***h(x)* [m]**	***h(x)* [m]**
0	0	0	0	0
0.3	0.009	0.017	0.008	0.015
0.6	0.040	0.072	0.036	0.064
0.9	0.102	0.183	0.091	0.163
1.2	0.212	0.382	0.191	0.339
1.5	0.405	0.728	0.364	0.647
1.8	0.405	0.728	0.364	0.647
2.1	0.405	0.728	0.364	0.647
2.4	0.405	0.728	0.364	0.647
2.7	0.212	0.382	0.191	0.339
3.0	0.102	0.183	0.091	0.163
3.3	0.040	0.072	0.036	0.064
3.6	0.009	0.017	0.008	0.015
3.9	0	0	0	0

The largest width and height are for the anechoic termination with a waveguide of $a = 0.8$ m. They amount to $2 \times 0.647 + 0,8 = 2.094$ m each.

The anechoic termination profiles for $a = 0.25$ ($n = 2$) and for $a = 0.8$ ($n = 4$) are shown in the Figures 1 and 2.

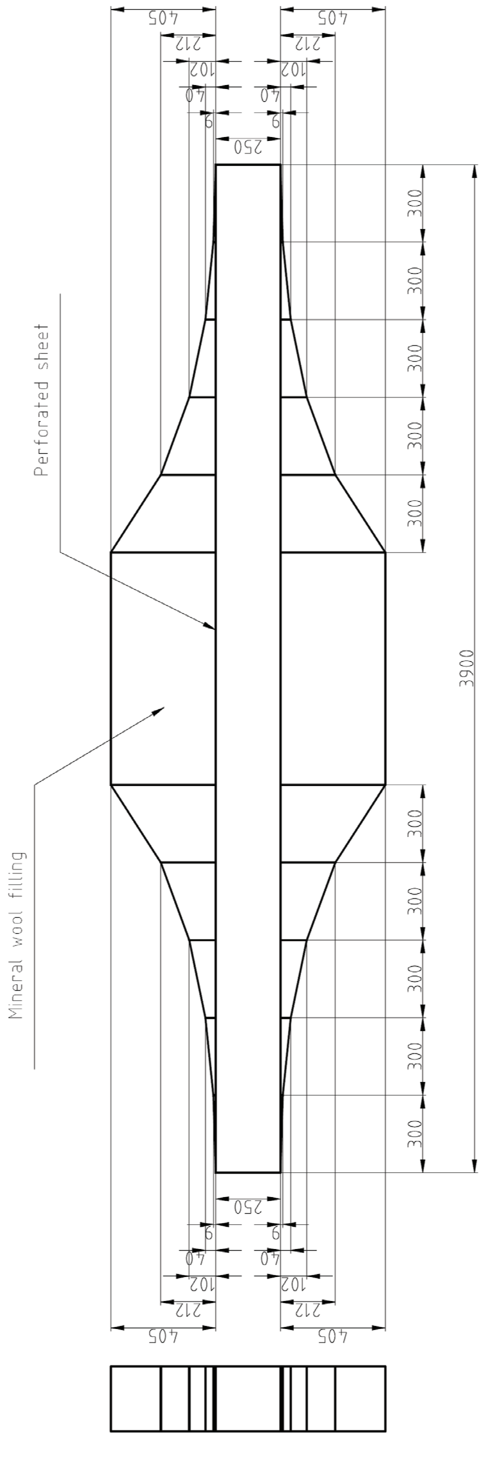

Figure 1. Cross-section and profile of the anechoic termination for the waveguide 0.25 × 0.25 m

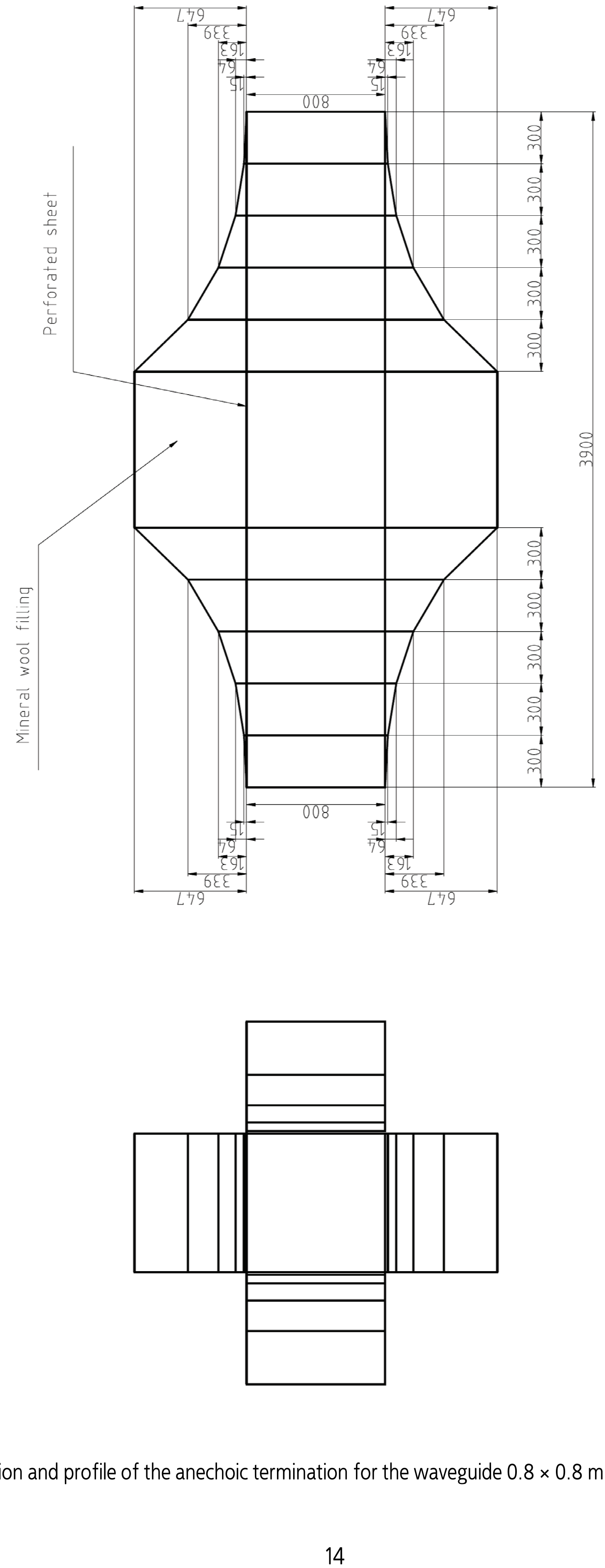

Figure 2. Cross-section and profile of the anechoic termination for the waveguide 0.8 × 0.8 m

At present, only the anechoic termination for the largest waveguide with a waveguide cross- section of 0.8 × 0.8 m has been realized and measured. Figure 3 shows one catenoidal section of the anechoic termination before assembly.

Figure 3. The anechoic termination before assembly

For this anechoic termination, the absorption coefficient as a function of frequency was measured. The measurement results are shown in Figure 4.

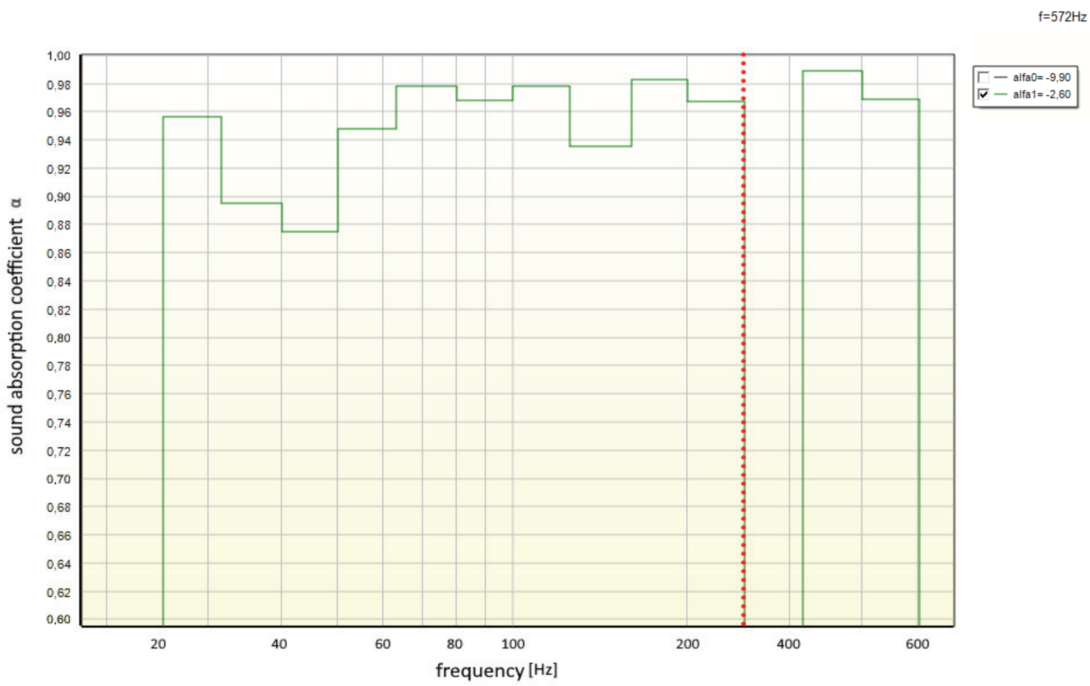

Figure 4. Measured sound absorption coefficient of the 80 × 80 cm anechoic termination

Condition (6) is satisfied in the frequency range above the 1/3-octave band of 50 Hz. The frequency of 572 Hz, for which a sharp drop in absorption coefficient is seen, lies above the required frequency of 215 Hz for this termination and is caused by the cover the microphone position and the nodal line of the waveguide.

5. Conclusions

In anti-noise solutions, the most difficult task is to ensure high attenuation in the low frequency range. This applies both to noise transmitted through obstacles (walls, partitions) and that transmitted in waveguides. Inadequate attenuation results in reflected waves which interferes with the travelling wave and creates standing waves. To prevent this, sound-absorbing materials or horns are used at the end of the waveguide. Hybrid solutions are most effective, and catenoid horns are best used as horns. Since it is extremely difficult to precisely manufacture a catenoid termination, shape approximation using stepped ducts is used. In this work, catenoidal shape approximation is used using tapered sections made of flat sections of sheet metal mounted at an angle that changes according to the chain curve. The interior of the main waveguide is not filled with sound absorbing material to ensure airflow. Sound absorbing material is used in panels mounted on the sides of the square main waveguide. The panels can in the simplest case be mounted on one side. To reduce the size of the whole structure, mounting on two or four sides is used. Waveguide terminations have been designed for three sizes of main waveguide cross-sections. So far, one termination has been implemented for the largest cross-section. Very good results were obtained, and the termination meets the requirements of the standard. The large cross-section is the most difficult case, so it is expected that the results will be even better for the other cross-sections.

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[3] European Standard EN ISO 7235:2009. Acoustics – Laboratory measurement procedures for ducted silencers and air-terminal units – Insertion loss, flow noise and total pressure loss.
[4] European Standard EN ISO 5136:2009. Acoustics – Determination of sound power radiated into a duct by fans and other air-moving devices – In-duct method. Annex E.

Chapter 2

The use of directional transducers to reduce exposure to noise

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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).

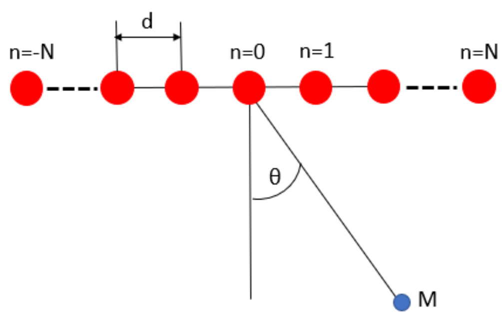

Figure 1. Linear loudspeaker array

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).

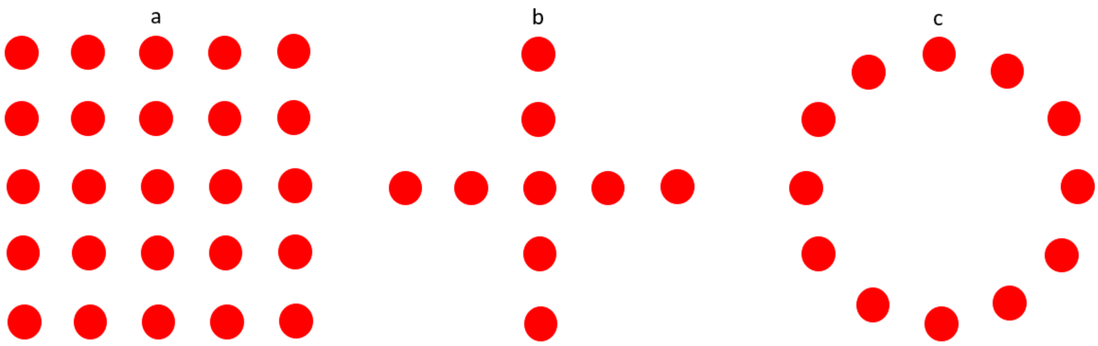

Figure 2. Examples of the geometric configurations of the loudspeakers forming the loudspeaker matrices

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 ($t' = t\text{-}z / c_0$), 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.

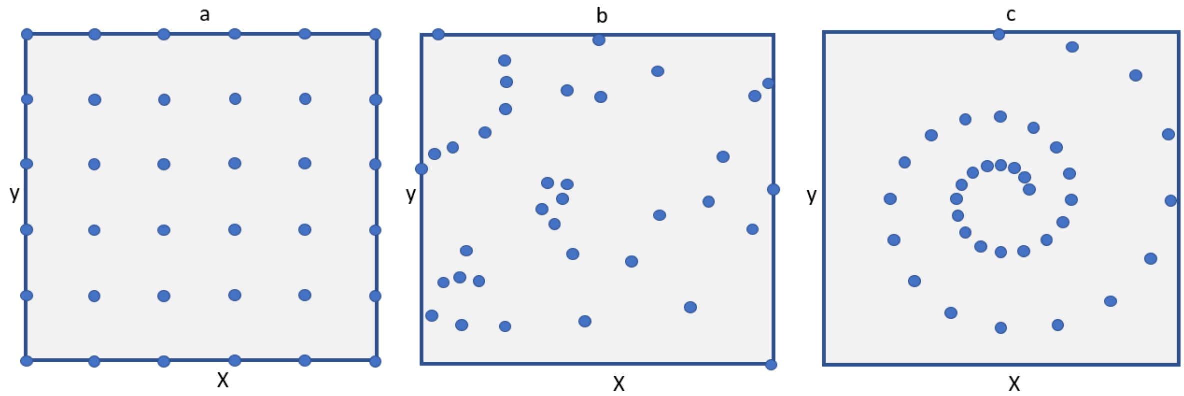

Figure 3. Examples of microphone matrix configurations

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.

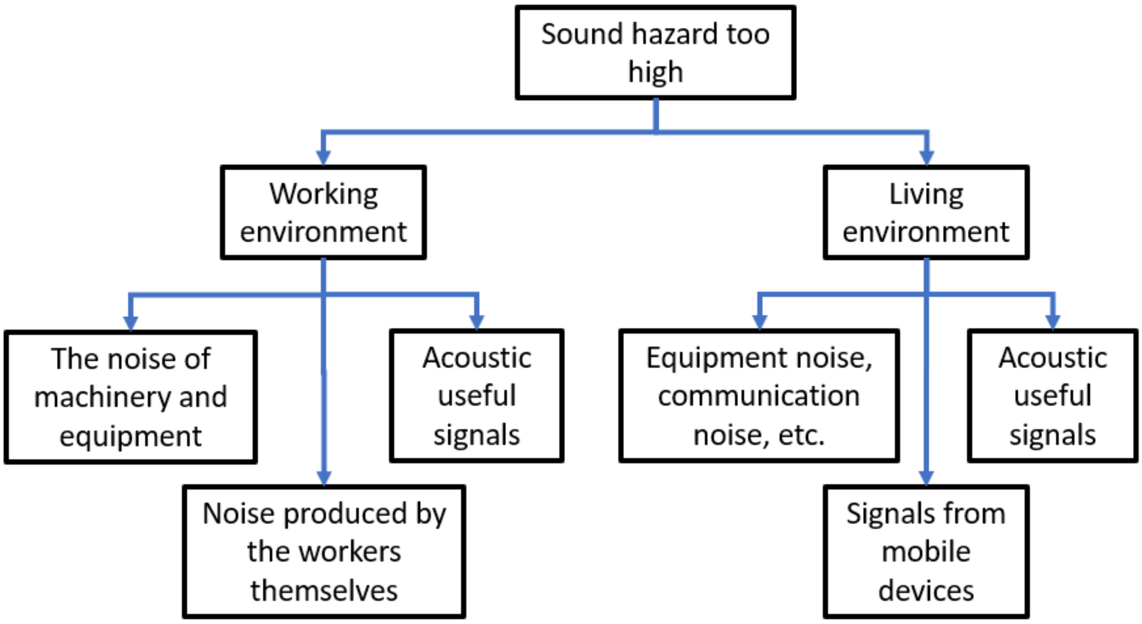

Figure 4. Danger related to sound with too high level of sound pressure in the work and living environment

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).

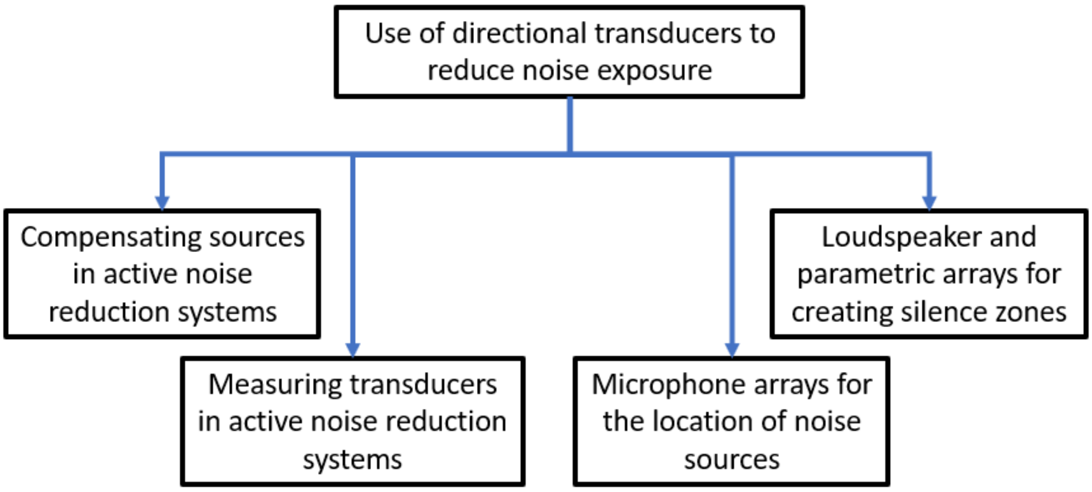

Figure 5. Areas of application of directional transducers in the elimination of exposure to noise

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

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Chapter 3

Review of evaluation criteria for infrasound and low frequency noise in the general environment

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Abstract
It has been suggested that infrasound (IS) and low frequency noise (LFN) may be responsible for adverse health effects in people living in the vicinity of wind farms. Many studies have indicated that the basic noise measure – an A-weighted sound pressure level (SPL) – is a less suitable descriptor for assessing the effects of IS and/or LFN. Thus, this paper reviews existing or proposed methods for evaluating infrasound and LFN in residential areas with regard with their impact on human health and wellbeing.

Keywords: infrasound, low frequency noise, environmental exposure, effects on humans, measuring methods, exposure limits

1. Introduction

Infrasound (IS) is defined as sound or noise whose spectrum lies mainly in the range from 1 to 20 Hz [1]. In turn, low frequency noise (LFN) – although its international definition has not yet been definitely formulated – is usually referred to as broadband noise with a dominant content frequencies from 10 to 250 Hz, but sometimes the LFN range is limited to 20–200 Hz or 20–500 Hz [2].

Both, IS and LFN comprise a common, everyday-life environmental exposure, produced by natural (sea waves, wind turbulence) as well as by man-made sources (industrial installations, domestic appliances, transportation) sources. Their prevalence in premises is mainly due to ventilation, heating and or air-conditioning systems as well as from outdoor sources of noise and poor attenuation of low frequency components by the walls, floors and ceilings. Moreover, propagation models and field studies have indicated that IS and LFS can propagate with less attenuation with distance than higher frequencies because of their lower sound absorption during passage through the air and on reflection from the ground. Moreover, especially LFN, may be amplified as a result of the phenomenon of resonance of rooms and structural elements of buildings [2, 3].

It has been suggested that IS and LFN may be responsible for adverse health effects in people living in the vicinity of wind farms. Thus, the aim of this paper was to review the evaluation criteria for infrasound and low frequency noise in residential areas in relation to their impacts on humans.

2. Perception of infrasound and its effects on humans

It has been commonly assumed that infrasound is inaudible. However, already in the 1930s this was known not to be true [4]. The perception of infrasound is based on hearing and vibrations. The threshold of auditory perception rises rapidly as the frequency falls, from approximately 65 dB at 32 Hz to 95 dB at 16 Hz, 100 dB at 3 Hz, and 140 dB at 1 Hz [2, 5].

The sound-induced vibrations will be perceivable only at relatively high sound pressure levels, 20 to 40 dB above the hearing threshold. The sensory mechanism is the same as in detecting mechanically induced vibrations [5-8]. Moreover, when infrasound becomes audible, it can be annoying. The annoyance associated with exposure to audible infrasound has been the subject of a number of laboratory experiments. For example, contours of equal annoyance were determined for pure tones within the frequency range from 4 to 31.5 Hz. These curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is observed for equal loudness curves, so the annoyance of infrasound is closely related to the loudness sensation [9].

The adverse effects of aural pain, speech interference and temporary threshold shift (TTS), normally appear at levels 30 to 40 dB above the hearing threshold. The threshold for aural pain is approximately 140 dB at 40 Hz and 160 Hz at 3 Hz. A tympanic membrane injury may be the result of exposure to extremely high sound pressure levels [6, 10]. In turn, TTS effects from audiometric frequencies above 125 Hz have been observed after infrasound exposures at 140 dB. As expected, the most significant effects can be observed at frequencies above 1 kHz. The TTS, often of less than 10 dB, have been found to disappear rapidly after exposure [3, 6, 11].

Infrasound as well as low frequency sound (10–75 Hz) may excite resonant vibrations in some parts of the human body e.g. abdomen, chest and throat. Such vibrations in the thorax/abdominal region normally appear at levels above 100–105 dB (40–60 Hz). The vibrotactile sensations in the abdomen and chest region due to infrasonic frequencies (4–20 Hz) appear at much higher levels, close to 130 dB [6, 12].

An American space research project has indicated that the maximum permissible short-term exposure to infrasound should be in the region of 140–150 dB. Beyond this the chest walls of the subjects would vibrate, with a sensation of gagging and blurring of vision. Moreover, the chest wall vibrations may interfere with the respiratory activity [5, 6].

Possible vestibular disturbances (described as the loss of the sense of balance, disorientation and nausea) have been investigated in several studies. The validity of these effects is controversial [6, 10, 12]. In view of some later research, infrasound at the levels normally experienced by man should not have any significant effect on the vestibular function [13].

A close correlation exists between the exposure to infrasound, its perception and the physiological disorders. Therefore, the acoustic pressure levels must always be high enough to allow perception, in order to induce physiological effects. This theory has been experimentally verified in laboratory studies. Reduction of wakefulness identified through changes in EEG, blood pressure, heart activity, respiration, and hormonal production, was found to occur only when the infrasound levels exceeded the hearing threshold. Under the same conditions the deaf subjects presented an absence of weariness [5, 6].

The physiological effects observed in experimental studies often seem to indicate a general slowdown of physiological and psychological functions. The reduction in wakefulness and related physiological responses are probably to be regarded as secondary reactions to a primary effect on the central nervous system (CNS). The effects of moderate infrasound exposure are thought to be based on the correlation between the hearing perception and the resulting CNS stimulation [14]. The participation of the reticular activating system and the hypothalamus is considered to be of great importance [5]. However, the changes in the physiological reactions are not only ascribed to sound at levels above the hearing threshold**.** The response of the CNS (including RAS, hypothalamus, limbic system, and cortical region) are probably also highly influenced by the quality of sound. Thus, some frequencies and characteristics are probably more effective than others in producing weariness [15].

To sum up, it is assumed that infrasound that cannot be heard is not annoying, and it is believed that it has no other adverse or health effects. It is also assumed that infrasound only slightly above the hearing threshold may be annoying.

3. Effects of LFN on humans

There is a large number of studies on health impacts due to occupational and environmental exposure to noise. However, there are still few studies focusing exclusively on health impacts and discomfort due to LFN. One of the main reasons for this is the low sensitivity of the human auditory system to low frequencies.

Since LFN includes both infrasonic and low audible frequencies, numerous effects attributed to IS are also reported to be induced by LFN, e.g., pressure sensation in the middle ear, resonant vibrations in some parts of the human body (mainly chest and stomach), speech interference, temporary loss of hearing acuity, and vestibular disturbance (although the latter effect is disputable in case of IS) [2, 3, 6, 10, 11, 16-18].

However, annoyance is the major and the most frequent effect of the LFN exposure on human subjects, especially at their homes, and it is often accompanied by secondary effects, such as headache, concentration difficulties palpitations and sleep problems [19]. Furthermore, some studies suggest an association between LFN and various physiological and psychological reactions such as annoyance, hearing threshold shift, concentration problems, lower sleep quality, mood effects [19-22] and also controversial conditions such as the so-called vibro-acoustic disease [23]. Additionally, adverse health effects from occupational exposure have been observed on memory, annoyance and performance [24-26]. Evidence on vascular and respiratory effects is inconclusive [27].

However, evidence, especially in relation to chronic medical conditions, is limited. Epidemiological research on LFN and health effects is scarce. LFN in the everyday environment constitutes an issue that requires more research attention [28, 29].

4. Measuring methods

The draft proposal of international standard [30] suggested the use of two weighting characteristics (named G1 and G2) in order to describe infrasound in the frequency region below 20 Hz (Figure 1). These curves were asymptotically weighted in straight lines with different slope. Between 1 and 20 Hz the lines had the slope of 12 dB per octave and 6 dB per octave for G1 and G2 curves, respectively. At frequencies above 20 Hz, both curves had cut-offs with the rates of 24 dB per octave. Below 1 Hz the slopes were 12 dB per octave and 18 dB per octave for G1 and G2 characteristics, respectively.

As human tolerance to infrasound is defined by threshold of hearing perception, the frequency-weighting characteristics G1 have the same slope between 1 and 20 Hz (close to 12 dB per octave) as the hearing threshold curves, equal loudness curves and equal annoyance curves. The G2 curve did not have a scientific basic; it was simply a result of a compromise between the G1 curve and linear curve. The G1 weighting network gave values that corresponded much better with the subjective annoyance rating than G2-weighting filter [9].

Thus, in the final version of ISO 7196:1995 [31] only the G1 curve was left and after slight modifications it was renamed as the G-weighting characteristics. Furthermore, the average hearing threshold for infrasound corresponds to tones each having a G-weighted SPL of approx. L_{pG} = 96 dB.

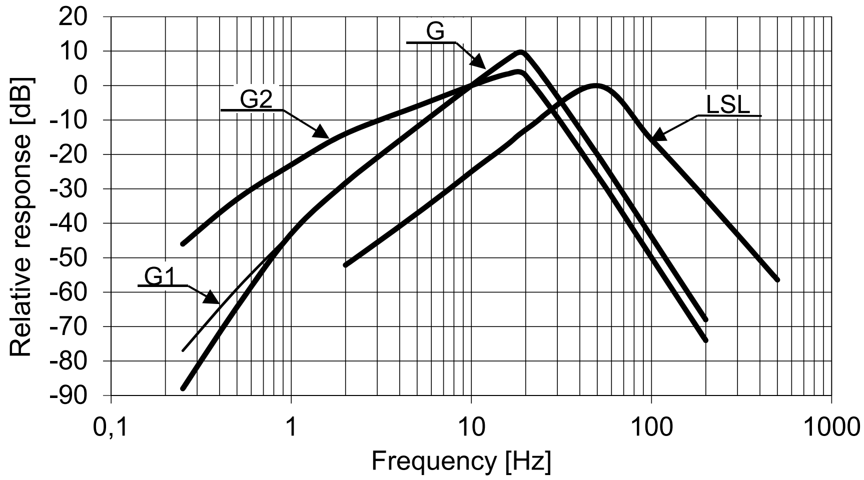

Figure 1. Nominal G1-, G2-, G- and LSL-weighting characteristics [30, 32]

For evaluating noise containing not only infrasonic but also the audible frequencies, especially in living environments, another type of frequency weighting curve named LSL (abbreviation for low-frequency sound level) was proposed in Japan. It had a dominant frequency of 50 Hz and +12 dB per octave and -18 dB per octave slopes in the lower and upper frequency range, respectively (Figure 1) [32].

Since the threshold of hearing perception defines human tolerance of infrasound it is sometimes thought that any pertinent hygienic evaluation of infrasound should consequently be based on the frequency analysis [15].

As regards LFN, many studies have indicated that A-weighted sound pressure level (SPL) is less suitable descriptor for assessing effects of LFN [18, 19, 33]. Therefore, the usage of the C-weighting has been proposed instead by WHO [34].

5. Review of exposure limits for infrasound

The first proposals of criteria for infrasound exposure were presented at Colloquium on Infrasound, in Paris, in 1973 [3]. During that conference two groups of researchers, one led by Stan (Figure 2) and the other led by Pimonow (Table 1), presented the results of their research. These studies suggested that exposure to infrasound at sound pressure levels (SPL) above 180 dB posed a risk of death, and that a 2-minute exposure at levels in the 150–172 dB range is tolerated by healthy individuals, while many hours of exposure to levels of 120–140 dB might induce fatigue and health disorders [3].

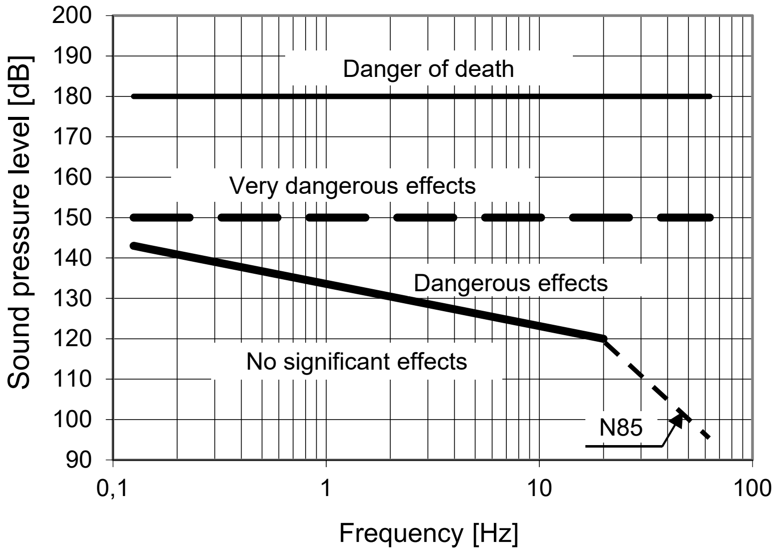

Figure 2. Limiting levels for effects of infrasound proposed by M. Stan [3]

Table 1. Zones of infrasound health effects specified by L. Pimonow [35]

Zone	Sound pressure level, L_p [dB]	Consequences
I	$L_p \geq 185$ dB	fatal danger (the variable pressure of such levels can induce pulmonary alveolar rupture)
II	$172 \geq L_p > 140$	2-minute exposure is tolerable for the healthy human
III	$140 \geq L_p > 120$	exposure is able to induce mild physical disturbances and fatigue in case of many hour exposures
IV	$120 \geq L_p$	no health harmful effects if time of exposure is less than several minutes; reactions of the long-time exposure are the subject for future studies

Somewhat later, the first criteria for assessing infrasound exposure began to be set. In the USA, in 1977 the Committee on Hearing, Bioacoustics and Biomechanics (CHABA) proposed limit values for urban exposure (uncontrolled population) (Table 2) [6].

Table 2. Limit values of the environmental exposure to infrasound according to CHABA [6]

Frequency f [Hz]	Permissible SPL [dB]			Notes
	Time of exposure T_e [min]			
	$T_e \leq 1$	$1 < T_e \leq 100$	$T_e > 100$	
$0,1 \leq f \leq 5$	120	$120-10 \lg T_e$	100	The threshold of annoyance related to the occurrence of vibrations in the building structures or the feeling of pressure in the middle ear
$5 < f \leq 20$	$120-30 \log(f/5)$	$120-30 \log(f/5) - 10 \lg T_e$	$100-30 \log(f/5)$	

6. Limit values of environmental exposure to infrasound

In Denmark a set of guidelines for measurement and assessment of environmental LFN, infrasound, noise and vibration was published in 1997 as Information from the Danish Environmental Protection Agency no. 9/1997 [36]. Given that the environmentally acceptable infrasound level must be below the hearing threshold (HT), thus the recommended limit value for infrasound inside dwellings during the day, evening and night and inside classrooms and offices is 85 dBG (Table 3). For occupied rooms in commercial enterprises the limit is 90 dBG. The noise is measured over a 10-minute period and a 5 dB penalty is added for impulsive noise e.g. single blows from a press or drop forge hammer [36].

Table 3. Recommended limits for infrasound, LFN and noise indoors according to the Danish Environmental Protection Agency no. 9/1997 [36]

Type of space	Infrasound* L_{Geq}	LFN $L_{p\,ALF}$	Noise $L_{p\,Aeq}$
Dwelling (evening & night)	85 dBG	20 dBA	30/ 25 dBA
Dwelling (day)	85 dBG	25 dBA	30 dBA
Classroom, office etc.	85 dBG	30 dBA	40 dBA
Other rooms in enterprises	90 dBG	35 dBA	50 dBA

*If the noise is impulsive, e.g. from single blows with a press or a forging hammer, the recommended limits are reduced by 5 dB

In Queensland (Australia), a low frequency noise guidelines have been developed by the Environmental Protection Agency [37]. These guidelines are applicable to infrasound and LFN emitted from industrial premises, commercial premises and mining operations (not blasting), and is intended for planning purposes as well as for the evaluation of existing problems. Similar to the Danish recommendations, the limit value of the G-weighted sound pressure level inside dwellings, classrooms and offices is 85 dBG.

In June 2004, the Ministry of the Environment of Japan published "Handbook to Deal with Low Frequency Noise, which suggest "reference values to deal with complaints about low level LFN from stationary sound sources like factory plant and facilities such as shops, which generate LFN continuously. This handbook is not applicable to fluctuating or impulsive LFN emitted by such sources as roads, airplanes, railways, and blasts. Regarding infrasound and analyzing the prevalence of complaints of mental and physical discomfort, if the measured G-weighted SPL is ≥ 92 dB, it is very likely that there is an effect of infrasound [38].

7. Criteria for assessing exposure to LFN indoors

Over the years many different methods have been suggested for the assessment of LFN in the general environment (dwellings) indoors. Exposure criteria are in use or are proposed in Sweden, the Netherlands, Denmark, Germany, Poland, Finland, the United Kingdom, Austria, Australia and Japan.

For example, the Swedish method is based on the frequency analysis in 1/3-octave bands from 31.5 to 200 Hz [20]. The measured (equivalent-continuous) SPLs are compared with criterion curve specified by the National Board of Health and Welfare (Table 4).

Table 4. Limit values of exposure to LFN indoors according to the Swedish National Board of Health and Welfare [20, 39]

f [Hz]	31.5	40	50	63	80	100	125	160	200
$L_{f\,eq}$ [dB]	56	49	43	41.5	40	38	36	34	32

In the Netherlands, several proposals of criteria for assessing LFN have been prepared, including a criterion based on the frequency analysis in the 1/3-octave bands from 20 to 100 Hz and the median hearing thresholds of the 10% best-hearing individuals from an unselected age group of 50-60 years taken as reference values (Table 5). These levels are typically 4-5 dB lower than the average threshold for otologically normal young adults (18-25 years) as given in [40]. Thus, this method determines if LFN is audible or not, rather that it is annoying [41, 42].

Table 5. Limit values of exposure to LFN indoors according to the Dutch audibility criterion [41]

f [Hz]	20	25	31.5	40	50	63	80	100
$L_{f\,eq}$ [dB]	74	64	55	46	39	33	27	22

The Finnish guidelines of the Ministry of Social Affairs define the permissible values of the 1-hour equivalent-continuous SPLs in the 1/3-octave bands from 20 to 200 Hz at night (Table 6) [44].

Table 6. Limit values of exposure to LFN indoors according to the Finnish guidelines [43]

f [Hz]	20	25	31.5	40	50	63	80	100	125	160	200
$L_{Aeq,\,1h}$ [dB]	74	64	56	49	44	42	40	38	36	34	32

In Denmark, according to the guidelines of Environmental Protection Agency [36], the exposure to LFN is evaluated based on the low frequency A-weighted sound pressure level ($L_{pA,\,LF}$), which is determined from the results of the frequency analysis using the following formula (1):

$$L_{pA,LF} = 10 \times \log \sum_{f=10Hz}^{160Hz} 10^{0,1 \times (L_{fieq} + K_{Af})} \tag{1}$$

where:

L_f is the measured sound pressure level in 1/3-octave frequency bands from 10 to 160 Hz, K_{Af} is the value of the A-weighted correction from 10 to 160 Hz.

In addition, a 5 dB penalty for impulsive noise is taken into consideration. The recommended limit values (of the $L_{pA,LF}$ levels averaged over 10 min) in dwellings are 20 dB during the night/evening and 25 dB during the day. On the other hand, the $L_{pA,LF}$ level in classrooms, offices etc. should not exceed 30 dB, while in other rooms it should be lower than 35 dB [36].

In Germany, according to the recommendation of DIN 45680:1997 [44], a difference between the (equivalent or maximum) C- and A-weighted SPLs ≥ 20 dB indicates the occurrence of LFN. The assessment is based on a frequency analysis in the 1/3-octave frequency bands between 10 and 80 Hz. However, in exceptional cases the 1/3-octave bands of 8 Hz and/or 100 Hz are also considered. The assessment takes into account the tonal character of the noise. The noise is considered tonal if in any 1/3-octave frequency band the sound pressure level is at least 5 dB greater than the levels in the two adjacent bands.

If the noise is tonal, the sound pressure level of the 1/3-octave band with tone is compared with the hearing threshold modified by penalty, depending on the frequency and a time of the day (Table 7).

Table 7. Criterion curve specified in DIN 45680:1997 [44]

f [Hz]	8	10	12.5	16	20	25	31,5	40	50	63	80	100
L_{HS} [dB]	103 +5/0	95 +5/0	87 +5/0	79 +5/0	71 +5/0	63 +5/0	55.5 +5/0	48 +5/0	40.5 +5/0	33.5 +5/0	28 +10/5	23.5 +10/5

*Penalty for tonal noise in the day/night period

On the other hand, in case of non-tonal noise, the A-weighted SPL in the 10–80 Hz frequency range is calculated based only on bands exceeding the hearing threshold levels LHs (close to those of ISO 226:2003 [40]. The maximum acceptable level for the A-weighted equivalent SPL (1080 Hz) is 35 dB during daytime and 25 dB during the night. In turn, the limit for the A-weighted maximum SPL is 45 dB during daytime and 35 dB during the night. night period, respectively [44].

In 1995-1998, the Polish criteria for the assessment of LFN in residential buildings in were developed the Building Research Institute. The frequency analysis in the 1/3-octave bands from 10 to 250 Hz was adopted as the basis for the evaluation of exposure to LFN from equipment installed inside and outside the building. The A10 characteristic has been accepted as the reference curve. (The reference curve has been derived from $L_{f\,A10} = 10 - K_{Af}$, where L_{fA10} is sound pressure level in the f-th 1/3-octave band, K_{Af} is the value of the A-weighting characteristics in the f-th 1/3-octave band; f is from 10 to 250 Hz) [45].

According to the Instruction No 358 of the Building Research Institute [46], LFN is annoying if the sound pressure levels exceed the A10 curve and simultaneously exceed the background noise level by more than 10 dB for tonal noise and by 6 dB for broadband noise.

In 2018, after some updates, the aforesaid method for evaluating exposure to LFN indoors has been published as Polish standard PN-B-02151-2:2018-2 [47]. According to this standard, the noise is considered as LFN if the difference between the (equivalent or maximum) C- and A-weighted SPLs exceeds 20 dB or if the noise spectrum measured in the 1/3-octave bands from 12.5 to 250 Hz has at least one component 5 dB above the reference curve A10.

In Great Britain, for a number of years, the so-called low frequency noise rating curves (LFNR curves), which were a modification of noise rating curves (audible) (NR curves), were used to assess LFN in residential premises. However, in 2005 new proposals of the criteria for the assessment of LFN disturbances were prepared by the Department for Environment, Food and Rural Affairs (DEFRA). These were based on measurement of equivalent-continuous sound pressure level ($L_{feq,T}$) and statistical levels L_{10} and L_{90} in 1/3-octave bands between 10 Hz and 160 Hz. The proposed reference values – based on the (Table 8) can be increased by 5 dB if the noise occurs only during daytime or if noise is steady [48]. A noise is considered steady if either L_{10}-L_{90} < 5 dB or the rate of change of SPL (measured with the time constant Fast) is less than 10 dB/s.

Table 8. Limit values for exposure to LFN indoors according to the DEFRA recommendations [48]

f [Hz]	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
$L_{f\,eq}$ [dB]	92	87	83	74	64	56	49	43	42	40	38	36	34

In the Australian state of Queensland, according to the Guidelines of the Environmental Protection Agency, the initial assessment of LFN is to check that the total sound pressure level in the living areas does not exceed 50 dB ($L_{LINeq} \leq 50$ dB) [36].

If $L_{LINeq} - L_{Aeq} > 15$ dB then further frequency analysis in the 1/3-octave bands between 20 and 200 Hz is required. In the next step, these results should be compared with the reference curve, i.e., with the median hearing threshold level for the best 10% of the older population (55-60 years old) (Table 9) to determine the degree of LFN audibility. It should be also check for the existence of an amplitude-modulating component, where the noise level changes cyclically at a particular 1/3-octave band frequency. The added perception of loudness caused by this attribute can be accounted for by subtracting a 5 dB penalty from the L_{HS} value [36].

For tonal noise, the level in the frequency band/s with the tone/s is compared to the hearing threshold level (L_{HS}) in the corresponding bands (Table 9). It is then found how much the tonal value is above the threshold level. The levels in the other frequency bands are not taken into account. The limit values for exceedance of the threshold table values by the equivalent level of the tone/s are as given in Table 10.

Table 9. Criterion curve for LFN indoors according to guideline of the Environmental Protection Agency in Queensland [36]

f [Hz]	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
L_{HS} [dB]	96	92	88	84	75	62	55	46	39	33	27	22	18	14	10

Table 10. Limit values for exceedance for annoyance due to tonal noise [36]

Period	**1/3-octave frequency band**			
	8 Hz to 63 Hz	80 Hz	100 Hz	> 100 Hz and < 200 Hz
Day	5	10	15	17
Evening/night	0	5	10	12

On the other hand, for the non-tonal noise, the low frequency A-weighted SPL ($L_{pA,LF}$) is determined based on results of frequency analysis using the equation (1). The noise is considered acceptable if the corresponding limit value given in the Table 11 is not exceeded.

Table 11. Limit values for non-tonal low frequency noise ($L_{pA,LF}$) [36]

Type of space	**$L_{pA,LF}$ (dBA)***
Dwelling, evening and night (18:00 – 7:00)	20
Dwelling, day (7:00 – 18:00)	25
Classroom, office, etc.	30
Rooms with commercial enterprises	35

*If the LFN is impulsive in nature (e.g., forge, disco music), the limit values are reduced by 5 dB

As mentioned earlier, the Ministry of the Environment of Japan published "Handbook to Deal with Low Frequency Noise", which suggest reference values to deal with complaints about low level LFN from stationary sound sources like factory plant and facilities such as shops, which generate LFN continuously. This handbook is not applicable to fluctuating or impulsive LFN emitted by such sources as roads, airplanes, railways, and blasts [38].

As regards LFN, the reference values have been established for complaints of mental and physical discomfort and because of rattling (vibration). These have been defined in the 1/3-octave bands 10–80 Hz (Table 12) and 5–50 Hz (Table 13), respectively.

Table 12. Reference values for complaints of mental and physical discomfort [38]

f [Hz]	10	12.5	16	20	25	31.5	40	50	63	80
L_f [dB]	92	88	83	76	70	64	57	52	47	41

Table 13. Reference values for complaints of rattling windows and doors [38]

f [Hz]	5	6.3	8	10	12,5	16	20	25	31.5	40	50
L_f [dB]	70	71	72	73	75	77	80	83	87	93	99

If the 1/3-octave band SPL is higher or equal to the reference values for mental and physical discomfort (Table 12), at any frequency band, it is highly likely that the frequency band is the cause of the complaint. Additionally, if the measured G-weighted SPL is 92 dB or higher, it is highly likely that there is an effect from infrasound. If the measured value is less than the reference value at every frequency, noise, ground vibration, and other factors are needed to be surveyed [38].

On the other hand, when 1⁄3-octave band SPL exceed the reference value for rattling of doors or windows (Table 13) in any frequency band, it is highly possible that this frequency band is the cause of the complaint. If the 1⁄3-octave band SPL are less than the reference value for complaints of rattling, however, rattling will occur rarely. In this case, it is necessary to look for another cause, for example ground vibration or noise, for the complaints [38].

So far, Denmark is one of the few countries where it has been established indoor acceptable LFN levels for wind turbine noise. According to Danish Turbine Noise Ordinance no. 1284 of 15 December 2011 [49], the basis for the assessment of LFN in dwellings (residential buildings) is the low-frequency A-weighted SPL ($L_{pA,LF}$) determined by the computational method. The calculated $L_{pA,LF}$ level at wind speeds of 6 and 8 m/s must not exceed 20 dBA.

8. Criteria for assessing exposure to LFN outdoors

In 1992, a draft version of standard was prepared in Poland which specified the limit values for environmental exposure to continuous and intermittent LFN outdoors. The assessment was based on measurements of sound pressure levels in 1/1-octave bands between 4 and 63 Hz (Table 14) [50].

Table 14. Permissible sound pressure levels in 1/1-octave bands from 4 to 63 Hz for LFN in the general environment outdoors [50]

1/1-octave frequency band [Hz]	Permissible sound pressure level [dB]	
	Continuous noise	Intermittent noise
4	102	102
8	90	90
16	78	78
31.5	65	60
63	51	56

In the United States, in 2005, Hessler [51] proposed criteria for low frequency industrial noise in residential areas, based on his experience in investigating and solving low frequency noise problems, mainly from open cycle combustion turbine installations. Although most LFN criteria are expressed in terms of 1/3-octave band spectra near the ISO 226:2003 [41] definition for the threshold of audible noise, these limit values were expressed as the C-weighted overall levels (Table 15). Their author believes that the recommended C-weighted limits are applicable to most common steady low-frequency noise sources in addition to combustion turbines due to the combined tonal and broadband character of the sound.

Table 15. Maximum allowable dBC levels at residential areas to minimize resident complaints from low-frequency industrial sources [51]

	For normal suburban/urban residential areas, daytime residual level, L_{90} > 40 dBA	For very quiet suburban or rural residential areas, daytime residual level, L_{90} < 40 dBA
For intermittent daytime only or seasonal source operation	70	65
Extensive or 24/7 source operation	65	60

Ideally, the LFN criteria should be set for indoors where the LFN complaints normally occur. However, for the purpose of planning, it is much easier to establish outdoor limit values. Table 16 presents exposure criteria which were proposed by Broner (2010) [52] based on a review of many case histories and the literature data.

Table 16. Criteria for assessment of LFN outdoors proposed by Broner [52]

	Sensitive receiver	Range criteria	Leq (dBC)
Residential	Night time or plant operation 24/7	Desirable Maximum	60 65
	Daytime or intermittent (1–2 hours)	Desirable Maximum	65 70
Commercial/office	Night time or plant operation 24/7	Desirable Maximum	70 75
Industrial	Daytime or intermittent (1–2 hours)	Desirable Maximum	75 80

It is worth noting that if the measured dBC level is fluctuating (at least ± 5 dBC), thus the above criteria should be reduced by 5 dBC. What's more, when measuring the noise, all energy down to 10 Hz should be considered and a minimum sampling duration of 3–5 minutes should be used so as not to average out the LFN fluctuations which are characteristic of many LFN problems. This is further to ensure that the low frequency sound level is sampled accurately.

According to the aforesaid Australian researcher [52], the noise levels to be recorded are the maximum and minimum C-weighted SPL's using the Fast time weighting, the L_{C10} and L_{C90} levels for the purpose of providing an indication of the level fluctuation of the LFN. The same metrics are to be recorded using the A-weighting instead of the C-weighting.

In Australian State of New South Wales, it is recommended to measure the C-weighted sound pressure levels at intermediate locations to identify any anomalies such as mechanical problem or a need for any further investigations. As the LFN limit values were adopted sound pressure levels (65/60 dBC) which were proposed by Broner (2010) [52]. In addition, a 5 dB penalty is applied to the measured noise level for the periods and meteorological conditions under which the LFN has been identified. Moreover, it has been assumed that the difference dB(C) – dB(A) > 15 dB indicates the presence of LFN [53].

The recommendations of the state of South Australia follow the suggestions made by the New South Wales Industrial Noise Policy, but do not provide any specific limit or required actions [53].

In Canadian province of Alberta, it is assumed that the LFN problem occurs when the time-weighted difference between C- and A-weighted sound pressure levels for the measured period of day or night time is ≥ 20 dB, and a clear tonal component is present within the frequency below 250 Hz [53]. When a LFN has been identified, measurements of C- and A-weighted SPLs are to be made simultaneously. The following two criteria indicate the presence of a low frequency noise measured at a dwelling. Satisfying only one criterion does not result in a finding that low frequency noise is present. Firstly, the isolated (e.g. non-facility noise, such as wind noise, has been removed) time-weighted average dBC – dBA value for the measured daytime or night-time period is equal to or greater than 20 dB. Secondly, a clear tonal component exists between 20 to 250 Hz, i.e., for the 1/3-octave bands from 20 to 250 Hz: (i) the linear sound pressure level of one band must be at least 10 dB or more above one of the adjacent bands within two one-third octave bandwidths, and (ii) there must be at least a 5 dB drop in level within two bandwidths on the opposite side of the frequency band exhibiting the high sound level.

If a LFN condition as defined above exists, 5 dB must be added to the measured comprehensive sound level. If this value exceeds the permissible sound level, the licensee must identify the source of the low frequency noise and implement noise attenuation measure to address the issue in a timely way. Once LFN control measures have been implemented, a follow-up comprehensive sound level and complaint investigation must be conducted to confirm that the low frequency noise condition has successfully been addressed. Since wind generates high levels of low frequency sound that can mask the assessment of low frequency noise. Measurements of LFN should only be taken when atmospheric conditions are favorable for accurate measurement [53].

In Japan, reference values for outdoor LFN measurements are specified in the handbook cited earlier. These values provide guidelines for how to handle complaints about rattling windows and doors, given for 1/3-octave bands from 5 Hz to 50 Hz [38].

9. Discussion and conclusions

Although, over one hundred years ago, the American scientist and businessman Charles F. Brush was the first to use wind energy to produce electricity, a wind turbines are relatively new sources of infrasound and LFN, and their effects on health and well-being are not fully recognized. Wind turbines are specific type of noise source, which has impact on large areas. The noise emitted by wind turbines does not resemble the common industrial noise – it has a different temporal-spectral characteristics [54].

Research on the impact of wind turbine noise (WTN) focuses on noise annoyance, sleep disturbance, quality of life, general health and mental health issues. Sustained research on the impact of wind turbine noise began in 2007 [55]. Recently, more and more attention has been given to of LFN and infrasound. In particular, it has been suggested that IS and LFN may be responsible for adverse health effects in people living in the vicinity of wind farms. Meanwhile, it does not seem to be completely true.

For example, recently a big cross-sectional study was carried out in Finland which aim was to analyze the role of infrasound in health ailments related to wind turbines [56]. The aforesaid study revealed that 70 out of 1.351 respondents (5%) reported symptoms which they attributed to infrasound from a wind farm). The symptomatic respondents lived closer to the wind farm than the asymptomatic respondents. Furthermore, they more often suffered from chronic diseases, complained about the annoyance of wind turbines and believed that wind turbines posed a health risk. What's more, out of all respondents, 10% considered wind turbine infrasound as a high risk to personal health, and 18% as a high risk to health in general [56].

In another Finish study, recordings of the wind turbine noise with the highest levels of infrasound and amplitude modulations were selected for laboratory experiment. It has been shown that people who have reported symptoms related to (infra)sounds showed no increased sensitivity to wind turbine infrasound. Total wind turbine SPL and amplitude modulation resulted in increased annoyance, not infrasound. In turn, the wind turbine IS or wind turbine sound annoyance were not related to either heart rate or heart rate variability, or to skin conductivity (physiological measures of stress) [57].

As regards results of new research concerning the impact of infrasound and LFN in general, most of them have looked at measuring brain activity in response to infrasound, often in comparison with low-frequency or normal sound. The latest research largely confirms the previous results. The perception of infrasound and low frequency sound is generally consistent with what it was known from the literature, and there is no indication that infrasound well below the threshold of hearing may have any effect on humans. This leads to the conclusion that low-frequency sound is part of the total sound of wind turbines and has the same effects normal sound [58, 59].

However, only a few jurisdictions (i.e., Danish, Australian and Japanese), have established IS limits, so far. These criteria are usually not greater than 85–90 dBG and none of them are specific to wind turbines. Furthermore, there are currently also no widely accepted international health based limits for LFN, specifically derived for wind turbines.

For example, LFN outdoor limits have been introduced by some states or provinces in Australia and Canada and by Japan, but they also do not directly apply to wind turbines. A number of them assume that the difference (dB(C) – dB(A)) > 20 dB indicates presence of LFN, and they set the upper limits of L_{Ceq} equal to 65 and 60 dB(C) during the day and night, respectively [53].

In turn, exposure criteria for the assessment of LFN in dwellings are in use or are proposed in some European countries, including Denmark, Germany, Sweden, the Netherlands, Finland, Poland, UK, as well as in Australia, Canada and Japan. However, to the best of the authors' knowledge, Denmark is one of the few countries with regulations that specify indoor acceptable LFN levels which are specific for wind turbine noise. As regards criteria concerning LFN indoors, the majority of them are based on the frequency analysis in 1/3-octave bands in various frequency ranges between 8 and 250 Hz. Basically, measured SPLs are compared with reference values. Only in the Danish and German methods are the results of frequency analysis subjected to further recalculations. On the other hand, low frequencies from 8 Hz or 31.5 Hz were included in guidelines used in German and Swedish criteria, respectively [48]. Also of note is that all criteria curves except Netherlands criteria are lower than the standard hearing threshold levels at frequencies below 31.5 Hz.

It is worth noting that indoor LFN limits provide a basis to address specific complaints from local residents; however, for wind farm development, regular monitoring of outdoor sound levels presents a more practical option.

Given evidence to support that specific wind farm noise acoustic characteristics [60, 54], such as amplitude modulation (AM) and tonality, LFN and infrasound components can contribute to higher perceived annoyance, a specific penalties for these characteristics should be developed. Penalties applied to LFN and infrasound may be more reliable if the real broadband nature of LFN and infrasound is considered [61]. Reasonable approach seems to deal with LFN could be based on allowable limits for 1/3-octave bands as well as an overall allowable limit. Moreover, the percentage of highly annoyed individuals and audibility of LFN and infrasound are highly variable between people and warrants further larger well-controlled studies.

Nevertheless, infrasound and LFN limits for wind farms cannot be recommended in the absence of definite evidence of health effects from IS or LFN. Thus, further studies are needed before firm conclusions can be drawn.

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Chapter 4

The risk of musicians' high sound exposure during performances of classical music

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Abstract
When playing instruments, musicians are exposed to loud sounds that can increase the risk of music-induced hearing loss (MIHL). The purpose of this study was to measure the sound exposure for a group of musicians playing classical music, and to examine how this exposure varies with the type of musical activity. Sound level was measured for a group of musicians using dual-channel noise dosimetry, with microphones attached near the right and left ear. The measurements were performed during individual practice and playing in musical ensembles. The equivalent sound level L_{Aeq} and daily sound exposure $L_{EX,8h}$ were measured separately for the right and left ear. In 74% of the measured samples the daily sound exposure ($L_{EX,8h}$) exceeded 85 dB. The data indicated a significant risk of music-induced hearing loss in musicians performing classical music, especially when playing the flute, violin, viola, trombone, and saxophone. Musicians playing violin, viola, flute, and harp experienced asymmetric sound exposure with significant difference between the right and left ear.

Keywords: sound exposure, music-induced hearing loss, noise dosimetry

1. Introduction

Musicians' exposure to high-level sounds during daily rehearsals and performances can lead to temporary and permanent hearing problems, even including noise-induced hearing loss (NIHL). Harmful sound pressure levels, although mainly associated with unwanted and unpleasant sounds, also occur during the daily work of musicians performing either classical and popular music [1-3] and can be as damaging to hearing as industrial noise [4].

When music is the cause of hearing loss, it is referred to as music-induced hearing loss (MIHL). A number of papers in the literature indicate that musicians are exposed to high-level sounds both when playing an instrument individually [5, 6] and when playing in chamber ensembles and orchestras [7, 8]. Most data focused on examining the risks associated with only one type of musical activity, most commonly playing in a large symphony orchestras, while there are few studies that take into account variety of musical activity as well as their duration throughout the day. The purpose of this study was to conduct sufficiently comprehensive measurement of musicians' exposure to sound, taking into account the variety of activities in which musicians can participate.

2. Methodology

The study was conducted with the participation of twenty-seven students from the Fryderyk Chopin University of Music in Warsaw (UMFC), playing: flute (1 person), clarinet (2), saxophone (1), French horn (2), trumpet (4), trombone (5), tuba (1), violin (3), viola (1), cello (2), double bass (1), harp (2) and percussion instruments (2).

The musicians indicated the most typical days in terms of the number of hours spent at the university and the type of activities performed. Sound pressure level was measured with the use of two dual-channel noise dosimeters (Svantek SV 102+), meeting the requirements of Class 2 sound level meters, equipped with SV 25D measurement microphones, which were calibrated before each measurement. On designated days, musicians were equipped with the dosimeter whose microphones were mounted on musicians' shoulders, approximately 10-15 cm from their ears, symmetrically on both sides of the head. For such instruments as violin, viola, harp, and trombone, the microphones were placed on the back of the arm due to the need to maintain the comfort of the musician playing. The dosimeters recorded the A-weighted equivalent continuous sound pressure level averaged over each second of measurement, which was saved to a result file. Further data analysis was performed using SvanPC++ and Matlab software. The A-weighted equivalent continuous sound pressure level L_{Aeq} recorded within one-second intervals was then used to calculate the daily sound exposure level, i.e., the A-weighted noise exposure level normalized to an 8-hour working day ($L_{\mathrm{EX,8h}}$) and represented musician's exposure to sound during full day of activities.

3. Results

The daily sound exposure level $L_{\mathrm{EX,8h}}$ is the major parameter used in the evaluation of the occupational hearing loss risk. At the workplace, $L_{\mathrm{EX,8h}}$ must not exceed 85 dB [9]. In this study, for each musician playing different instrument, the value of $L_{\mathrm{EX,8h}}$ was determined for each day of their activity. Depending on particular person the measurement included one to seven days.

The daily sound exposure level $L_{\mathrm{EX,8h}}$ exceeded the permissible value of 85 dB for 31 out of 42 days (74%) on which measurements were conducted. In more detail, the $L_{\mathrm{EX,8h}}$ values of 85-90 dB and

90-95 dB occurred at the highest rate of 24% and 40%, respectively (Figure 1). In 7% of the measured days, the $L_{EX,8h}$ values were in 95-100 dB range, and in 2% (i.e., one day), exceeded 100 dB. It is remarkable that the $L_{EX,8h}$ levels were below 85 dB for relatively small fraction (26%) of the measurement days.

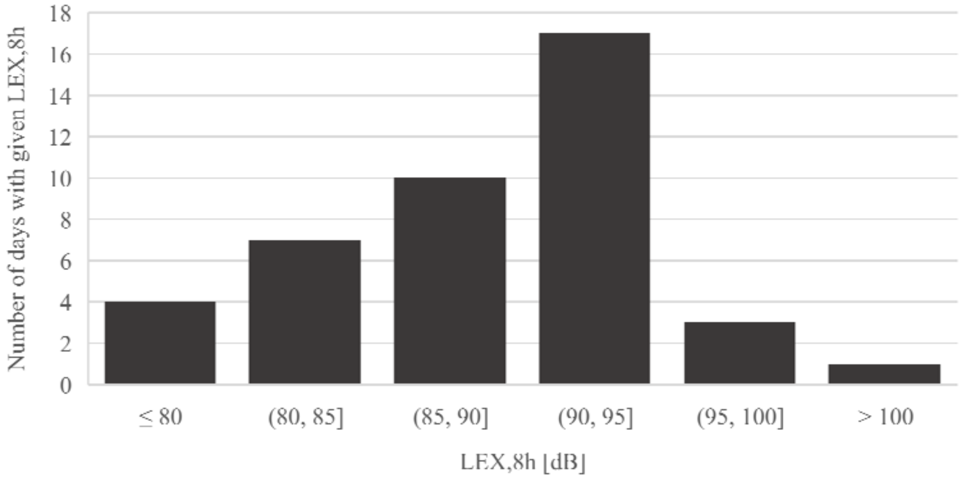

Figure 1. Histogram of the $L_{EX,8h}$ values

Figure 2 shows values of L_{Aeq} recorded for each instrument at different activities. In most cases, the highest L_{Aeq} were found during musicians' individual practice. The highest values of 104.9 dB and 103.5 dB were measured in solo flute and violin playing. Smaller but still significant values of 95 were observed for musicians playing the violin, trumpet, and harp. Playing percussion, trombone, French horn and clarinet produced levels exceeding 90 dB. This shows that individual practice can be an important component of musicians' daily sound exposure.

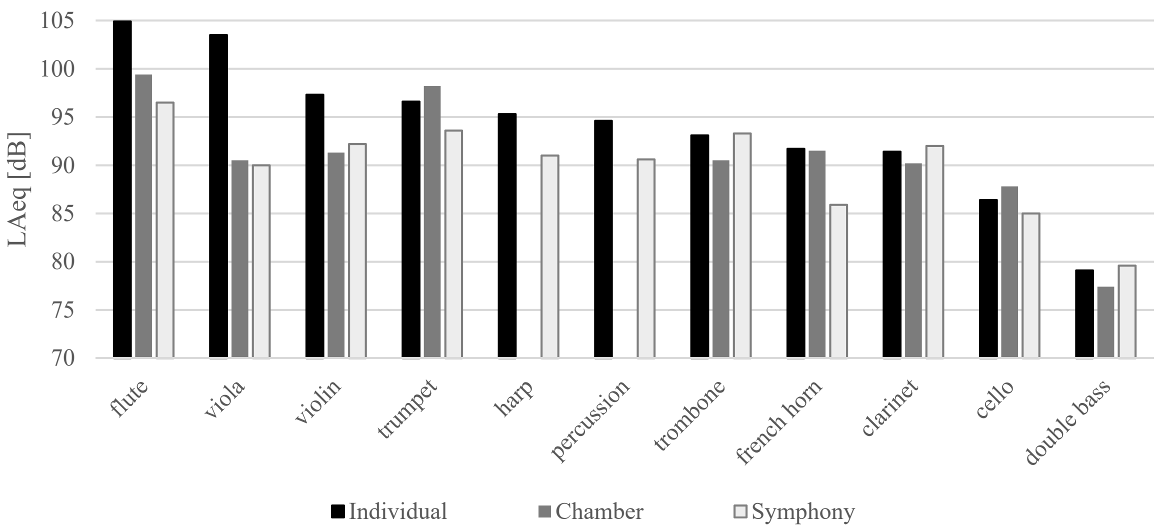

Figure 2. A-weighted equivalent continuous sound pressure level (L_{Aeq}) during individual practice, playing in chamber ensembles and symphony orchestra

Playing in chamber ensembles, was associated with the highest L_{Aeq} experienced by flutists (99.4 dB) and trumpeters (98.2 dB). For musicians playing French horn, violin, trombone, viola, and clarinet, the L_{Aeq} levels were lower but still exceeding 90 dB. As is the case of individual playing the lowest L_{Aeq} values occurred for cellists and double bass players. Playing in symphony orchestra was associated with the highest L_{Aeq} of 96.5 dB for flutist. The L_{Aeq} values exceeded 90 dB for musicians playing trumpet, trombone, violin, clarinet, harp and percussion.

Analysis of the differences in L_{Aeq} levels between the right and left ears are shown in Figure 3. Positive values indicate that the right ear was more exposed than the left ear. This was the case for harp, flute, French horn, percussion, double bass and saxophone players. Negative values in Figure 3 occurring for viola, violin, tuba, clarinet and trombone mean that the left ear was more exposed to sound than the right ear. However, significant interaural L_{Aeq} differences were observed for viola, violin and harp, and to a lesser extent flute players. In the case of other instruments the interaural difference in L_{Aeq} was less than 2 dB and cannot be considered significant.

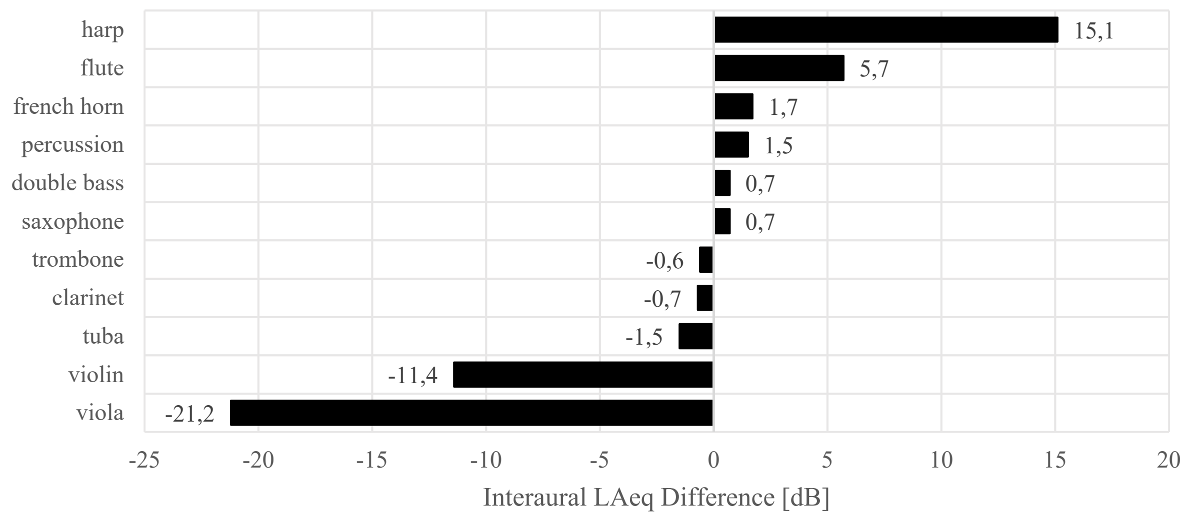

Figure 3. Interaural differences in A-weighted equivalent continuous sound pressure level, L_{Aeq}; positive and negative values indicate respectively more exposed right or left ear

4. Conclusions

This study analyzed the sound exposure of musicians during individual practice, playing in chamber ensembles and in symphony orchestra. Obtained musicians' daily sound exposure level ($L_{EX,8h}$), calculated from the equivalent sound level L_{Aeq} measured using noise dosimetry, can be considered as affecting their hearing for the majority of conditions.

Although musicians devoted an average of 4 hours per day to professional musical activities, yet the 85 dB value of the $L_{EX,8h}$ level was exceeded in 74% of occurrences. The sound generated by many instruments was of such a high SPL that even within a short exposure time (as compared to an 8-hour work day) the sound dose to which musicians were exposed was significant.

The highest L_{Aeq} were recorded during individual practicing. This indicates that this important activity in every musician curriculum is a significant threat to hearing. For flute and viola L_{Aeq} during individual practice exceeded 100 dB, for violin, trumpet and harp values were greater than 95 dB.

Significant asymmetry of L_{Aeq} between the right and left ears was recorded for harp, flute (right ear more exposed), violin and viola (left ear more exposed), which is related to the way the instrument is held, at close proximity to the right or left ear.

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Chapter 5

Assessment of noise annoyance in medical facilities

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Abstract
Inadequate acoustic conditions at workplaces in medical facilities are the result of noise coming from outside of the room, noise from any apparatus or tools used and reverberation noise, resulting from room characteristics. The assessment of noise annoyance in workplaces at selected medical facilities in Poland was carried out. This assessment was conducted by means of a direct-personal interview technique using a categorized paper questionnaire interview among 301 people (physicians, nurses and diagnostic laboratory staff). The obtained results showed among others that noise is the biggest source of annoyance for nurses, less for employees of diagnostic laboratories and physicians. The average grading of noise annoyance in workplaces on a scale from 0 to 10 was 2.77, and therefore the noise annoyance was assessed as slightly.

Keywords: noise, medical facility, workplace, annoyance

1. Introduction

According to the latest data of the Statistics Poland [1], in 2020 Poland 542,186 persons were employed in the "Human health care and social work activities" section. Among this group of employees, 17,501 persons were exposed to the risks arising from work environment, i.e. they were exposed to hazards connected with the work environment, strenuous work or mechanical factors associated with particularly dangerous machinery and devices.

The risks arising from work environment concern exposure to chemicals, dusts, noise, mechanical vibrations, hot or cold microclimate, radiation, electromagnetic fields, biological agents, etc. On the other hand, the risks arising from strenuous work include excessive physical exertion and insufficient lighting. In turn, risks associated with particularly dangerous machines and devices in medical facilities is associated with the use of saws and high-speed drills (used during surgical procedures).

The quoted at the beginning data of the Statistics Poland, as well as literature data (e.g. [2-8]) and the results of own research (i.e. conducted by the Central Institute for Labour Protection – National Research Institute (CIOP-PIB)) [9-11] in the field of objective assessment of working environment factors in medical facilities confirm the occurrence of cases in which the limit values of factors harmful to health in the work environment are exceeded. In the case of noise in operating rooms, the A-weighted sound pressure level from saws and drills reaches up to 110 dBA, e.g. during hip replacement, the levels measured by CIOP-PIB employees reached values within 90 dBA.

The paper discusses the results of surveys on the assessment of working conditions in medical facilities due to noise.

2. Research method

According to surveys conducted periodically by the European Foundation for the Improvement of Living and Working Conditions (Eurofound) in Dublin as part of the reviews of working conditions, there is a need to assess hazards in the working environment both by objective and subjective methods. Subjective risk assessments are determined by the individual characteristics of employees, the psychological conditions of their work, as well as the sense of occupational risk. They constitute an indirect method for the employees' assessment of occupational hazards and their effects on health and life. The significance of subjective studies is directly linked to the health definition adopted by the World Health Organization: "*Health is not just the absence of disease or disabilities, but the full physical, mental and social well-being*".

Pursuant to the approved methodological concept, a survey was carried out by means of the technique of the direct interview – personal with the use of the categorized paper-form PAPI structured interview. Each of the respondents answered questions included in the questionnaire. The questionnaire comprised close-ended questions, multiple-choice questions, short or single-word responses and open-ended questions enabling a respondent's free response. The survey was carried out in the area of 5 voivodeships: Mazowieckie, Greater Poland, Silesian, West Pomeranian and Lesser Poland.

3. Characteristics of the studied group

The survey was carried out among 301 respondents (N = 301):

- 151 physicians,
- 120 nurses,
- 30 employees of diagnostic laboratories.

Considering the key division into physicians, nurses and diagnostics laboratory staff from the perspective of the research project, the division of surveyed group, including gender is presented in the following way: men are overrepresented among surveyed physicians – 56.3%, whereas groups of nurses and diagnostics laboratory staff are predominated by women, 99.2% and 60.0% respectively. There is a statistically significant correlation between practiced profession and gender (as relevance = 0.000, that is less than standard threshold of 0.050). Nearly all nurses are women. There is a strong relationship between gender and occupational group $\chi^2 = 94.49$; $p < 0.001$, Cramer's coefficient gauge is $V = 0.560$.

Taking into consideration the type of performed work, it follows that surveyed physicians comprise the oldest age group. The youngest group of respondents accounted for diagnostics laboratory staff. There is a strong correlation between age and occupational group $\chi^2 = 30.619$, $p = 0.001$, Cramer's coefficient gauge is $V = 0.225$ – the correlation is weak.

4. Test results

4.1. Characteristics of working conditions

Definitely top rated working conditions are evaluated by the surveyed physicians – up to 55.0% of indications to answer "very good". Also, the diagnostics laboratory staff highly evaluate their working conditions. The working conditions are relatively worst rated by the surveyed nurses (Table 1). Statistical tests corroborate substantial disparities observed in distribution of responses, which is confirmed by Chi-squared test: $\chi^2 = 49.514$ (Table 2). There is a statistically significant correlation between the evaluation of working conditions and the exercised profession (as relevance = 0.000, that is less than standard threshold of 0.050).

Table 1. Overall appraisal of working conditions and in division into job positions

Rating scale	General results		Physicians		Nurses		Diagnostics laboratory staff	
Very good	115	38.2%	83	55.0%	21	17.5%	11	36.7%
Good	136	45.2%	45	29.8%	72	60.0%	19	63.3%
Average	49	16.3%	22	14.6%	27	22.5%	0	0.0%
Poor	1	0.3%	1	0.7%	0	0.0%	0	0.0%
Very poor	0	0.0%	0	0.0%	0	0.0%	0	0.0%
In total	301	100.0%	151	100.0%	120	100.0%	30	100.0%

Table 2. Overall appraisal of working conditions and in division into job positions – statistical tests

Chi-square tests			
Parameter	Value	df	Asymptotic relevance (bilateral)
Pearson's Chi-squared test	49.514[a]	6	0.000
Likelihood ratio	56.878	6	0.000
Linear relationship test	7.282	1	0.007
N key observations	301		
Symmetric measures			
		Value	Approximate relevance
Nominal by Nominal	Phi	0.406	0.000
	Kramer's V	0.287	0.000
N key observations		301	

The ANOVA non-parametric test for Kruskal-Wallis ranks proved that there is a difference in the appraisal of the working conditions by the particular occupational groups $\chi^2 = 30.84$; $p < 0.001$. The comparison by pairs was made with an application of post-hoc Dunn's test for professional groups. Significant differences were noted between physicians and nurses ($p < 0.001$) and between diagnostics laboratory staff and nurses ($p = 0.018$).

The working conditions are estimated at the lowest rate by nurses, average grade $R_{Avr} = 182.35$ (the scale was designed in such way that if the higher score is, the worse working conditions are), considerably worse comparing to physicians and diagnostics laboratory staff. Diagnostics laboratory staff rate their working conditions as higher, $R_{Avr} = 137.48$. Physicians evaluate their working conditions as highest, $R_{Avr} = 128.77$, however the difference between their appraisal of the working conditions and diagnostics laboratory staff' appraisal is irrelevant.

4.2. Nuisance from factors in work environment

The assessment of nuisance from particular environmental factors proceeded according to scale from 1 to 5, where 1 means no effect of nuisance of a given factor, and 5 signifies the highest level of nuisance. Results were presented by means of average grade, which was accorded to each of the mentioned sources causing a discomfort of work. Among the factors set, the highest rate was given to noise annoyance in the work environment. Average rating of this source of nuisance in the workplace amounted to 2.02 in scale from 1 to 5. The remaining factors of the work environment able to constitute the source of nuisance obtained a much lower average grading. The surveyed employees also pointed to such nuisance factors as: lighting – the average grade is 1.52, mechanical factors causing injuries (e.g. mobile machines and their components, slippery uneven surfaces) – the average grade is 1.37, microclimate – the average grade is 1.27, dusts and chemical substances – the average grade is 1.23, and odour – the average grade is 1.20. Respondents are to a lesser extent exposed to risk of such nuisance as mechanical vibrations (affecting arms or full body) – the average grade is 1.18 and optical radiation (UV, IR) – the average grade is 1.13.

4.3. Nuisance of noise sources in the workplace

According to the respondents, the source of noise causing the highest level of nuisance is the movement of persons inside the building – 51.5% indications. A very high percentage of respondents also pointed to such noise sources as: conversations (including phone calls) – 47.5%, ringing telephones – 42.9% and outdoor traffic (road, railway, air) – 40.9% indications. Subsequent factors such as technical installations of the building (e.g. air-conditioning, elevators), tools, devices as well as apparatuses and medical equipment were indicated by 32.9% and 29.2% of the respondents respectively. Other sources of noise being some sort of nuisance also include: machines and appliances located outdoors (e.g. transformers, wind turbines) – 28.2%, alarm bells – 22.9% and lighting – 19.2% indications.

4.4. Noise annoyance nuisance in the workplace

The crucial issue, which formed the basis for further in-depth analyses necessary for the determination of the correlation between a subjective risk assessment of noise in the workplace, its circumstances and experienced ailments was indication of noise annoyance in the workplace. Each of the respondent made a subjective assessment of noise annoyance by using the scale from 0 to 10, where lower values stand for no annoyance, higher values denote very burdensome noise. The average grading of noise nuisance in the workplace in scale from 0 to 10 was 2.77, and hence the noise annoyance was assessed as slightly. According to data, nurses are those, who assess noise nuisance in the workplace at the highest degree. The average grading in case of nurses equalled 3.47, among diagnostics laboratory staff – 2.37, however among physicians – 2.30.

Based on data, it needs to be ascertained that there is the correlation between an occupational group and noise nuisance in the workplace $\chi^2 = 106.839$; $p < 0.001$. The correlation is weak – coefficient Eta = 0.284 (Table 3).

Table 3. Noise nuisance in the workplace – statistical tests

Chi-squared tests			
Parameter	Value	df	Asymptotic relevance (bilateral)
Pearson's Chi-squared test	106.839[a]	16	0.000
Likelihood ratio	122.134	16	0.000
Linear relationship test	6.638	1	0.010
N key observations	301		
Directional measures			
			Value
Nominal by Sectional	Eta	Dependable variable Noise annoyance in the workplace	0.284
		Dependent variable Group	0.471
Symmetric measures			
		Value	Approximate relevance
Nominal by Nominal	Phi	0.596	0.000
	Kramer's V	0.421	0.000
N key observations		301	

The ANOVA non-parametric test for Kruskal-Wallis ranks showed that there is a difference in the assessment of noise nuisance in the workplace in relation to respective occupational groups $\chi^2 = 27.77$; $p < 0.001$. The comparison by pairs was made with an application of post-hoc Dunn's test for the professional groups. Material differences were noted between physicians and nurses ($p < 0.001$) and between diagnostics laboratory staff and nurses ($p = 0.012$).

Noise annoyance in the workplace is the most closely felt by nurses, average grade $R_{Avr} = 182.95$ (scale was designed in such way that if the higher score is, the higher nuisance is). Noise in the workplace is less inconvenient to diagnostics laboratory staff $R_{Avr} = 132.57$ and to physicians $R_{Avr} = 129.27$.

5. Statistical analysis

In order to show the correlation of noise annoyance in the workplace with other working conditions, Spearman's analysis of the correlation has been made for all respondents (see Table 4). The analysis of the individual quantitative and ordinal variables for experiencing arduousness of noise in the workplace has been presented below.

First of all, a statistical relevance was analysed. If it is lower than 0.050 it means that a given variable significantly correlates with nuisance grading. In such case, additionally the correlation coefficient was taken into consideration – the correlation coefficient takes values from "-1" to "+1". The correlation is stronger, if the value of correlation coefficient will be further from 0.

Positive values denote that with the raising value of a single variable, the other's value increases, and negative values vice versa – with the rise in value of a single variable, it decreases. Considering foregoing information, it arises that a strong dependence concerns working hours on a daily and weekly basis, and sensation of noise and the duration of work in the place of employment. The longer daily/weekly working time, the noise annoyance is higher. Then, the longer job seniority in a particular place of employment, the noise annoyance is lower. The statistically significant scores are highlighted in red (Table 4).

Table 4. Noise annoyance and the number of working hours and job seniority – statistical tests

Spearman's Rho		**Age**	**How many hours a week do you work? open-end question**	**How many hours a day do you work? open-end question**	**How long have you been working in your profession/place of employment (years)? open-ended question**
Noise annoyance in the workplace	Correlation coefficient	0.019	0.687**	0.687**	-0.176**
	Relevance (bilateral)	0.749	0.000	0.000	0.002
	N	301	301	301	301

The correlation of noise annoyance in the workplace with other working factors, well-being and health conditions is presented in the Table 5. The statistically significant scores are highlighted in red.

Table 5. Analysis of correlation of the noise annoyance in the workplace with other working factors, well-being and health conditions

Working factor, well-being and health conditions (question)	**Spearman's Rho**		
	Noise annoyance in the workplace		
	Correlation coefficient	**Relevance (bilateral)**	**N**
How much time do you work in the above-assessed noise?	-0.081	0.163	301
How do you assess your working conditions?	0.709	0.000	301
Mechanical vibrations (affecting arms and full body)	0.204	0.000	301
Noise	0.686	0.000	301
Lighting	0.402	0.000	301
Microclimate	0.423	0.000	301
Optical radiation (UV, IR)	0.247	0.000	301
Mechanical factors causing injuries (e.g. mobile machines and their components, slippery uneven surfaces)	0.095	0.099	301
Dusts and chemical substances	0.377	0.000	301
Odour	0.245	0.000	301
Tools, devices, apparatuses and medical equipment	0.437	0.000	301
Lighting fixtures	0.469	0.000	301
Technical installations of the building (e.g. air-conditioning, elevators)	0.624	0.000	301
Alarm bells	0.342	0.000	301
Ringing telephones	0.366	0.000	301
Conversations (including talks on the phone)	0.563	0.000	301
Movement of persons inside the building	0.699	0.000	301
Machines and appliances located outside the building	0.607	0.000	301
Transformers, wind turbines	0.587	0.000	301
Lighting arduousness in the workplace	0.751	0.000	301
How long do you work in the conditions of the above-assessed lighting?	0.123	0.033	301
Microclimate annoyance in the workplace	0.338	0.000	301
How long do you work in the above-assessed micro-climate?	0.031	0.590	301
I need a complete silence to sleep well at night	-0.324	0.000	301
I need quiet surrounding to work on new tasks and assignments	0.027	0.640	301
When I am at home, I get accustomed to prevalent noise quickly	0.411	0.000	301
I grow really upset when I hear someone talking while I strive to fall asleep	-0.269	0.000	301
I am very sensitive to noisy sounds from the neighborhood	-0.351	0.000	301
When people are loud around me, I cannot concentrate on my work	-0.045	0.438	301

Working factor, well-being and health conditions (question)	Spearman's Rho		
	Noise annoyance in the workplace		
	Correlation coefficient	Relevance (bilateral)	N
I am sensitive to noise	-0.420	0.000	301
My efficiency is considerably lower in noisy surroundings	-0.110	0.058	301
I do not feel well-rested if the preceding night had been noisy	-0.219	0.000	301
I do not mind living by the noisy street	0.446	0.000	301
I am able to accept other discomforts for a quiet place of residence	-0.394	0.000	301
I need peace and quiet to fulfill challenging tasks	0.075	0.195	301
I can fall asleep despite an occurring noise	0.290	0.000	301
How do you assess the general state of your health?	0.450	0.000	301

6. Conclusions

Noise is present in the workplace of almost all nurses (98.3%) and diagnostics laboratory staff (90.0%) and for the majority of physicians (68.9%). For physicians, to a greater extent than in the case of other professional groups, the source of noise is the medical activities performed (e.g. the use of surgical instruments). For nurses, to a greater extent than for other groups, the source of noise is technical installations/devices (e.g. air conditioning, lighting fixtures), noise penetrating from other rooms or corridors, conversations of staff or patients and noise penetrating from outside the building to the room. However, for diagnostics laboratory staff, more than for other groups, the source of noise are the drive systems of tools, equipment, medical devices. It was found that nurses asses noise annoyance in the workplace at the highest nuisance. The average rating of its nuisance on a scale of 0 to 10 (lower values mean noise that is not burdensome or not burdensome, higher values are very annoying noise) is small and amounts to 2.77, while in the case of nurses it is 3.47, and in the case of diagnostics laboratory staff and physicians it is 2.37 and 2.30 respectively.

On the basis of the obtained results it was found that the statistically significant correlations with positive direction of noise annoyance in the workplace with individual operating conditions occur for the following variables:

- assessment of the working conditions Rho = 0.709; $p < 0.001$;
- environmental factors being the source of annoyance:

- mechanical vibrations (affecting arms and full body) Rho = 0.204; $p < 0.001$,
- lighting Rho = 0.402; $p < 0.001$,
- microclimate Rho = 0.423; $p < 0.001$,
- optical radiation (UV, IR) Rho = 0.247; $p < 0.001$,
- dusts and chemical substances Rho = 0.333; $p < 0.001$,
- odour Rho = 0.245; p <0 .001;

■ frequency of noise sources annoyance:
  - tools, devices, apparatuses and medical equipment Rho = 0.437; $p < 0.001$,
  - lighting fixtures Rho = 0.469; $p < 0.001$,
  - technical installations of the building (e.g. air-conditioning, elevators) Rho = 0.624; $p < 0.001$,
  - alarm bells Rho = 0.342; $p < 0.001$,
  - ringing telephones Rho = 0.366; $p < 0.001$,
  - conversations (including talks on the phone) Rho = 0.563; $p < 0.001$,
  - movement of persons inside the building Rho = 0.699; $p < 0.001$,
  - transformers, wind turbines Rho = 0.587; $p < 0.001$;

■ lighting annoyance in the workplace Rho = 0.751; $p < 0.001$;
■ working time in conditions related to lighting Rho = 0.123; p = 0,033;
■ microclimate annoyance in the workplace Rho = 0.388; $p < 0.001$;
■ sensitivity to noise – "*When at home I get accustomed to noise around quickly*" Rho = 0.411; $p < 0.001$;
■ sensitivity to noise – "*I do not find it annoying to live by the noisy street*" Rho = 0.446; $p < 0.001$;
■ sensitivity to noise – "*I am able to fall asleep despite the noise*" Rho = 0.290; $p < 0.001$;
■ overall evaluation of health condition Rho = 0.450; $p < 0.001$.

On the basis of the obtained results it was found that the statistically significant correlations with negative direction of noise annoyance in the workplace with individual operating conditions occur for the following variables:

■ necessity to raise voice at work Rho = -0.253; $p = 0.022$;
■ sensitivity to noise – "*I need a complete silence to sleep well at night*" Rho = -0.324; $p < 0.001$;
■ sensitivity to noise – "*I grow very annoyed when I hear someone talking when I try hard to fall asleep*" Rho = -0.269; $p < 0.001$;

- sensitivity to noise – "*I am very sensitive to noises coming from the neighbour area*" Rho = -0.351; p < 0.001;
- sensitivity to noise – "*I am sensitive to noise*" Rho = -0.420; p <0 .001;
- sensitivity to noise – "*I do not feel well-rested if the previous night had been noisy*" Rho = -0.219; p < 0.001;
- sensitivity to noise – "*I am able to accept other inconveniences for a quiet place of residence*" Rho = -0.394; p < 0.001.

Acknowledgements

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- a research task carried out within the scope of the fifth stage of the National Programme "Improvement of safety and working conditions" supported within the scope of state services by the Ministry of Family, Labour and Social Policy, task no. 3.SP.10 entitled "Ensuring integration with European networks active in the field of occupational safety". The Central Institute for Labour Protection – National Research Institute is the Programme's main co-ordinator.

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Chapter 6

Visualizations of sound behind the space-coiling metamaterial

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Abstract
Acoustic metamaterials are artificial structures that allow to control the propagation of the sound waves. Space-coiling structures are a specific type of metamaterial structure that have great potential to provide narrowband noise reduction and allow for efficiently reflect of sound waves especially in the low frequency range. Many examples of these structures were described with the results of numerical studies or results acquired by transmission loss measurements. The article concerns 3D-printed space-coiling type metamaterial. The construction of metamaterial as well as results of its tests in semi-anechoic chamber (including visualizations of sound intensity level distribution) were presented.

Keywords: space-coiling metamaterials, environmental engineering, sound visualizations

1. Introduction

Acoustic metamaterials are artificial materials, which can be used to control propagation of the sound waves and are used, for example, in acoustic cloaking [1, 2]. Properties of the acoustic metamaterials are determined by its internal structure. By using i.e. specific shape of the structure it is possible to obtain negative refraction [3-5], negative bulk modulus [6-8] or negative mass density [9-11]. The fact that such acoustic metamaterials can be used in acoustic lensing was proven and described [12, 13].

Certain group of acoustic metamaterials have a specific structure (called space-coiling) and are mainly used in aeroacoustics. Their principle of operation is to reduce the effective speed of sound wave, which is possible by extending the path of sound wave propagation. The fact that the space-coiling metamaterials can achieve negative refraction index has been confirmed experimentally [14]. It is also possible to create a space-coiling metamaterial which can enable almost any acoustic wavefront manipulation [15]. In most research described in the literature, the meander structure of space-coiling metamaterials are considered [14, 16, 17] and they are highly effective in controlling low-frequency sound [18]. These structures can be easily made by 3D printer [19, 20].

Initially, models of acoustic metamaterials are checked by numerical simulations which allow examine its properties before creating them [21]. To assess the properties of developed acoustic metamaterial the measurements with using a Impedance tube are performed [22, 23]. In this case it is possible to determinate sound absorption coefficient and sound transmission loss but it does not allow to illustrate the behavior of the sound wave behind the acoustic metamaterial.

This article presents visualizations of sound wave parameters like sound intensity level and sound pressure level behind the exemplary acoustic space-coiling metamaterials.

2. The structure of space-coiling metamaterial

As the space-coiling metamaterial typical labyrinthine structure with meander routes were designed in SolidWorks 2020. The dimensions of the metamaterial depended on possibility to its manufacture with use of 3D printer. For this reason the primary model (shown in Figure 1 included three meander routes in one piece were designed. The channel width was 3 mm, height of the primary model was equal 150 mm.

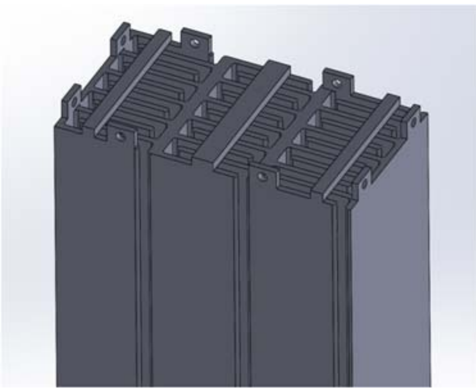

Figure 1. Primary model of space-coiling metamaterial structure

The primary model was created from PLA material by using a 3D printer. Diameter of nozzle was 0.6 mm, and the layer height was set at 0.4 mm. The infill has been set to 0%. Middle-walls of the structure has been fill with polyester resin. At the top of the each primary model a special mounting hooks were added, enabling serial and parallel connection of the metamaterial structure. The structures have been combined by screw connections. Two metamaterial construction was under investigation (shown in Figure 2), 8 primary models in: single and double row. Studies results for a single row structure were described in article [24]. In this article we consider on double row structure.

Figure 2. Space-coiling metamaterial construction under investigation

3. Results of the studies

3.1. Measurement setup

Measurements were carried out with using Scan & Paint 3D system in semi-anechoic acoustic chamber. The system include an anemometer probe that allows sound pressure measurement and direct measurement of acoustic particle velocity in three directions. Measurements were taken by moving the probe with the spherical marker. Marker combined with spherical camera and appropriate software enable to evaluate the position of the probe in relation to the tested metamaterial structure.

To reduce the impact of diffracted waves on measurement results the space-coiling metamaterial was placed in specific window made of wavy sound-absorbing foams. That window were suspended 1.2 meter above the floor and 1 meter away from noise source. As a white noise source Avantone MixCube loudspeaker driven by Behringer A800 amplifier and B&K1049 signal generator were used. The speaker was located in front of the structure. Experimental setup in shown in Figure 3.

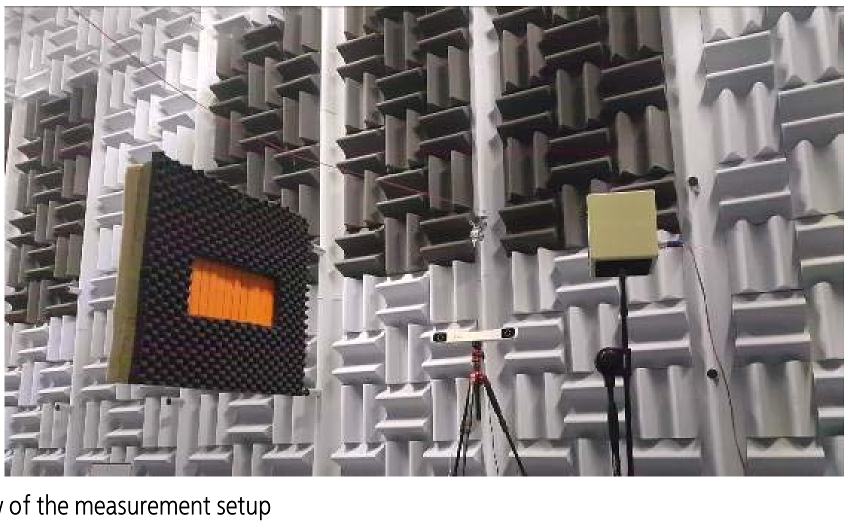

Figure 3. The view of the measurement setup

Measurements were taken in front of and behind the metamaterial structure in the frequency range from 100 to 9000 Hz.

3.2. Results and discussion

Sound pressure level and particle velocity level were averaged for piece of volume with width 2 centimeters. From these parameters, the value and direction of the sound intensity vector, which characterize the sound wave propagation and energy distribution close to the metamaterial, were obtained. The obtained results were based on a 30-minute measurements. Each vector acquired in visualizations takes include at least half second of measurements. Due to wide frequency range of test signal, the results of measurements were mainly visualized in a one-third octave band. Three types of results were noticed during the analyzes. In first type, intensity vectors perpendicular to the metamaterial surface occurs. An example of such results are shown in Figure 4.

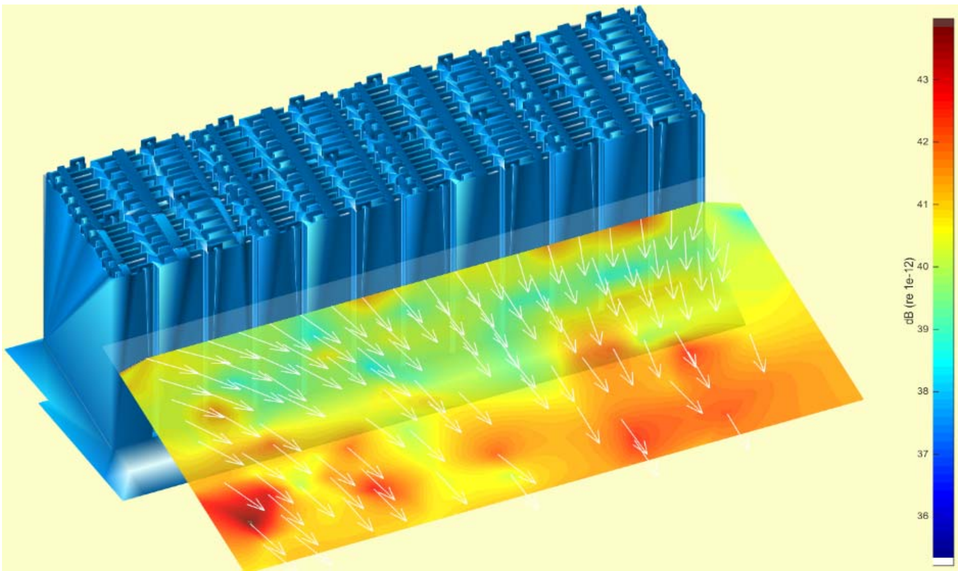

Figure 4. Visualization of sound intensity level distribution – nominal frequency 200 Hz (One-third octave band)

For nominal frequency of 200 Hz, the sound wave passes through the structure perpendicularly. Small deviations occur at the edges of the structure. This proves the low efficiency in eliminating noise for these frequency components. In second type of results, tendency of the sound intensity vectors to deviate can be observed. On Figure 5 the visualization of sound intensity level for nominal frequency 630 Hz are presented. The lowest values of sound intensity level can be found in the middle part of the structure. The vector distribution also indicates the propagation of sound energy from the side sectors of the structure. These results may indicate the insulating properties of the structure in this frequency range. Third group are results in which the intensity vectors form ordered patterns indicates properties of the structure to change direction of sound wave propagation. An example of such results can be visualizations for frequencies: 1600 Hz (Figure 6) and 2500 Hz (Figure 7). In order to better observe these properties, the visualizations were presented with increased mesh resolution (with width 5 millimeters).

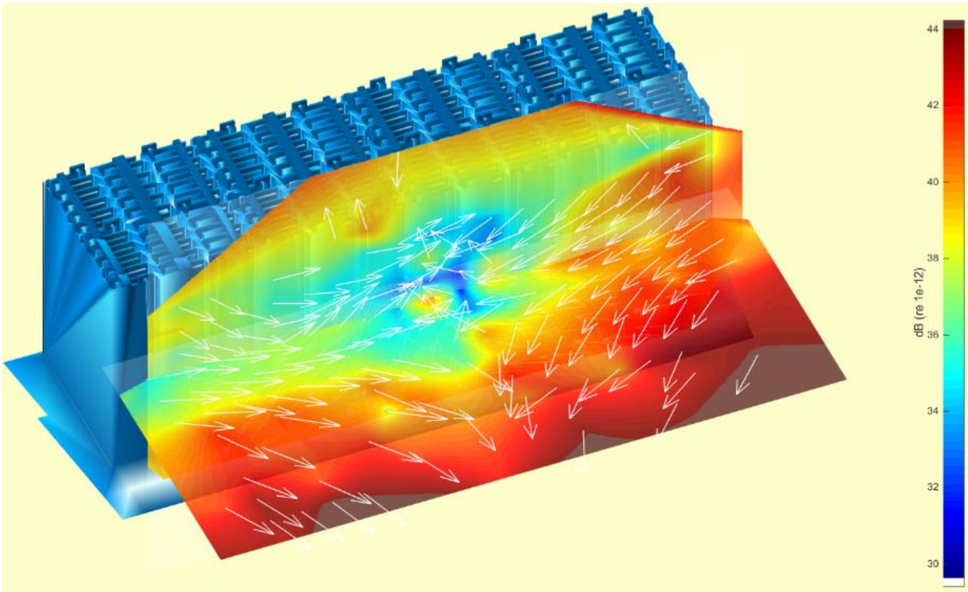

Figure 5. Visualization of sound intensity level distribution – nominal frequency 630 Hz (One-third octave band)

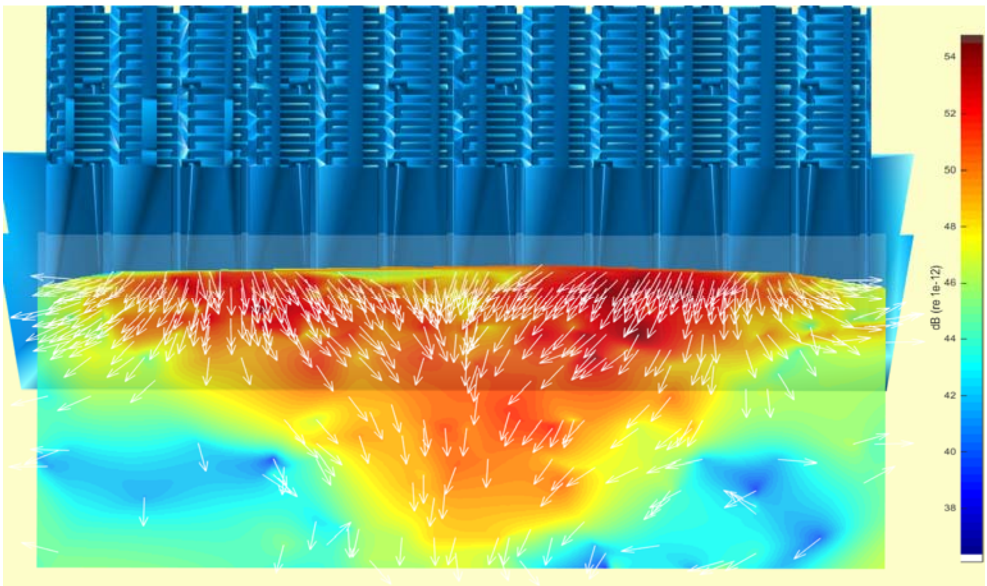

Figure 6. Visualization of sound intensity level distribution – nominal frequency 1600 Hz (One-third octave band)

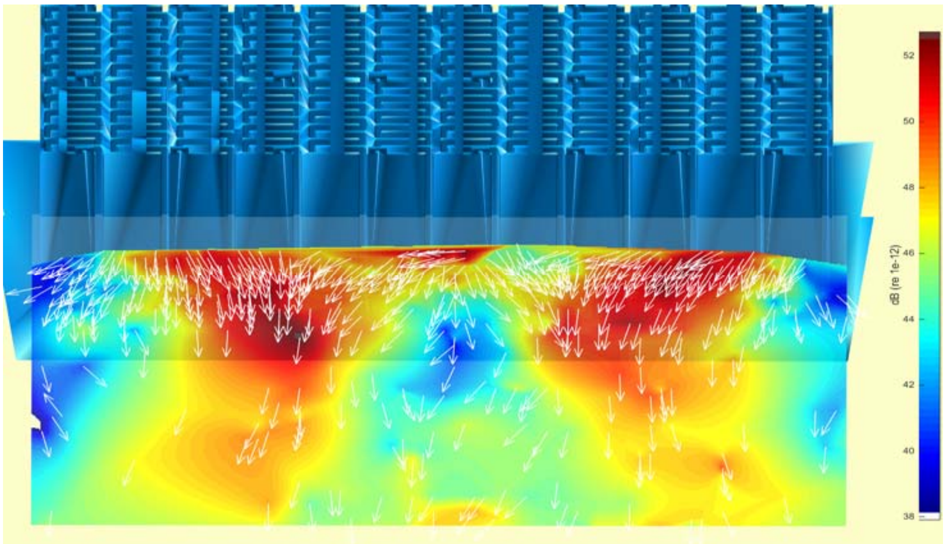

Figure 7. Visualization of sound intensity level distribution – nominal frequency 2500 Hz (One-third octave band)

In both cases two radiating zones of sound are visible. At 1600 Hz beam is created between these zones but at frequency two separate narrow beams occur. These effects appear in the range of the band gap typical for space-coiling metamaterials and they are due to local resonances inside the structure.

4. Conclusion

Studies were not intended to prove the occurrence of the phenomena typical for acoustic metamaterial (like negative bulk modulus or negative mass density) but for illustrate the energy distribution behind the designed structure. Achieved sound intensity patterns indicate the presence of local resonances in the structure. Visualizations of sound intensity level can be useful in evaluating the solution especially where the metamaterial structure is tested under laboratory conditions.

Acknowledgements

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Chapter 7

The concept of vibration isolation with variable stiffness with the use of magnetic elements

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AGH University of Science and Technology

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Abstract
The aim of the work is to develop the concept of elements of the vibration isolation system using the magnetic field of solid magnets and to determine the influence of this field on the physico-mechanical parameters of the selected type of elastomer, which was subjected to static and dynamic load over a wide range of speed at room temperature. The article presents both theoretical foundations of the proposed solution and its experimental verification.

Keywords: vibration isolation system, solid magnets, elastomeric materials

1. Introduction

This paper shows a preliminary concept of vibration isolation systems, in which the use of magnetic elements in the elastomer structure is proposed. In addition, a pilot study of the physical-mechanical properties of elastomeric materials with magnets has been carried out and they can be used in the application to vibration isolation systems in the future. A discrete-continuous model of the vibration isolation system, both under kinematic and force excitation, consisting of an elastomer and a pair of neodymium magnets oriented uniquely with respect to each other, was developed. Their application, causes a change of both stiffness and damping in the vibration isolation system. This paper presents the results of preliminary tests of the elastomer and magnet pair system, which were performed at room temperature. As part of the work, it was also necessary to design a fixture for the testing machine that would allow safe testing for different temperatures in the climate chamber, as well as testing for different compositions of elastomers and magnets. The scope of this article covers:

1. development of a conceptual model of a vibration isolation system using constant field magnets,

2. development of a concept and design of a structural fixture for testing elastomeric components with permanent magnets in a testing machine,
3. development of testing methodology for elastomeric elements with permanent magnets,
4. preliminary results of elastomer testing with permanent magnets.

2. Physical and mathematical models of the vibration isolation system with elastomers and magnetic elements

The adopted physical model of the vibration isolation system with kinematic forcing, shown in Figure 1, consists of a protected object of mass m (1), an elastomer (2) in which permanent magnets are located (3) and where they facing each other with opposite poles. The elastomer (2) is forced kinematically according to the law of motion *y(x,t)*.

We treat the above model as a discrete-continuous system, which is described by a system of partial and ordinary differential equations, with boundary and initial conditions. The equations describing the vibrations of this conceptual vibration isolation system were derived assuming that there is no dependence of elastomer parameters on the magnetic field generated by permanent neodymium magnets. In these models, the magnets are facing each other with identical poles, which leads to the presence of a repulsive force.

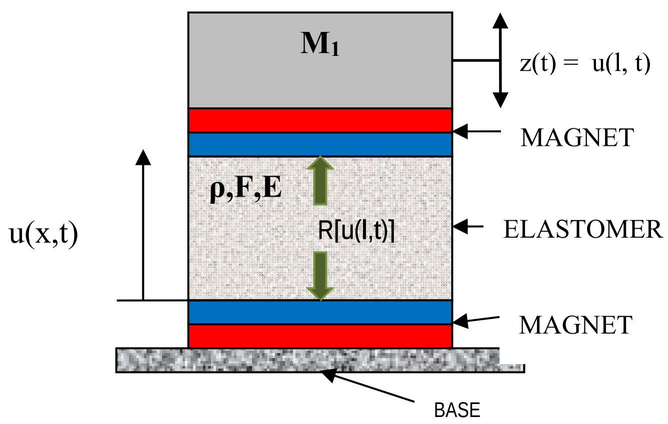

Figure 1. Schematic of the physical model of vibration isolation under kinematic forcing with a magnetic element

The differential equation describing the model with kinematic forcing (Figure 1), was derived assuming that the characteristics of the rubber is linear and has a continuous structure, then the vibration of the elastic element is described by a partial differential equation having the following form:

$$\frac{\partial^2 u(x,t)}{\partial t^2} = a^2 \frac{\partial^2 u(x,t)}{\partial x^2}. \tag{1}$$

For relation (1) we introduce the following boundary conditions:

$$\begin{aligned} &(M_1 + m_1)\ddot{z} + EF\frac{\partial u(l,t)}{\partial x} = R[u(x,t)] \\ &u(0,t) = 0 \end{aligned} \tag{2}$$

where:

E – dynamic Young's modulus, *ń* – density of the rubber material, *F* – rubber cross-sectional area, M_1 – mass of the isolated object, m_1 – mass of the magnet, *R[u(x,t)]* – force between magnets as a function of distance change.

The relation describing the interaction of two cylindrical permanent magnets is very complex [1], but it can be reduced to a simplified formula of as follows:

$$\begin{aligned} R[u(x,t)] = A[&\frac{1}{u(x,t)^2} + \frac{1}{(u(x,t)+2h)^2} + \\ &- \frac{1}{(u(x,t)+h)^2}] \end{aligned} \tag{3}$$

where:

$A = \frac{\pi\mu}{4} M^2 r^4$ – constant [Nm²], *M* – magnetization [Am²/m³], r – radius of curvature of the magnet [m], *u(x,t)* – function of changing distance between magnets [m], h – magnet height [m], μ – magnetic permeability.

The relation (3) allows to determine the constant A based on the determined curve from the tests on the testing machine (Figure 2), the force F(x) can be determined for the position and type of the magnetic element of interest [2, 3].

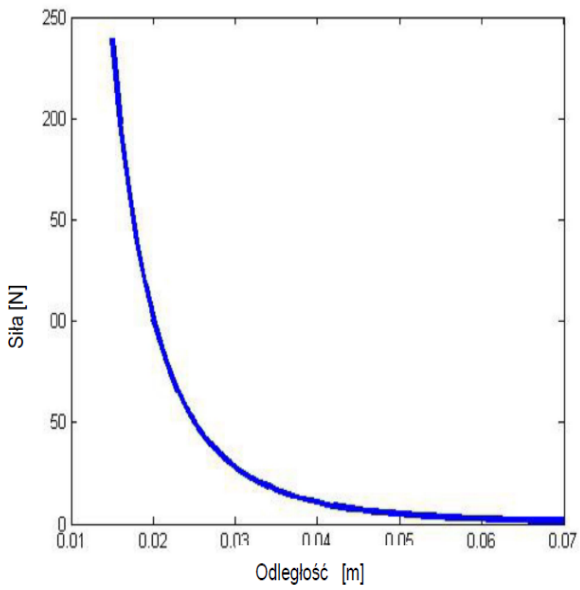

Figure 2. The distance dependence of the force for a magnet with diameter equal to 40 [mm] and height of 8 mm

Solution of the problem (1) with boundary conditions (2) is a nonlinear problem. It can be solved by linearizing relation (3), but assuming that the distance between magnets is significant, much larger than "l". Hence, practically the fastest and most convenient way to solve this problem is to use the FEM (Finite Element Method). However, in order to have input parameters for the model created by the FEM method, it is necessary to obtain these parameters by experimental investigation.

The study of the vibration isolation system with permanent magnets and rubber can be carried out by the method presented in [3], however, the problem of the possibility of the magnets affecting the elastomer parameters should be noted. Therefore, additional tests must be performed independently of the magnets themselves and the elastomer itself and then their combination to determine if such a phenomenon occurs. The problem required to be solved was the lack of a fixture that would allow us to perform tests for different compositions of magnets and elastomers. In order to do so, we made a dedicated fixture (Figure 3) for the Instron 8872 testing machine shown in Figure 4. Making a dedicated fixture was necessary in order to be able to perform the tests, the idea of which is shown in the block diagram shown in Figure 5.

Figure 4. Photo of the fixture

Figure 5. Instron 8872 testing machine

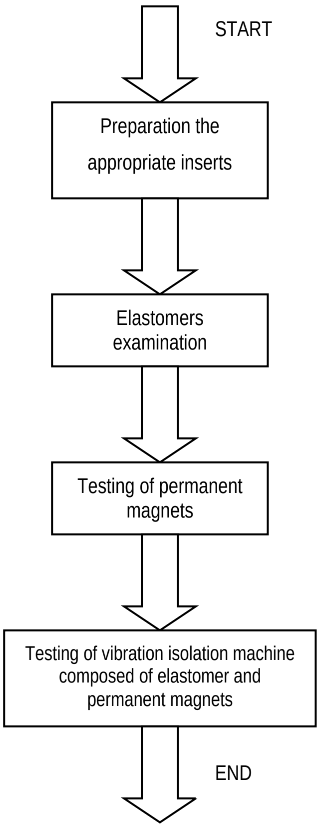

Figure 5. Block diagram of testing vibration isolator containing elastomer and pair of permanent magnets

3. Preliminary results of elastomer tests without and with magnets

Preliminary tests of the elastomer with a bulk density ρ = 699 kg/m^{-3}, porosity 38% and Shore A hardness 32°Sh, were carried out on the stand shown in Figure 4 at room temperature 20°C and for different strain rates. Parameters such as pore volume and sample hardness calculation were performed based on the methodology presented in [4], which was also used in the determination and calculation of elastomer parameters such as:

1. strain – ε_L,
2. modulus of elasticity for the linear section – E_L,
3. conventional modulus of elasticity for longitudinal section – $E_{L\text{-}20\%}$,
4. coefficient of damping (loss), stiffness for the linear section (k_L) and for the nonlinear section ($k_{L\text{-}20\%}$).

The results of these tests are presented in Table 1 and Table 2. Table 3 shows the results of calculations of the quasi-static and dynamic stiffness coefficient of the tested elastomer for a range of linear and nonlinear deformations as a function of the strain rate of the elastomer without and with magnets applied.

Table 1. Results of tests of conventional ε_L and conventional modulus of elasticity E_L as a function of the strain rate v of elastomer

System	ε_L [%]			E_L [MPa]		
	0.1 mm/s	a) 1.0 mm/s	b) 3.0 mm/s	c) 0.1 mm/s	d) 1.0 mm/s	e) 3.0 mm/s
Without magnets	14.05	12.8	14	0.44	0.47	0.50
With magnets	12.3	8.6	7.4	1.59	1.61	1.6

Table 2. Results of the conventional $E_{L-20\%}$ elastic modulus and damping factor (measure of dissipation) ψ as a function of strain rate v of the elastomer

System	$E_{L-20\%}$ [MPa]			[-]		
	f) 0.1 mm/s	g) 1.0 mm/s	h) 3.0 mm/s	i) 0.1 mm/s	j) 1.0 mm/s	k) 3.0 mm/s
Without magnets	0.76	0.78	0.82	0.22	0.29	0.27
With magnets	4.94	5.78	5.69	0.30	0.32	0.35

Table 3. Results of calculations of stiffness coefficient k_L for linear deformation range and $k_{L-20\%}$ for nonlinear deformation range as a function of strain rate v of elastomer

System	k_L [MN/m]			$k_{L-20\%}$ [MN/m]		
	l) 0.1 mm/s	m) 1.0 mm/s	n) 3.0 mm/s	o) 0.1 mm/s	p) 1.0 mm/s	q) 3.0 mm/s
Without magnets	0.76	0.78	0.82	0.22	0.29	0.27
With magnets	4.94	5.78	5.69	0.30	0.32	0.35

Figure 6 and Figure 7 show examples of hysteresis loops obtained by testing the elastomer without magnets and with magnets applied according to the scheme presented in Figure 1.

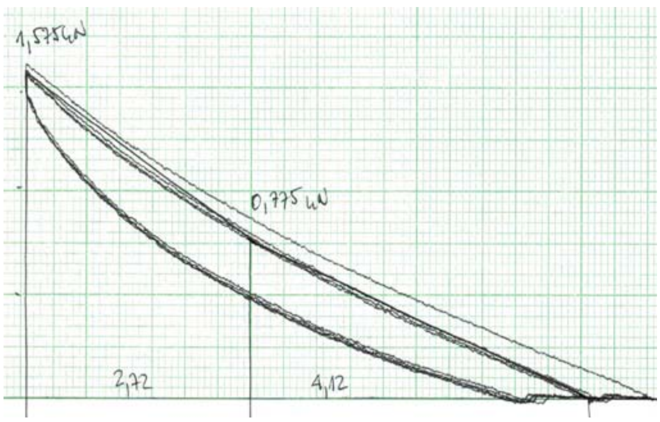

Figure 6. Hysteresis loop for elastomer without magnets at room temperature

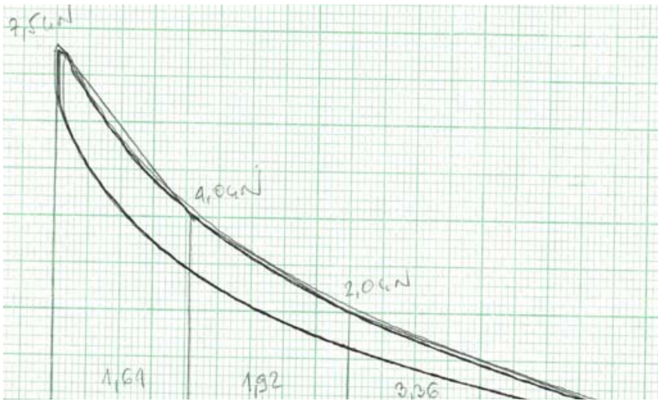

Figure 7. Hysteresis loop for elastomer with magnets at room temperature

The results were compared according to the relation:

$$y = \frac{x_z - x_{bez}}{x_{bez}} \cdot 100\%$$

where:

x_z – parameter of material with magnet, x_{bez} – parameter of material without magnet.

The results of the calculations are summarized in Table 4, Table 5 and Table 6.

Table 4. Comparison of results of tests of conventional ε_L and conventional modulus of elasticity E_L as a function of the strain rate v of elastomer

ε_L [%]			E_L [%]		
0.1 mm/s	1.0 mm/s	3.0 mm/s	0.1 mm/s	1.0 mm/s	3.0 mm/s
-12.46	-32.81	-47.89	261.36	242.55	220.00

Table 5. Comparison of results of the conventional $E_{L\text{-}20\%}$ elastic modulus and damping factor (measure of dissipation) ψ as a function of strain rate v of the elastomer

$E_{L\text{-}20\%}$ [%]			ψ [%]		
0.1 mm/s	1.0 mm/s	3.0 mm/s	0.1 mm/s	1.0 mm/s	3.0 mm/s
550.00	641.02	593.90	36.36	10.34	29.63

Table 6. Comparison of results of calculations of stiffness coefficient k_L for linear deformation range and $k_{L\text{-}20\%}$ for nonlinear deformation range as a function of strain rate v of elastomer

k_L [%]			$k_{L\text{-}20\%}$ [%]		
0.1 mm/s	1.0 mm/s	3.0 mm/s	0.1 mm/s	1.0 mm/s	3.0 mm/s
262.07	238.71	218.18	550.00	641.46	386.11

By analyzing the above results, there is a significant increase in the stiffness of the system as well as the damping ratio, however, it is significantly less than the stiffness.

4. Summary

This paper shows the methodology for testing elastomers with permanent magnets. It was also shown that the use of permanent magnets significantly affects the change in stiffness and damping of elastomers. The use of permanent magnets in the construction of vibration isolators is justified in some cases as it allows the stiffness to be controlled, i.e. the mechanical system can be tuned in such a way as to minimize the dynamic effects on the protected object. The analytical solution is too time-consuming, if possible, so at present it is proposed to use numerical methods to approximate the solution of this problem. Therefore, it is necessary to carry out experimental studies with this type of vibration isolation systems, the results of which will be the input parameters for the calculation of numerical models and will allow simulations of the dynamics of this type of isolation systems.

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Chapter 8

Use of tuned mass dampers (TMD) to reduce vibrations caused by wind on the spire of a tower building

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Abstract
The paper presents results of the use of tuned mass dampers to reduce vibrations caused on the spire of the Varso Tower building. Based on the literature, the description of the wind forces that cause vibrations and the basis for the selection of the TMD parameters have been presented. To verify the effectiveness of the new TMDs, the structural damping ratio of the spire with installed and activated TMDs has been determined by measuring the ambient vibrations of the spire. The natural frequencies were determined using the commercial signal processing software ARTEMIS, which incorporates Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification Methods. Three TMDs have been tuned for the first three natural frequencies. The recorded accelerations were analyzed and the structural damping ratios for the relevant modes were determined, which were found to be above the target values.

Keywords: tower building, spire vibration, wind-induced vibration, tuned mass dampers (TMD)

1. Introduction

Spiers are mounted on many tall buildings, which perform an architectural function but are also used to place e.g. radio transmitters, radars, etc. The Varso Tower building is 310 m high and is currently the tallest building in the European Union. The height of the spire is 80 m. Figure 1 shows a list of tall buildings with spires.

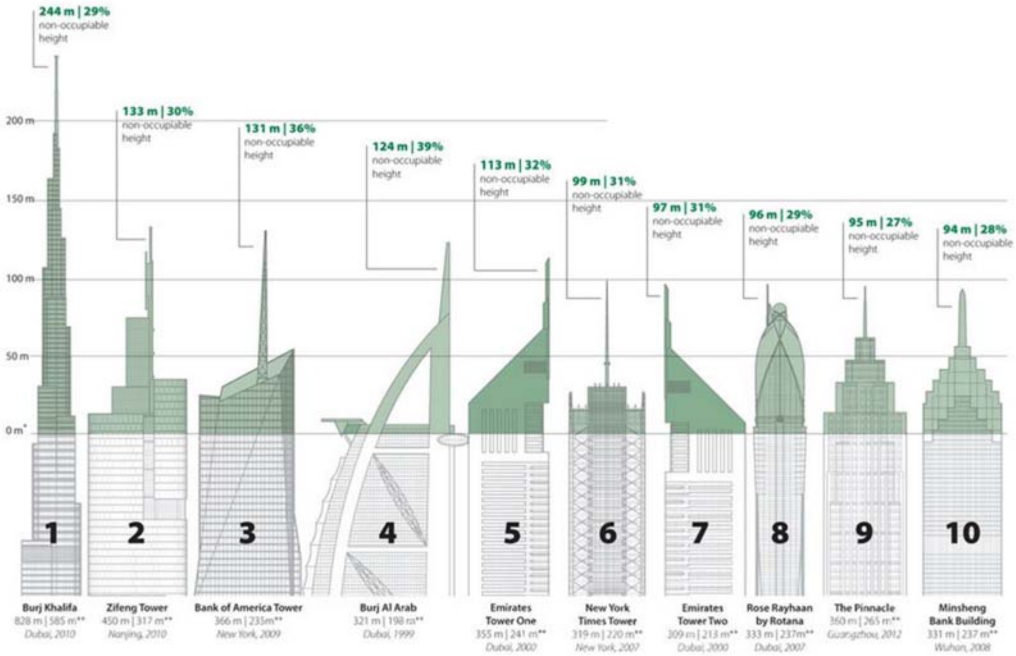


Figure 1. Tall buildings with spiers [1]

Figure 2 shows the view of Varsow Tower building with the spire. An important issue is the determination of the spire natural frequenicies and the damping of the needle's structure as they determine the increase in vibration amplitudes during resonance vibrations. Vibrations are excited due to the wind flow. The paper will describe the excitations from the wind, the selection of TMD parameters, their design and experimental tests aimed at determining the natural vibrations of the spire (Enhanced Frequency Domain and Stochastic Subspace Identification Method). Finally, information on the effectiveness of the TMD in damping the needle's vibrations is given.

Figure 2. View of the Varso Tower building with spire

2. Wind loads in tall buildings

In tall buildings, the different loads shown in Figure 3 occur during airflow [2]. These are the forces resulting from the interaction of forces from the wind with respect to the structure of the building. During the flow around the round elements, turbulence occurs as shown in Figure 3.

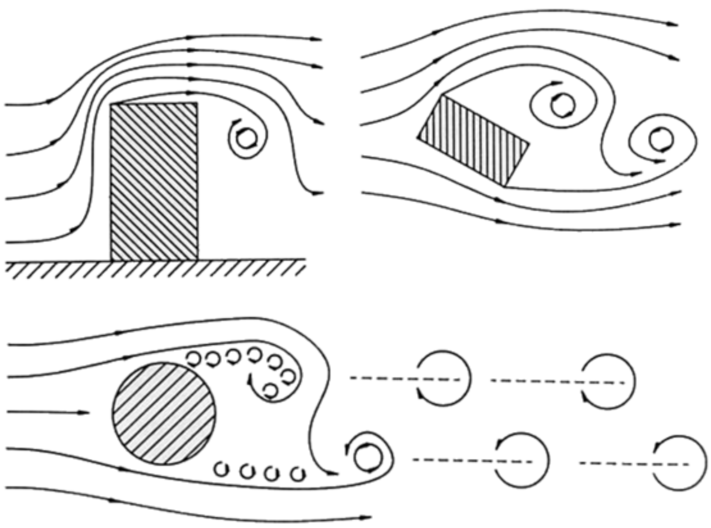


Figure 3. Wind Excitation [2]

Wind excitation acting on the building structure and on the spire has a stochastic nature similar to white noise [2]. It can be assumed that the wind force is the sum of the mean wind vector $v(z)$ dependent from the height and a dynamic, or turbulence, component $v_{dyn}(z,t)$:

$$v(z,t) = v(z) + v_{dyn}(z,t).$$

When the air flows around the spire, its bending vibrations occur, and at natural frequencies, due to the resonances higher amplitudes can be observed.

3. Dynamic model of TMD

The calculation of TMD parameters as effective mass, stiffness of spring elements, tuning frequency and damping ratio can be determined based on two degree of freedom model shown in Figure 4.

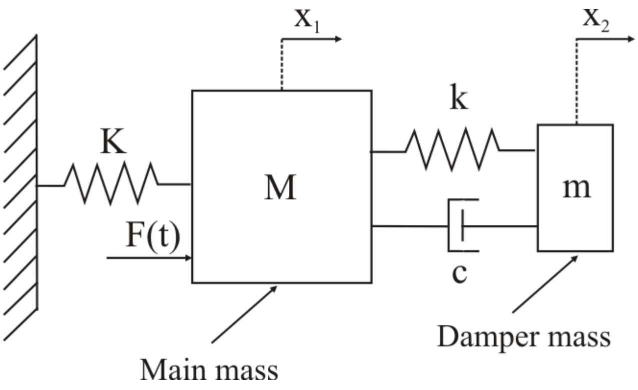


Figure 4. Dynamic model of TMD

The equations of motion for the system from Figure 4 are as follows:

$$M \cdot \ddot{x_1} + c \cdot (\dot{x_1} - \dot{x_2}) + K \cdot x_1 + k \cdot (x_1 - x_2) = F_0 e^{i\omega t} \quad (1)$$

$$m \cdot \ddot{x_2} + c \cdot (\dot{x_2} - \dot{x_1}) + k \cdot (x_2 - x_1) = 0. \quad (2)$$

Solutions can be defined as:

$$x_1 = \bar{x}_{o1} \cdot e^{i\omega t} \quad (3)$$

$$x_2 = \bar{x}_{o2} \cdot e^{i\omega t} \quad (4)$$

$\bar{x}_{o1}, \bar{x}_{o2} \rightarrow$ complex vibration amplitudes of masses M and m.

After introduction of terms (3) and (4) in (1) and (2) can be written:

$$-M \cdot \omega^2 \cdot \bar{x}_{o1} + i \cdot \omega \cdot c \cdot (\bar{x}_{o1} - \bar{x}_{o2}) + K \cdot \bar{x}_{o1} + k \cdot (\bar{x}_{o1} - \bar{x}_{o2}) = F_0 \quad (5)$$

$$-m \cdot \omega^2 \cdot \bar{x}_{o2} + i \cdot \omega \cdot c \cdot (\bar{x}_{o2} - \bar{x}_{o1}) = 0. \quad (6)$$

The complex amplitude of the vibration of mass M is given by:

$$\bar{x}_{o1} = F_0 \frac{(k - m\omega^2) + i \cdot \omega \cdot c}{[(-M\omega^2 + K)(-m \cdot \omega^2 + k) - m\omega^2 \cdot k] + i \cdot \omega \cdot c \cdot (-M \cdot \omega^2 + K - m \cdot \omega^2)} \quad (7)$$

and the magnitude as:

$$|\bar{x}_{o1}| = F_0 \sqrt{\frac{(k - m\omega^2)^2 + \omega^2 \cdot c}{[(-M\omega^2 + K)(-m \cdot \omega^2 + k) - m\omega^2 \cdot k] + \omega^2 \cdot c^2 \cdot (-M \cdot \omega^2 + K - m \cdot \omega^2)}}. \quad (8)$$

Damping reduces the vibration amplitudes in the resonance ranges and increases the frequency ranges in which vibration reduction occurs.

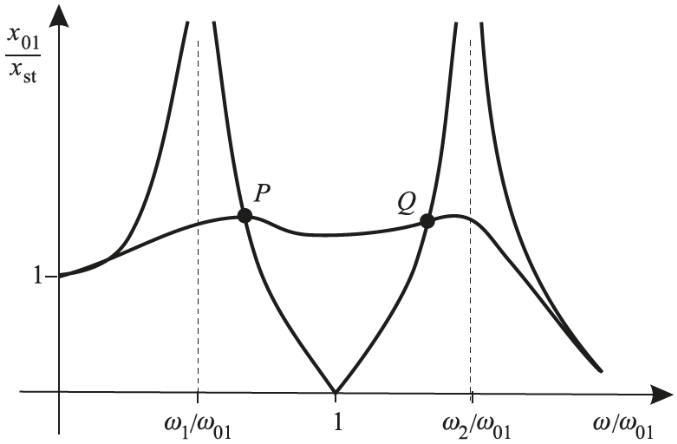


Figure 5. Vibration amplitude of the main mass

In addition to the TMD and its damping coefficient *c*, the efficacy of TMD strongly depends on the ratio between the structures mass and the TMD mass $\mu = m/M$. By comparing the results, the optimal values (minimum amplification) can be found for the TMD parameters.

Information on the optimal damping of TMD can be found in the available literature. In [3, 4] it is indicated that to obtain optimal damping the intersection points of the frequency characteristics P and Q should be at the same value of the coefficient of the amplitude amplification (Figure 5).

There are two basic parameters of the TMD frequency ratio and damping ratio ($\xi = \frac{c}{2\sqrt{km}}$) which should be considered.

The frequency ratio is defined as:

$$\alpha = \frac{\text{natural frequency of the damping mass}}{\text{dominant frequency of the main mass}}.$$

The optimal frequency ratio is given by [3]:

$$\alpha_{opt} = \frac{1}{1+\mu}. \tag{9}$$

The optimal damping ratio can be obtained depending on the character of the excitation force [4] :

- for the periodic excitation force:

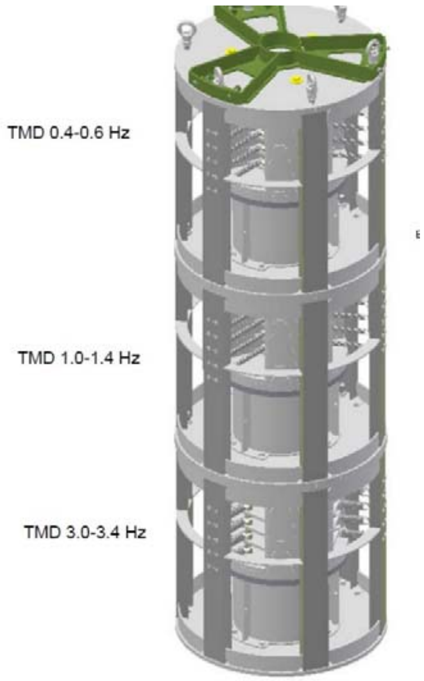
$$\xi_{opt} = \sqrt{\frac{3\mu}{8(1+\mu)}} \tag{10}$$

▪ for random excitation force:

$$\xi_{opt} = \sqrt{\frac{\mu(1+3\mu/4)}{4(1+\mu)(1+\mu/2)}}. \quad (11)$$

4. Description of TMD

The TMD damper consists of 3 segments to suppress the three basic natural frequencies around 0.5 Hz, 1.2 Hz and 3.2 Hz (Figure 6). These frequencies have been established from vibration measurements.



a)

b)

Figure 6. View of the TMD used in the spire; a) CAD model, b) photo

A TMD design procedure follows the following main steps:

1. Establish the desired responses of the structure and the TMD for design loads.
2. Choice TMD's mass, m, and determination mass ratio μ.
3. Determine the optimum tuning frequency ratio, α_{opt} expressed as the ratio between the optimal frequency and dominant structural frequency.
4. Calculation of the spring constant k.

5. Determine the optimal damping ratio of the TMD, ξ_{opt}.
6. Calculation of the damping constant c.
7. Determine the performance of a TMD.

The vibrating mass in all three segments of TMD was 750 kg (the total mass of every segment was 1300 kg) and the damping ratio 14-16%.

5. Determination of the structural damping ratio with installed TMDs

For the vibration test a Data logger box has been used. The measuring system complies with the device standard DIN 45669 C3 HV1-80 and is shown in Figure 7 and consists of:

- **Sensors:** ADXL3552 triaxial accelerometer
- **Data Acquisition:** Data Translation DT9837B
- **Analyzer software:** MATLAB R19.

Figure 7. The Wireless transducer for vibration measurements

To verify the effectiveness of the new TMDs, the structural damping ratio of the spire with installed and activated TMDs has been determined by measuring the ambient vibrations of the spire for a time period of 1000 seconds. The spire was dynamically excited by the ambient wind, which causes a broad band stochastic excitation of the spire. This enables one to determine all relevant vibration modes.

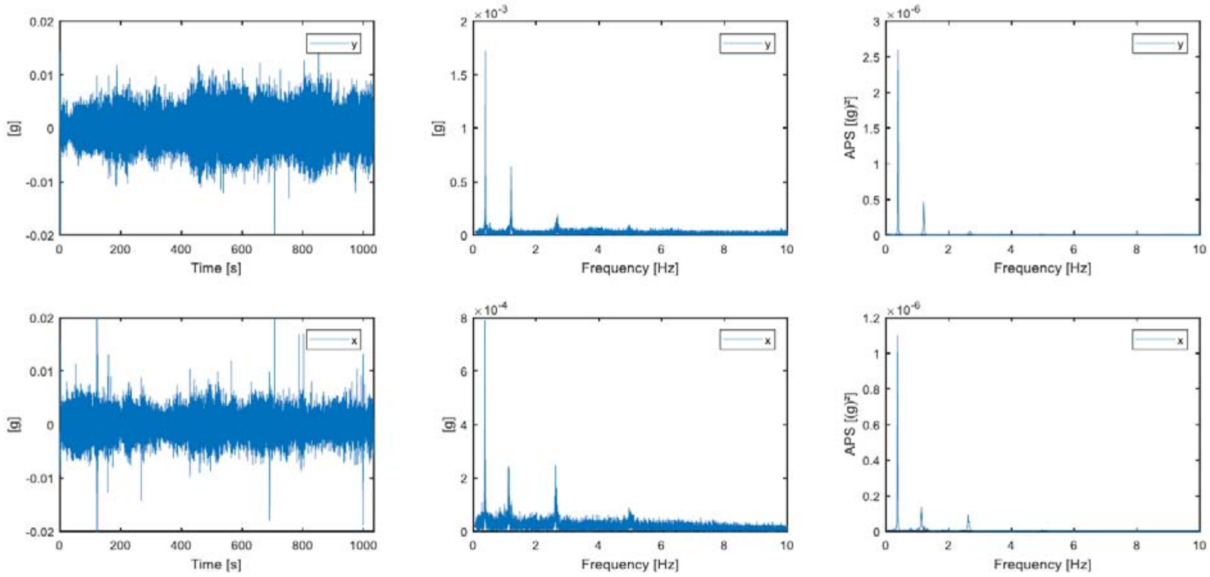


Figure 8. Results from Vibration Measurements

Figure 8 shows the time histories of the horizontal accelerations (x- and y- direction) recorded at the spire as well as the corresponding frequency spectra and the averaged Auto-Power Spectra (APS). The results obtained from the experimental modal analysis are presented in Table 1.

Table 1. Natural frequencies, modal masses and damping (logarithmic decrement δ) of the spire

Mode	f_i [Hz]	m_{Modal} [kg]	mass ratio	achieved damping δ	TMD Displacement +/- [mm]
1	0,452	15709	0,048	0,45	95
2	0,488	15011	0,050	0,32	100
3	1,148	10152	0,074	0,33	80
4	1,252	10261	0,073	0,5	65
5	1,591	10335	0,073	0,26	80
6	1,97	10227	0,073	0,14	*80**
7	2,199	9949	0,075	0,12	*80**
8	2,43	9681	0,077	0,11	*80**
9	2,597	9522	0,079	0,085	*80**
10	3,116	9001	0,083	0,38	*80**
11	3,256	8881	0,084	0,41	*30***
12	3,343	8815	0,085	0,62	*30***
13	3,467	8726	0,086	0,56	*30***
14	3,676	8595	0,087	0,51	*30***
15	4,058	8404	0,089	0,41	*30***
16	4,223	8340	0,090	0,31	*30***

** undamped max deflections +/- 320 mm*
*** undamped max deflections +/- 200 mm*

It can be seen that first three modes per direction are being dominantly excited and could be identified by the ambient vibration tests. The following dominant natural frequencies have been identified:

$$f_1 = 0{,}45 \text{ Hz}, f_2 = 1{,}2 \text{ Hz}, f_3 = 3{,}2 \text{ Hz}.$$

6. Methods and results

In addition, natural frequencies were determined using the commercial signal processing software ARTEMIS [5] which incorporates enhanced frequency domain decomposition and Stochastic Sub-space Identification Methods. Enhanced frequency domain decomposition (EFDD) and the Stochastic Subspace Identification [6] are widely used techniques for output-only modal parameter identification. The EFDD method is based on the computation of response spectra. Long records are, therefore, required to keep low the error on spectrum estimation low and to extract modal parameters in a reliable way. Commissioning Report – Spire Varso Tower – HB Reavis Construction PL.

The stochastic subspace identification algorithm was applied to identify structures using an output-only model. Stochastic Subspace Identification methods work in time domain and are based on a state-space description of the dynamic problem. The system identification results at different model orders are compared to distinguish true structural modes from spurious modes in the so-called stabilization diagrams.

The stochastic subspace identification (SSI) method is considered as a robust output-only identification technique compared to other available methodologies [7]. SSI algorithms identify a stochastic state-space model of the structure. The resulting model can be then translated into a more convenient structural model form for engineering interpretation of the results. The state-space model can be related to both modal model and Finite Element (FE) model formulations. The method works in the time domain and is based on a state space description of the dynamic problem assuming a linear behavior of the structure and a time invariant dynamic response of the system due to a white-noise excitation. The systemidentification results at different model orders are compared to distinguish true structural characteristics modes from spurious modes in the so-called stabilization diagrams (Figure 9).

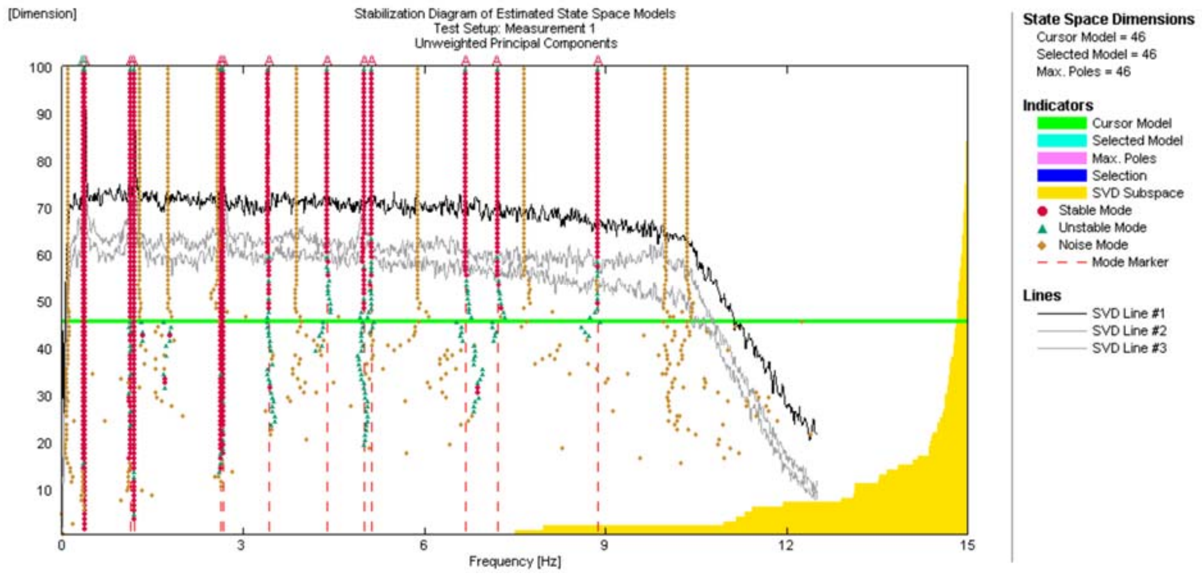


Figure 9. Stabilization Diagram of Estimated Space Models

These diagrams are a popular way to select the identified system model, as the true structural modes tend to be stable for successive model orders, fulfilling certain stabilization criteria that are evaluated in an automated procedure. The identified modes and the damping ratios for each mode are summarized in Table 2.

Table 2. Identified natural frequencies of the spire and damping ratios (after mounting of TMD)

Mode	Frequency [Hz]	Std. Frequency [Hz]	Damping Ratio [%]	Std. Damping Ratio [%]	Comment	Creation Date & Time
SSI-UPC Mode 1	0.3574	0.0008265	2.335	0.0443	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 2	0.3816	0.0005408	2.593	0.0326	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 3	1.138	0.005474	2.488	0.0372	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 4	1.205	0.00139	1.819	0.0309	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 5	2.622	0.00158	0.789	0.07871	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 6	2.665	0.001482	1.789	0.1307	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 7	3.418	0.00489	4.395	0.0958	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 8	4.392	0.002204	2.801	0.04616	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 9	4.995	0.001441	1.303	0.09564	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 10	5.13	0.003569	3.72	0.02741	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 11	6.688	0.001415	3.469	0.01628	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 12	7.209	0.01179	3.441	0.04448	Found automati...	26-03-2021 14:05:17
SSI-UPC Mode 13	8.874	0.0008495	4.776	0.04722	Found automati...	26-03-2021 14:05:17

7. Summary and conclusions

Measurements were performed at the completed spire of the Varso Tower in Warsaw /Poland to verify the effectiveness of the installed, tuned, and activated TMDs. The effectiveness of TMD can be assessed by determining the overall structural damping and comparing it with the target value. According to [2] an overall structural damping ratio of d = 0.08, respectively. D = 1.273% is required to effectively reduce vortex shedding induced spire vibrations.

The recorded accelerations were analyzed with an Operational Modal Analysis (OMA) software and the structural damping ratios for the relevant modes were determined and found to be above the target values. Accordingly, it can be concluded that the TMDs are fully effective and a resonant vortex-shedding excitation of the spire can be avoided.

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Chapter 9

Evaluation method of hand-arm vibration using high-speed camera

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Abstract
High-speed cameras are increasingly used in various fields of science and technology. Their usefulness is particularly appreciated during the analysis of rapidly changing physical phenomena. They also make it possible to study the oscillatory motion of objects. The article presents an attempt to use a high-speed camera to test vibrations occurring in the working environment. A proposal for a method of identifying and evaluating vibrations based on the analysis of the motion image of elements of hand tools obtained with the use of a high-speed camera was presented. The algorithm of the developed method was verified while working with typical hand tools. To compare the obtained results, the values of vibration acceleration obtained by means of a standard measurement system based on piezoelectric vibration transducers were used. The research also provided information on the limitations and conditions of using the high-speed camera for vibration testing in the work environment. The differences in the values of exposure to vibrations determined with the use of a high-speed camera and a standard measurement system show that the presented method of vibration identification and evaluation can be successfully used for vibration tests at workplaces.

Keywords: vibration, high-speed camera, research

1. Introduction

Increasingly used high-speed cameras allow for non-contact studies of the movement of various objects and their structures [1-15]. This allows you to replace standard measurement methods based on the use of sensors placed directly on the tested object with methods based on image analysis.

In many situations (e.g. the movement of very small elements or delicate structures) this is the only way to obtain information about the phenomena that are taking place. The use of non-contact techniques also affects the elimination of phenomena related to changes in the parameters of mechanical systems caused by placing additional masses of sensors in them. This has a direct impact on the accuracy of measurements of physical parameters of motion. Research conducted in many centers confirms the possibility of using non-contact techniques, including those based on the use of high-speed cameras, also in the field of measurement and analysis of mechanical vibrations [1-4, 7-10, 12-15]. However, this involves the need to solve problems concerned with the ensuring of correct work conditions of high-speed camera to obtain useful results. The most important of them are: the correct selection of optical components of the camera, the use of appropriate parameters for image capture, provide adequate lighting and ensuring a stable camera position during recording. An additional issue is the question of how the vibration measurements results obtained using a high-speed camera differ from the results obtained by classical methods. Until now, high-speed cameras have not been used to measure vibrations affecting an employee in a working environment. This way of measurement is not taken into account by the vibration test methods given in the relevant standards, e.g. [16, 17]. The use of high-speed cameras opens up new possibilities for analyzing the effects of vibrations on individual parts of the body of an employee operating tools and machines. The purpose of the presented research was to develop and check the hand-arm vibration test method using a high-speed camera.

2. Proposal of evaluation method of hand-arm vibration

The proposed method of identification of exposure to vibrations in the working environment using the image of the oscillatory motion of machine / tool elements is based on the analysis of the displacement time signal of a selected point (points) on the vibrating object recorded by a high-speed camera. The rules for selecting of measurement points and coordinate systems used during measurements in workplaces have been taken from the standard EN ISO 5349:2001 [16,17] for hand-arm vibration tests.

The displacement time signal of the observed point $s(t)$ is obtained as a result of the virtual or real marker tracking algorithm using Movias image analysis software. After double differentiating the displacement time signal, the vibration acceleration time signal $a(t)$ at the selected point is obtained (formula 1).

$$a(t) = \frac{d^2 s(t)}{dt^2}. \tag{1}$$

Then the spectrum of the vibration acceleration signal $a(f)$ is determined (formula 2).

$$a(f) = \int_{-\infty}^{+\infty} a(t) e^{-j2\pi f t}\, dt. \tag{2}$$

According to the EN ISO 5349 [16, 17] and EN ISO 8041 [18] standard for hand – arm vibration measurements correction filter W_h is used.

After correction the vibration acceleration spectrum $a(f)$ with the correction filter W_h, the corrected vibration acceleration spectrum $a_h(f)$ (formula 3) is obtained at a given measuring point.

$$a_h(f) = a(f) \cdot k_l(f) \tag{3}$$

$k_l(f_i)$ – correction coefficient, l – correction filter W_h, f – frequency.

Due to the correction characteristics of W_h, (high attenuation for frequency components over 600 Hz) the range of analyzed vibration frequencies was limited to 1000 Hz.

By using an operation analogous to integration (formula 4), a corrected total value of vibration acceleration is obtained a_h.

$$a_h = \sqrt{\sum_{f=f1}^{f2} a_h^2\,(f)} \tag{4}$$

f1 – lower limit frequency of the analyzed range, *f2* – upper limit frequency of the analyzed range.

The value of daily exposure to hand-arm vibration is determined from formula (5):

$$A(8) = \sqrt{\frac{1}{T_0}\sum_{i=0}^{n}(a_{hv,i}^2 \cdot t_i)} \tag{5}$$

$$a_{hv,i} = \sqrt{a_{hx,i}^2 + a_{hy,i}^2 + a_{hz,i}^2}\ ,\ \mathrm{m/s^2}$$

$a_{hv,i}$ – value of the sum of vibration acceleration vector for the *i*-th operation carried out by the worker exposed to hand-arm vibration, m/s^2, i – number of operation carried out by the worker exposed to hand-arm vibration, n – total number of operations carried out by the worker exposed to hand-arm vibration, t_p – duration of the *i*-th operation, min, T_0 = 8h (480 min).

The presented assumptions was based on the determination of vibration acceleration due to the possibility of reference the obtained results directly to the limit values set out in applicable law. (However, it is possible to adapt the method in which instead of vibration acceleration, can be used velocity, displacement or energy of vibration.)

The proposal of the evaluation method of hand-arm vibration using high-speed camera has been developed taking into account also results of pre-tests covering the selection of optics, recording parameters and lighting. The algorithm of the method is presented on the diagram in Figure 1. The method is implemented in three subsequent phases:

1. The first phase (blue blocks in the algorithm diagram) involves determining test conditions such as location, number of measuring points and choosing the type of marker (physical or virtual). Because the accuracy of measurements, better results with subsequent tracking of measurement movement points are obtained when the physical marker is selected. In the first phase, preparatory activities for image recording are also performed, such as the selection of recording parameters (recording speed – frame rate depending on the frequency range of the analyzed vibrations, resolution, shutter speed value, recording time) and optical elements cooperating with the camera. The choice of focal length of the lens or the decision to use teleconverters and / or intermediate rings depend primarily on the distance between the camera and the moving object. Indirectly, the optical set used and the recording parameters chosen are related to the selection of lighting, which is an equally important element during image recording. When using long focal length lenses and recording at high speeds it is necessary to use very strong continuous light sources.

2. The recording of the oscillatory motion image and preparation of data for analysis (yellow blocks in the algorithm diagram) are implemented in the second phase of the algorithm. It includes the recording of video images, e.g. using the Photron FASTCAM Viewer software in a format that allows subsequent analysis and tracking of the oscillatory movement of selected measuring points using the MoviasNeo 2D v. 2.54 software. When tracking the movement of measuring points, the highest accuracy was obtained when using the spline function for interpolation. In this method, the coefficients of interpolating polynomials are determined in such a way as to ensure at points not only the interpolation function but also its derivatives. This is important for later double differentiating the obtained time signal of the displacement of the measuring point.

   The correlation coefficient value should not be less than 0.95 during the entire tracking operation of the measuring points. The best tracking results (especially with fast-changing signals) were obtained with the number of prediction points being limited to 1.

The second phase of the algorithm also includes choosing the right conversion factor value, which is equivalent to calibrating a classic measuring system using a reference source. The conversion factor value has a direct impact on the results of quantitative analysis.

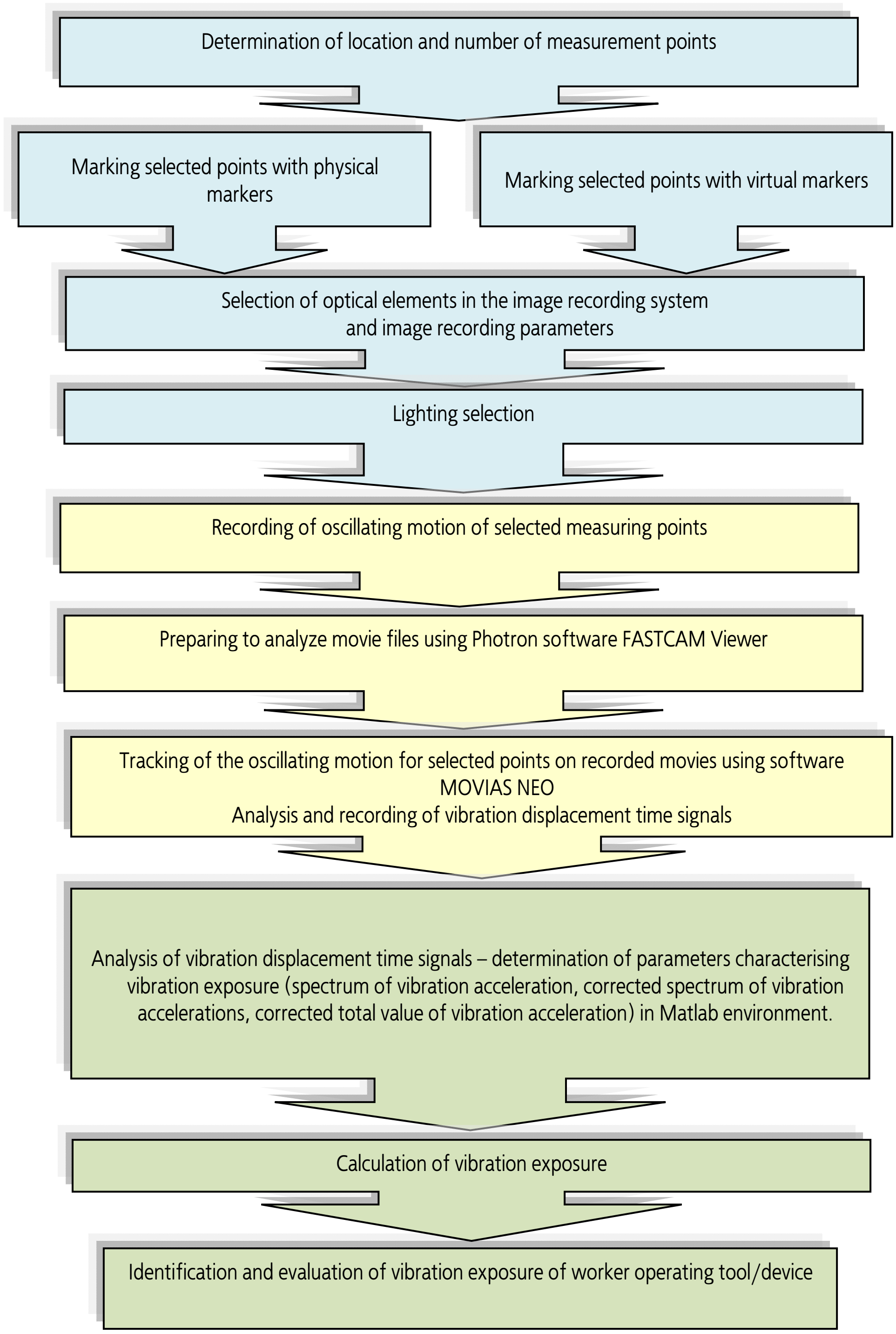

Figure 1. Algorithm diagram for identifying employee exposure vibrations in working environment based on the analysis of the oscillatory movement of machine / tool elements

3. The third phase of the method algorithm (green blocks in the algorithm scheme) contains data analysis and calculations. By double differentiating the time signals of vibration displacement

by using CFC (Channel Frequency Class) filters, vibration acceleration time signals are obtained. On their basis, uncorrected and corrected spectra of vibration accelerations are determined;

a calibration correction is also made taking into account the reference values of the reference vibration source. The corrected vibration acceleration spectrum is used to calculate the total vibration acceleration values.

The analyzes and calculations are repeated for each measuring direction X, Y, Z and then after taking into account the exposure time, the daily (or short-term) vibration exposure is determined according to the standard EN – ISO 5349. Based on it, identification and assessment of vibration exposure of the operator operating the tested tool / device is carried out.

3. Verification research

The performed verification tests of developed method consisted in the simultaneous recording and analysis of vibration signals using two measuring systems differing in the method of vibration detection:

- reference system: B&K 4393V piezoelectric vibration transducers with B&K NEXUS 2692-14 preamplifier and B&K Pulse multi-analyzer system; the vibration transducer has the following main technical parameters:
  - type of transducer: charge (DeltaShear),
  - frequency range: 0.1 ÷ 16500 Hz,
  - sensitivity: 0.316 pC / ms^2,
  - eight: 2.4 g;
- high-speed camera Photron FASTCAM SA1.1; during camera image recording, the TAMRON 18-400 mm F / 3.5-6.3 Di II VC HLD lens was used (with the KENKO 2x TELEPLUS PRO 300DGX teleconverter and 68 mm MeiKe intermediate rings); the following values of record parameters were used:
  - frame rate: 2000 frames / s,
  - resolution: 1024 pixels x 1024 pixels,
  - shutter speed value: 1 / frame,
  - record duration: 16.7 s,
  - video recording format: AVI.

Selected values were determined by 32 GB memory size of the camera and desired duration of recording. According to the sampling theorem frame rate 2000 fps should ensure correct analysis of recorded images of measurement object in frequency range from ~0 Hz up to 1000 Hz. A 1 mm diameter circular graphic marker was used to mark the measuring points. The Quadralite Atlas LED 60W continuous light lamps and LED torch Bailong T808 CREE XM-L were used for lighting. For measurements using reference system standard procedure was used (based on the EN ISO 5349:2001).

For measurements using high-speed camera the calculations were carried out on the basis of the obtained time signals of vibration displacement of measurement points. Then acceleration time signals were determined. On the base of these signals the frequency characteristics of vibration acceleration, total corrected (W_h characteristic) vibration acceleration values were calculated.

3.1. Measurement results

Simultaneous measurements of the vibration parameters using two mesuring systems were carried out for ten hand tools (vibration sources) applied successively. The measurements have been performed on the handles of the selected tools, during typical operations for each of the tools An example of measuring point location, orientation of the coordinate system and the transucer attachment method is ilustrated on the Figure 2.

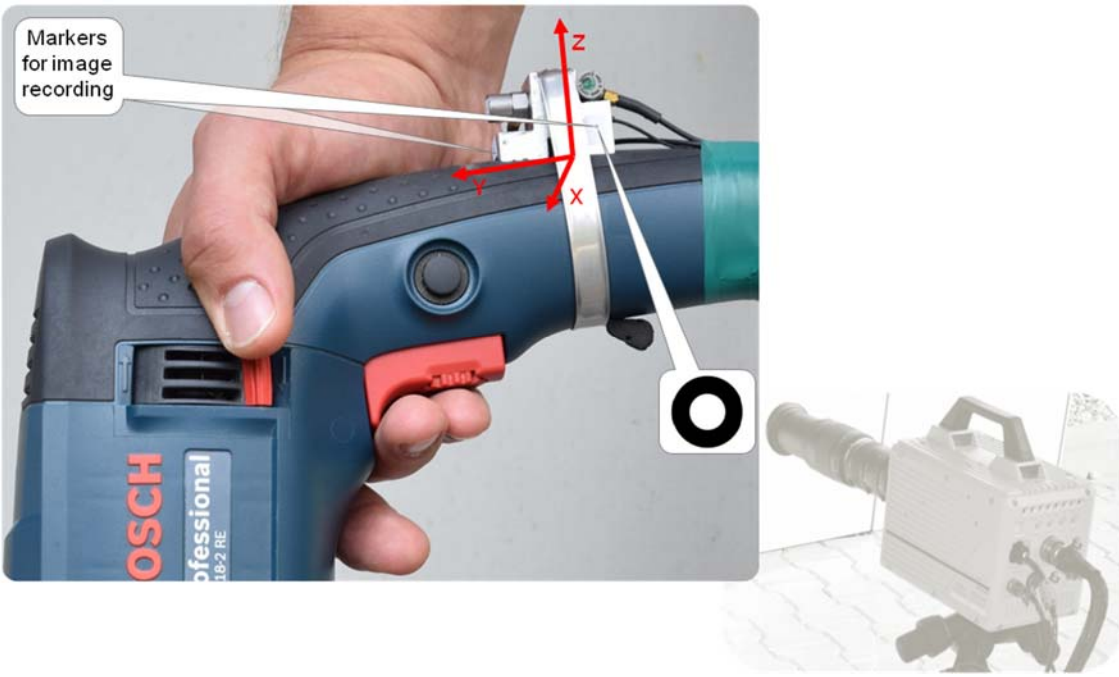

Figure 2. An example of measuring point location, orientation of the coordinate system and the transucer attachment method during high-speed camera recording

The calculation results of corrected values of vibration acceleration a_h in three directions (X, Y, Z) and vector sum values a_{hv}, as well as difference between results from two measuring systems are presented in Table 1. In the tables, the reference measuring system is marked as *Pulse* and high-speed camera as *Camera*.

Table 1. Corrected values of vibration acceleration a_h and vector sum values a_{hv} for selected hand tools

Measurement object	Component	a_h, ms^2		Difference [%]	Vector sum value a_{hv}, ms^2		Difference [%]
		Pulse	Camera		Pulse	Camera	
Pneumatic wrench I	X	3.92	3.40	13.4	6.90	6.88	0.3
	Y	1.27	1.32	4.3			
	Z	5.54	5.84	5.1			
Pneumatic wrench II	X	6.06	6.17	1.9	6.68	6.75	1.0
	Y	1.85	1.78	3.5			
	Z	2.14	2.07	3.3			
Brushcutter Kawasaki TH34	X	3.89	3.80	2.5	7.19	6.96	3.1
	Y	3.18	3.42	6.8			
	Z	5.13	4.74	7.7			
Electric scissors Hecht 655	X	5.49	5.48	**0.2**	5.79	5.73	1.0
	Y	1.32	1.26	4.9			
	Z	1.30	1.13	13.2			
Electric Saw FPCS1800A	X	2.67	2.99	10.8	3.12	3.31	**5.7**
	Y	1.08	0.93	**14.4**			
	Z	1.19	1.07	10.5			
Combustion Saw Stihl 025 (front handle)	X	8.73	8.47	2.9	13.15	12.88	2.1
	Y	9.24	9.11	1.4			
	Z	3.39	3.31	2.4			
Combustion saw Stihl 025 (rear handle)	X	10.02	10.00	**0.2**	21.64	22.78	5.0
	Y	12.59	14.19	11.3			
	Z	14.19	14.75	3.7			
Saw for plastics Bosch GSG 300	X	2.09	1.93	7.7	2.40	2.27	5.5
	Y	0.80	0.80	0.9			
	Z	0.86	0.88	2.5			
Oscillating grinder CMI C-SS 200	X	7.08	7.07	**0.2**	7.19	7.19	**0.1**
	Y	0.47	0.48	0.6			
	Z	1.14	1.23	7.1			
Cordless screwdriver Makita DF347D	X	4.28	4.37	2.1	4.47	4.59	2.5
	Y	0.90	1.04	13.1			
	Z	0.92	0.91	1.3			
Jigsaw machine Bosch GST 150BCE	X	3.81	3.73	2.0	6.92	6.99	1.1
	Y	4.65	4.63	0.6			
	Z	3.42	3.79	9.8			

3.2. Evaluation results and discussion

Analyzing the results from Table 1, it can be stated that the values of corrected vibration acceleration directional components obtained using the high-speed camera and the reference system do not differ by more than 14.4%. In 23 cases out of 30 these differences are less than 8%. Even more favorable results were obtained when comparing the corrected vector sums: in all cases, the differences did not exceed 5.7%.

The achieved compatibility of results is greater than in tests by E. Bressel, G. Smith and D. Nash [3] carried out for several selected frequencies (29 Hz, 34 Hz, 39 Hz, 44 Hz, 49 Hz, 53 Hz) of vibration. The biggest differences obtained in them amounted to over 50%. Because piezoelectric transducer was then attached to the human tissue, the conditions of the tests may raise some doubts.

As an element of statistical analysis of presented results, the correlation coefficient was calculated for examined vibration parameters. Values in Table 2 show good compatibility of the results obtained with the developed method and obtained of using the reference standard measuring system.

Table 2. Correlation coefficient for corrected acceleraion values obtained using two meauring systems

Analyzed parameter	a_h	a_{hv}
Correlation coefficient value	0.9965	0.9988

The presented comparison results show that the test results obtained with the use of high-speed camera are reliable and can be used in assessing exposure to vibration.

Daily vibration exposures were determined based on calculated values of corrected vibration acceleration and vector sums. During the daily exposure determination, a total exposure time to vibration during a work shift was 4 hours. For exposure assessment, daily limit value for hand-arm vibration exposure 2.8 m/s^2 used in Poland (given in the ordinance of the Minister of Family, Labor and Social Policy of 12 June 2018 on the highest permissible concentrations and intensities of factors harmful to health in the working environment, Journal Of Laws of 2018, item 1286) has been applied. Determined using reference measuring system and high-speed camera values of daily exposures for operators of selected hand tools as well as evaluation results obtained using standard method and presented developed method contains the Table 3.

Table 3. Daily vibration exposure and evaluation results obtained using reference measuring system and developed method

Measurement object	Daily vibration exposure A(8), m/s²		Difference [%]	Exposure	
	Pulse	Camera		Pulse	Camera
Pneumatic wrench I	4.88	4.86	0.3	high	high
Pneumatic wrench II	4.72	4.77	1.0	high	high
Brushcutter Kawasaki TH34	5.08	4.92	3.2	high	high
Electric scissorsHecht 655	4.09	4.05	1.0	high	high
Electric Saw FPCS1800A	2.21	2.34	**5.7**	medium	medium
Combustion Saw Stihl 025	15.30	16.11	5.0	high	high
Saw for plastics Bosch GSG 300	1.70	1.61	5.4	medium	medium
Oscillating grinder CMI C-SS 200	5.08	5.08	**0.0**	high	high
Cordless screwdriver Makita DF347D	3.16	3.25	2.6	high	high
Jigsaw Machine Bosch GST 150BCE	4.89	4.94	1.0	high	high

Based on the obtained results, it can be concluded that full compatibility of exposure assessments carried out based on the developed method of identification and using the standardized method has been achieved.

The results summarized in the table 3 show that at 4 hours of exposure, out of 10 tools tested, 8 of them cause high vibration exposure to worker. Only in two cases this exposure was moderate. This means that of the 10 tools tested, only 2 tools allow their safe use for 4 hours during a work shift.

4. Conclusions

Tests performed using a high-speed camera allow obtaining the same or very similar results to those obtained with the use of classic measurement systems. The test results confirmed the possibility of use of high-speed camera for research of low frequency vibration even at low displacements. It can be assumed that by using higher frame rates it will be possible to obtain similar results also at higher frequencies (i.e. up to 1000-1500 Hz).

Due to the need for a high zoom of the measuring point image, the use of a camera to analyze vibration is limited to situations where movement occurs within the range of the frame. At frequencies above 50-70 Hz, with amplitudes of *nm*, it may not be sufficient to use classic lenses and other optical elements (teleconverters, intermediate rings). The analysis of oscillatory motion recorded in the range of 2-3 pixels has no substantive justification. The proper operation of the camera is associated with ensuring adequate stabilization of its position, which significantly hinders its use in motion.

The results of verification tests show that the presented method of vibration identification and assessment, after taking into account the described limitations, can be successfully used for research vibration in the working environment.

The main advantage of vibration testing using a high-speed camera is the ability to obtain additional information about the phenomena observed during vibration generation and their impact on other mechanical systems, often without the need for further identification, analysis and interpretation. The dynamic development of the production technology of image recording devices, microprocessors, new generation computer memories and techniques based on image recognition and analysis allows us to predict that the use of high-speed cameras also for vibration analysis will be ever wider.

Acknowledgments

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Chapter 10

Sensitivity and response to temperature changes of selected smart materials

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Abstract
The paper presents research intended to applications of piezoelectric materials to measure the parameters of hand-arm vibration. The measurements take into account both the vibration energy passed into the hand-arms and the working conditions. The following piezo films were selected: DT4-052K/L polyester film with a thickness of 52 microns PVDF, and LDT4-028K with a thickness of 28 microns PVDF. The research of piezoelectric smart materials was based on determining the frequency characteristics of piezo films. The materials were excited without hand-arm system load and using noise signal from the range 2 to 1600 Hz. The sensitivity for different sizes of the piezo films and response time to temperature changes were presented.

Keywords: piezoelectric materials, hand-arm vibration, piezo film sensors

1. Introduction

Piezoelectricity is the charge that accumulates in certain solid materials in response applied mechanical stress. These materials generate an electric charge proportional to that stress. This is called *the direct piezoelectric effect* and it may be used for example to construction of piezoelectric, vibration forces or temperature sensors [1-7].

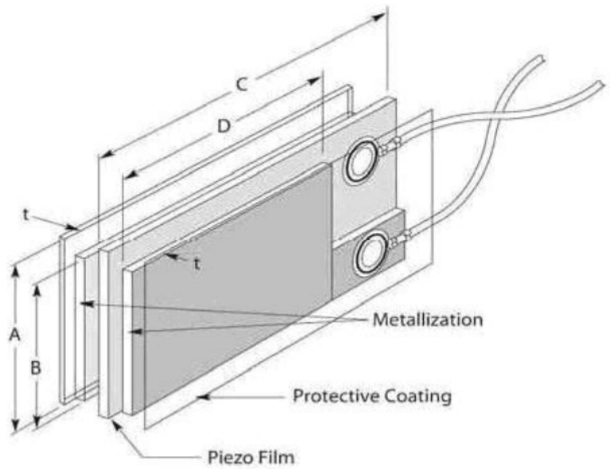
There are many areas where piezoelectric phenomena is used extensively. A dynamic development of new piezoelectric materials has been seen in recent years. One of the most popular piezoelectric material is polyvinylidene fluoride – PVDF [8-10]. PVDF is usually performed in a thin film of thickness from a few to several hundred microns (so-called piezo film). Due to its properties as both PVDF and its copolymers [11] have found applications in many fields, such as the manufacture of underwater acoustic transducers, seismographs, pumps and valves, sensors, traffic, switches. They are also used for nondestructive testing of materials and often in medicine, including the manufacture of artificial muscle, skin, and human organs [1, 12, 13].

Research carried out at CIOP-PIB intended to applications of piezoelectric materials to measure the parameters of hand-arm vibration. These measurements take into account both the vibration energy passed into the hand-arms and the working conditions (forces exerted by the operator of the tool, ambient temperature, personal protective equipment). Practical application of PVDF film as a vibration sensor is involved with their frequency characteristics during exposition to vibration, sensitivity to electromagnetic interferences and the response to temperature variability.

2. Tested objects

The following piezo films from among smart materials available on the market were selected: DT4-052K/L polyester film with a thickness of 52 microns PVDF, and LDT4-028K with a thickness of 28 microns PVDF. The parameters of both piezo films were shown in Table below.

Table. Parameters of selected piezo film sensors



Description	Dimension (mm)				Metalization, µm	Capacitance, nF
	A film	B electrode	C film	D electrode		
DT4-052K/L	22	19	171	156	70	5.70
LDT4-028K	22	19	171	156	205	11.00

Research were carried also with smaller elements: 19 mm × 86 mm and 19 mm × 43 mm. Preliminary tests confirmed the sensitivity of film to interference caused by electromagnetic fields from the vibration exciter and the electrical grid in the laboratory. Application of thin aluminum shield (thickness 0.2 mm) caused 99% elimination of electromagnetic interference. PVC tape was used as an insulating layer.

3. Test method

3.1. Determination of the frequency characteristics

The research of piezoelectric smart materials was based on determining the frequency characteristics of piezo films. The materials were excited without hand-arm system load and using noise signal (PSD 0.1 $(m/s^2)^2/Hz$) from the range 2 to 1600 Hz, which include frequencies analysed in the assessment of exposure to hand-arm vibration at workplace – 5.6 ÷ 1400 Hz. Tests were carried out at ambient temperature 21 ÷ 23°C.

Diagram of the measuring system to determine the frequency characteristics of piezo films without hand-arm system load is shown in Figure 1.

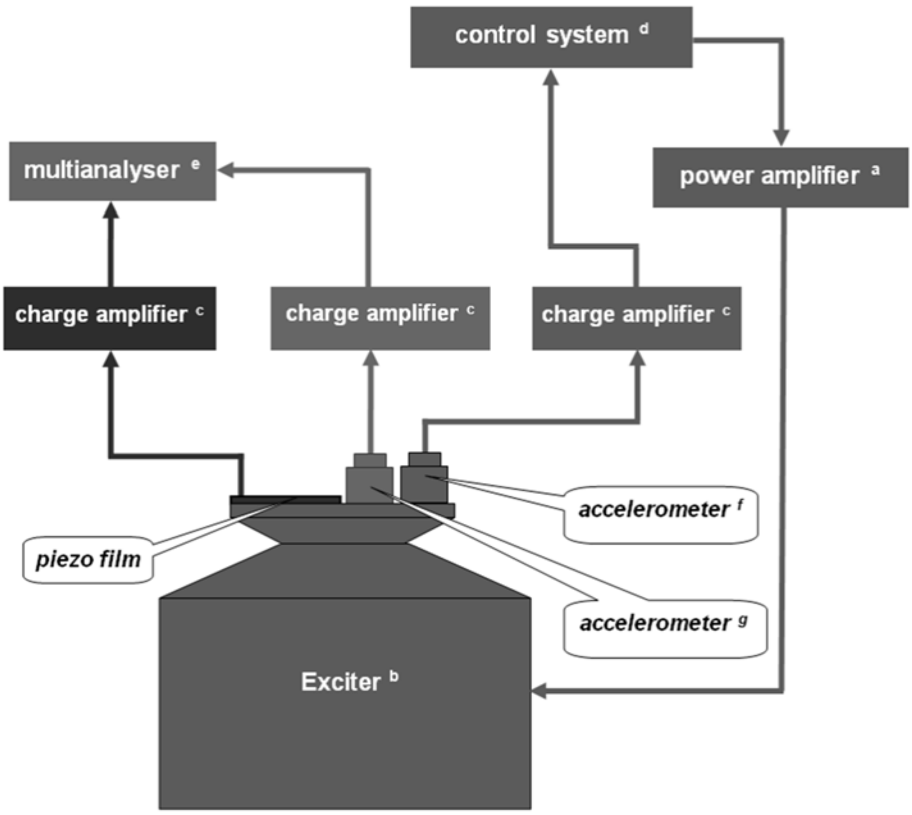


Figure 1. Diagram of the test stand for determining the frequency characteristics of piezo films; a – PA 2000 (LDS), b – V721 (LDS), c – 2626 (B&K), d – VibPilot (M+P International), e – PULSE (B&K), f – 4371 (B&K), g – 4384V (B&K)

The analysis of the recorded signals was performed in the frequency range from 1 Hz to 1600 Hz (with a resolution of 1.0 Hz) using multianalyser PULSE. Frequency characteristics of selected piezo films are shown in Figure 2.

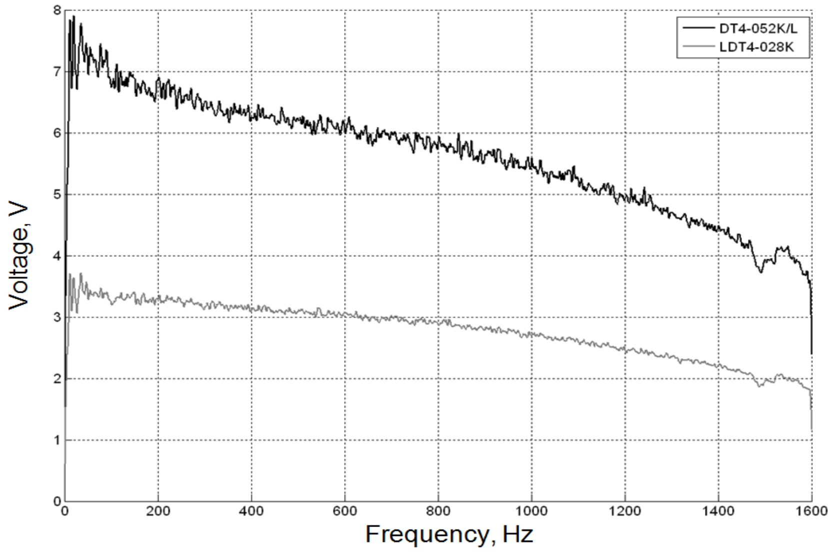


Figure 2. Frequency characteristics of piezo films type LDT4-028K and DT4-052K/L

In order to check how the sensitivity of the piezo film changes when its dimensions are reduced, the frequency characteristics (Figure 3) for piezo film strips with dimensions: 171 mm × 19 mm (complete), 86 mm × 19 mm (a half), 43 mm × 19 mm (a quarter) and the strip folded in half were compared.

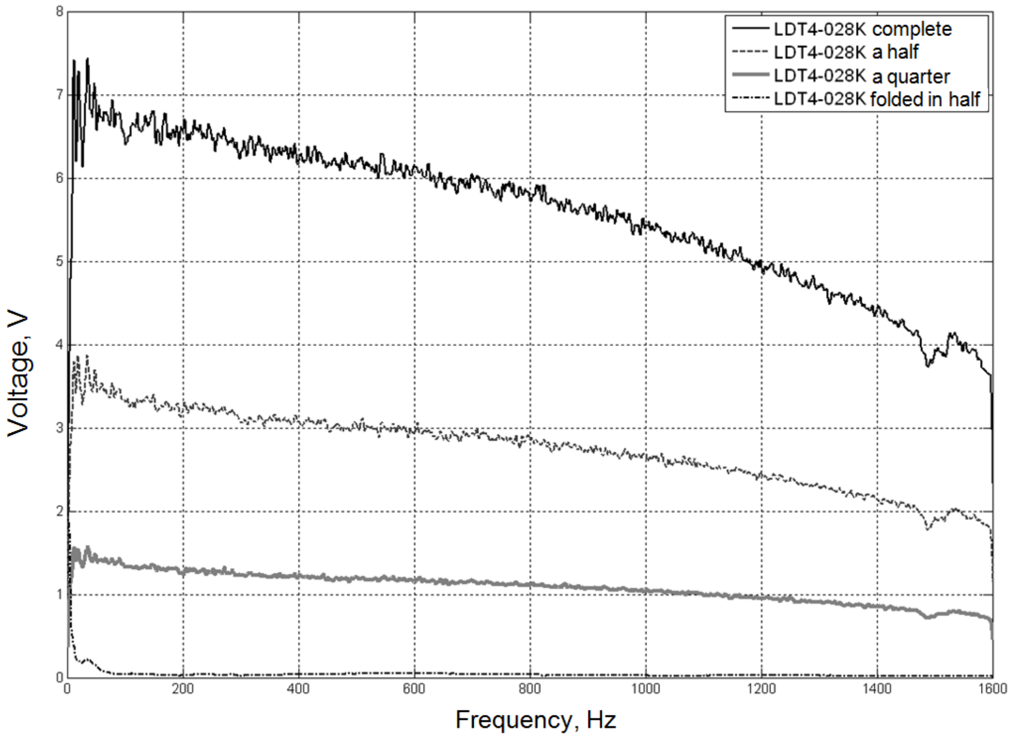


Figure 3. Frequency characteristics for different dimensions of piezo film type LDT4-028K

3.2. The response to temperature change

Determination of response time to temperature changes of direct piezo element environment was carried by reason of expected employee hand contact with the adaptor made of piezo film. As a heat source, 12 V / 50 W bulb was used, which at a distance of 20 mm from the piezo film surface allowed to obtain the temperature ca. 70°C. Thanks to the insulation of piezo film, electromagnetic field generated by the bulb, exciter or grid in the laboratory can be excluded.

A Figure 4 presents timing of the DT4-052K/L response to cycle of turning on and off the light bulb. In both cases, the reaction time was less than 20 ms. Frequency characteristics of the item DT4-052K/L during series of turning the bulb on and off were shown in Figure 5. The dominant components appear at frequencies below 1 Hz.

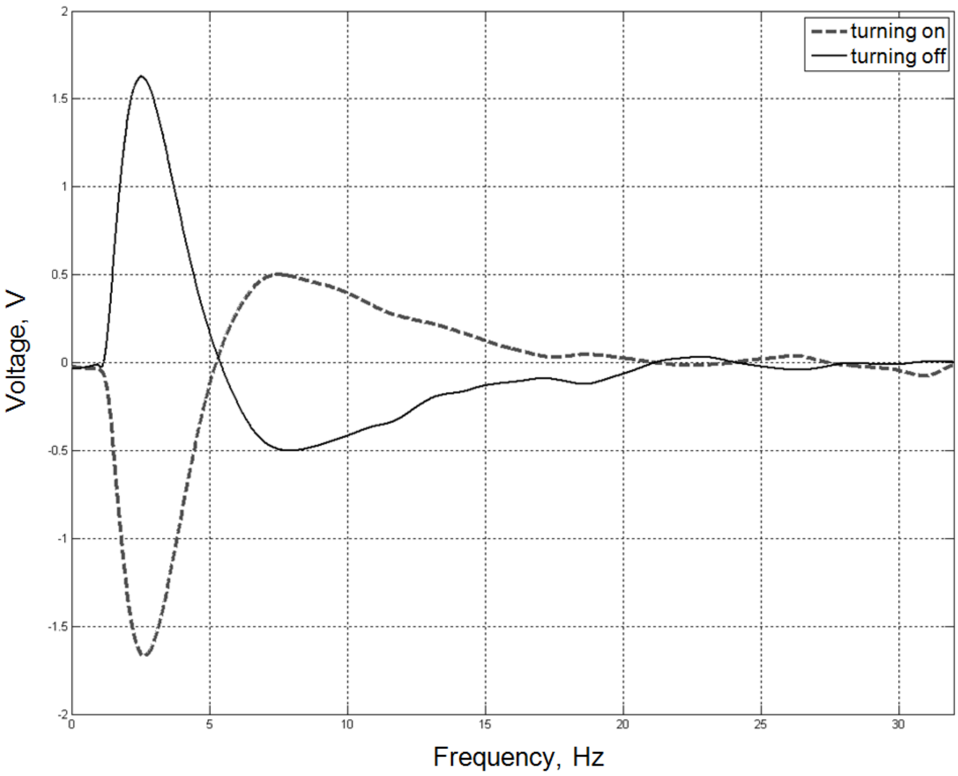


Figure 4. Timing of the DT4-052K/L response to cycle of turning on and off the light bulb

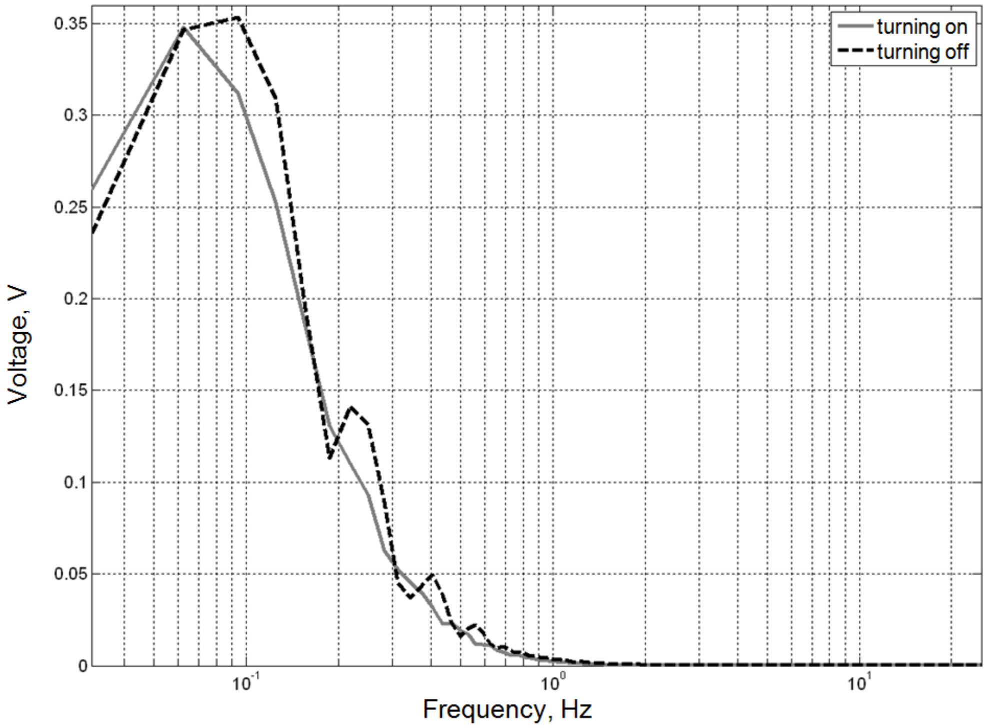


Figure 5. Frequency characteristics of DT4-052K/L during turning on and turning off the light bulb

A similar test was performed using a camera flash as a source of heat. In this way, even shorter time duration of pulse thermal was obtained. Figure 6. shows the timing of the DT4-052K/L response to the camera flash.

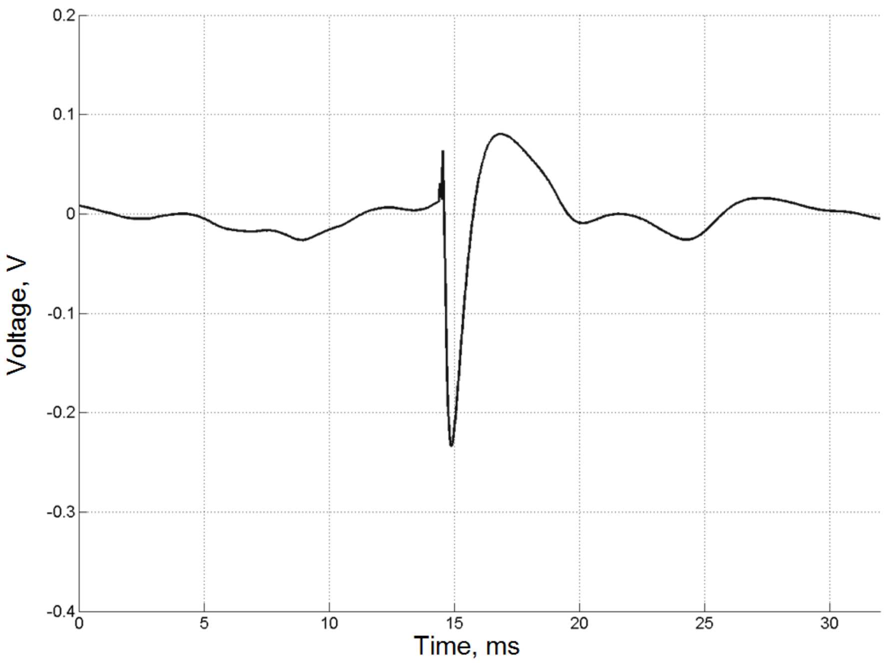


Figure 6. Timing of the DT4-052K/L response to the camera flash

Recorded reaction time of piezo film was approximately 5 ms.

4. Conclusions

The results confirmed the sensitivity of the tested piezo films to the noise signal stimulation and also to temperature changes of direct environment. Frequency characteristics for LDT4-028K are a bit more flat than for DT4-052K/L. The output voltage in almost entire measurement range is two times lower. It means that the DT4-052K/L has almost throughout the frequency range two times greater sensitivity than the element LDT4-028K. It is associated with higher (1.86-times compared to LDT4-028K) piezo film thickness.

The obtained characteristics have also shown how the charge sensitivity changes depending on the size of piezo film. Reducing the surface of the tested strip causes more and more flat frequency characteristics, but also it reduces the charge sensitivity: about 2-times for half of the strip, 5-times for the quarter and 20-times when the strip is folded in half. The results will be used in further studies on applicability of piezoelectric materials to vibration measurements in work environment.

Acknowledgments

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Chapter 11

Selection of the vibration impact estimation parameter for environmental assessments

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Abstract
Frequently encountered problem with estimating the impact of vibrations for new investments, which may have adverse effects, it seems important to select an assessment parameter that will ensure compliance with the relevant legal provisions. In this papers shows the correct selection of the parameter for the assessment of the impact of vibrations for new or renovated sections of railways in relation to the current legal situation in our country. It also shows the practical aspect of the issue with the use of examples of implementation based on vibration measurements made for investments that may have a significant impact on the environment in terms of vibration generation.

Keywords: vibration, vibration influence on humans in buildings, vibration comfort, human perception, transport vibration

1. Introduction

Due to the more and more frequently encountered errors, which pose a problem related to the estimation of the impact of vibrations for new investments, which in turn may have adverse effects and affect the comfort of people in the neighboring buildings [1], the correct selection of the evaluation parameter seems to be important. It is designed to meet the relevant legal provisions and, above all, efficiently to protect people in buildings located in the vicinity. In these papers was introduced correct selection of the parameter to assess the impact of vibrations for new or renovated sections of railways and others investments.

2. The origin of the problem

Because of recent increase in expenditure on investments in transport infrastructure, the construction market is experiencing a revival in the creation of new communication routes and the renovation of the existing ones. According to Regulation of the Council of Ministers of 10th September, 2019 on projects that may significantly affect the environment [2] they include, among others:

§1:

29) railway lines [...]

31) motorways and expressways [...]

§ 2:

60) railway lines [...]

62) hard surface roads [...]

63) tram lines, overhead or underground railways, including metro [...].

For investments of this type, it is necessary to develop an environmental impact assessment, and as part of such an assessment, the selection of an appropriate parameter concerning the impact on the environment, also with regard to vibrations. Unfortunately, often due to the superficial knowledge of the issue by the authors of the report, there may be a situation where the parameter used for such an assessment will be incorrectly defined. In this case, the interests of both the investor and the local residents are not adequately protected despite the apparent fulfillment of the conditions required by Polish law.

3. Example of implementation of the procedure based on the decision of the District Management for Environmental Protection

This publication was inspired by the analysis of the terms of the contract, which were included in one of the procedures concerning post-completion research based on the District Management for Environmental Protection (DMEP) decision. In the announced tender for the performance of works for the assessment of the impact of vibrations and noise, objections were raised with regard to the currently applicable legal provisions:

1. What is the legal basis for choosing a parameter for the assessment of the impact of vibrations, which is the impact on buildings and not on people in buildings, which is contrary to the provisions [3] Art. 3 point 13b in the Regulation [2] (which refers to the protection of the environment and counteracting pollution).

2. Specifying only the Standard [4] Why is the impact on buildings, and not on people in buildings, a critical parameter for the assessment of the impact of vibrations, which is contrary to the provisions of Art. 3 point 13b (which refers to the protection of the environment and counteracting pollution)? The purpose of this standard is to estimate the impact of vibrations on the structure of buildings, i.e. to what extent their structure is resistant to vibrations. In essence, it is the building structure that is less sensitive

to vibration than the effects on people in the buildings. According to this rule, it is the people in the building that will experience the negative impact of vibration first, and only then the structure of the building. So, is the Principal's goal to protect empty buildings and their structures, or is the influence of vibrations affecting people significant? It should be the basic criterion to be met in accordance with [5] – Assessment of the impact of vibrations on people in buildings, and not adopted by the Employer.

3. In addition, the legislator, in Art. 3 point 49 of the Act [3], defines "pollution" by emission (vibrations are also included in the emissions in accordance with Article 3 point 4b), which may be harmful to human health or the environment, may cause damage to material goods, may deteriorate the aesthetic values of the environment or may conflict with other, justified ways of using the environment.

The interpretation used by the Principal allows only the protection of material goods while disregarding the impact of vibrations on people, which is contrary to the provisions of the Act [3], which was referred to.

As a conclusion, on the basis of the issued decision, the performance of measurements of the impact of vibrations on buildings, excluding analyzes of the impact of vibrations on people in buildings, does not protect the interests of the Principal against future claims for vibration emissions, which results directly from [3] Article 6.1, 2, Article 7.1 and 2 of the Act [2], and thus – the issued decision has a legal defect and as such its execution should be immediately suspended.

The answer that was obtained from DMEP to the allegations made does not exhaust the points contained in the inquiry and does not substantively explain the reasons for making such decisions [Quoted]: *„[…]*

1. The condition concerning the assessment of the impact of vibrations on buildings was formulated in this and no other way, as its content was based on the documentation collected in the administrative procedure, including the report on the environmental impact of the project.

2. The body cooperating in the proceedings aimed at obtaining, inter alia, the decision on environmental conditions is also the sanitary inspection body, whose competences include, first of all, the analysis of the impact of implemented projects on the living conditions and health of people. The sanitary inspection authority also participated in the proceedings cited in the correspondence, and the conditions for the implementation of the project indicated by this authority were fully included in the position of the Regional Director for Environmental Protection.

3. It should also be pointed out that the decisions of administrative bodies are issued on the basis of the legal provisions in force in Poland, to which the norms cited in the above-mentioned writing does not *belong. Moreover, it is not the competence of a state administration body to indicate to experts who perform specialized tests, legal norms to be applied in their performance.*

To sum up, the authority here does not see the legal flaws in the issued environmental decision, which has in fact already been "consumed" by issuing a decision based on it, taking into account the conditions for the implementation of the project, arising in the procedure of issuing a building permit decision, as well as a building permit. The investment has been completed and commissioned".

As can be seen, the decision is issued only seemingly in accordance with the regulations, as shown below. Additionally, it is contrary to common sense. It remains to be determined who is responsible for the enforcement of the procedure throughout the procedure, which will properly protect the interests of all parties, including people living in the vicinity of the investment being implemented. Otherwise, the law thus interpreted should be considered harmful. It should be mentioned that the law clearly specifies the requirements in this respect.

The basic document regulating the legal issues of environmental protection is the Act [3]. Pursuant to its provisions (Art. 3 point 13), environmental protection is understood *as taking or omitting actions that enable the preservation or restoration of natural balance; this protection consists in particular in:*

a) rational shaping of the environment and management of environmental resources in accordance with the principle of sustainable development,

b) counteracting pollution,

c) restoring natural elements to their proper condition.

And when it comes to the impact on the environment, it also means the impact on human health (Art. 3 point 11). In Art. 3 also states that whenever the act mentions:

(…)

4) emissions – it means direct or indirect input, as a result of human activity, into air, water, soil or soil:

a) substances,

b) energies such as heat, noise, ***vibration*** or electromagnetic fields.

(…)

49) pollution – shall mean the emission that may be harmful to human health or the state of the environment, may cause damage to material goods, may deteriorate the aesthetic values of the environment or may conflict with other, justified ways of using the environment;

(…)

The juxtaposition of these records shows that vibrations are classified as energy, energy is classified as emission, and emissions are classified as pollutant, that is:

vibrations = energy = emission of pollution into the environment

Thus: all provisions and requirements in the Act [3] relating to the emission of pollutants also apply to the emission of vibrations (the same applies to noise). In connection with this, it is worth quoting several articles of the law in question, which are related to protection against vibrations:

Art. 6

1. Whoever undertakes activities that may have a negative impact on the environment, is obliged to prevent this impact.

2. Whoever undertakes activities, the negative impact of which on the environment is not yet fully identified, is obliged, guided by caution, to take all possible preventive measures.

Art. 7

1. Whoever pollutes the environment bears the costs of removing the effects of this pollution.

2. Whoever may cause pollution of the environment bears the costs of preventing this pollution. (…)

Art. 137

Counteracting pollution consists in preventing or limiting the release of substances or energy into the environment.

(…)

Art. 139

The managers of these facilities ensure compliance with environmental protection requirements related to the operation of roads, railways, trams, airports and ports.

Pursuant to Art. 137 counteracting vibrations consists in preventing the emission of vibrations or limiting the emission of vibrations into the environment.

Article 139 obliges the administrators of roads, railways, trams, airports and ports to comply with the environmental protection requirements related to the operation of these facilities. In the light of this article and Art. 7, if there is a complaint about excessive vibrations, e.g. road vibrations in a given building, the road operator is obliged to check, at his own expense, what is the impact of road vibrations on this building and on people in this building. And if the excessive impact of vibrations is confirmed, he should repair any damage to the building at his own expense and take steps to remedy the situation (protect the building against excessive vibration impact).

Requirements regarding the necessity to take into account the influence of vibrations in the design of buildings are also included in [6], which § 325 reads as follows:

§ 325. Appropriate location of buildings

1. Residential buildings, collective residence buildings and public utility buildings should be located in places least exposed to the occurrence of noise and ***vibrations****, and if they occur and their levels will result in exceeding the permissible noise and vibration levels in the premises of these buildings, specified in the* ***Polish Standards*** *on admissible sound level values in rooms and the assessment of the impact of* ***vibrations*** *on buildings and people in buildings, effective protection should be used.*

§ 326. Acoustic insulation

1. The level of noise and ***vibrations*** *penetrating into rooms in residential buildings, collective residence buildings and public utility buildings, with the exception of buildings for which it is necessary to meet specific noise protection requirements, may not exceed the permissible values specified in the Polish Standards on noise protection for rooms in buildings and the assessment of the impact of* ***vibrations*** *on people in buildings, designated in accordance with Polish Standards on the method of measuring the A sound level in rooms and assessing the impact of* ***vibrations*** *on people in buildings.*

4. Practical example based on the results of vibration measurements

In the laboratory's measurement practice, so far there has been no situation in which the measured level of the impact of vibrations on people in a building (in accordance with [5]) would be lower than the impact of vibrations on the structure of this building (in accordance with [4]). Therefore, the measurement of the impact of vibrations on the building structure is the appropriate parameter for assessing the impact of vibrations on the environment when the impact of vibrations on people is consciously ignored.

This mainly applies to vibrations caused by construction works in the vicinity of existing buildings. Then the main goal is to protect the structures of these buildings against damage, while the assessment of the impact of vibrations on people in these buildings is omitted due to the temporary nature of this impact. It is assumed that in order to enable construction works to be carried out, people must bear the nuisance of vibrations and noise caused by these works, provided that they are not carried out at night. ***Similar approach is to the influence of short-term vibrations, such as e.g. the effects of mining tremors, quarrying shots, etc., here the aim is also to protect the structure of buildings against***

damage. On the other hand, in cases where both influences are taken into account, i.e. on the structure of the building and people in this building, as is the case when monitoring long-term dynamic effects, e.g. transport vibrations – the decisive factor will always be the impact on people in the building in accordance with the standard [5]. Such a system was implemented in the Warsaw Metro and since 2003 to date no violations of the impact of vibrations on the structure have been recorded, but the threshold for perceptibility of vibrations by people in buildings has been exceeded many times [7] (see Figure 1).

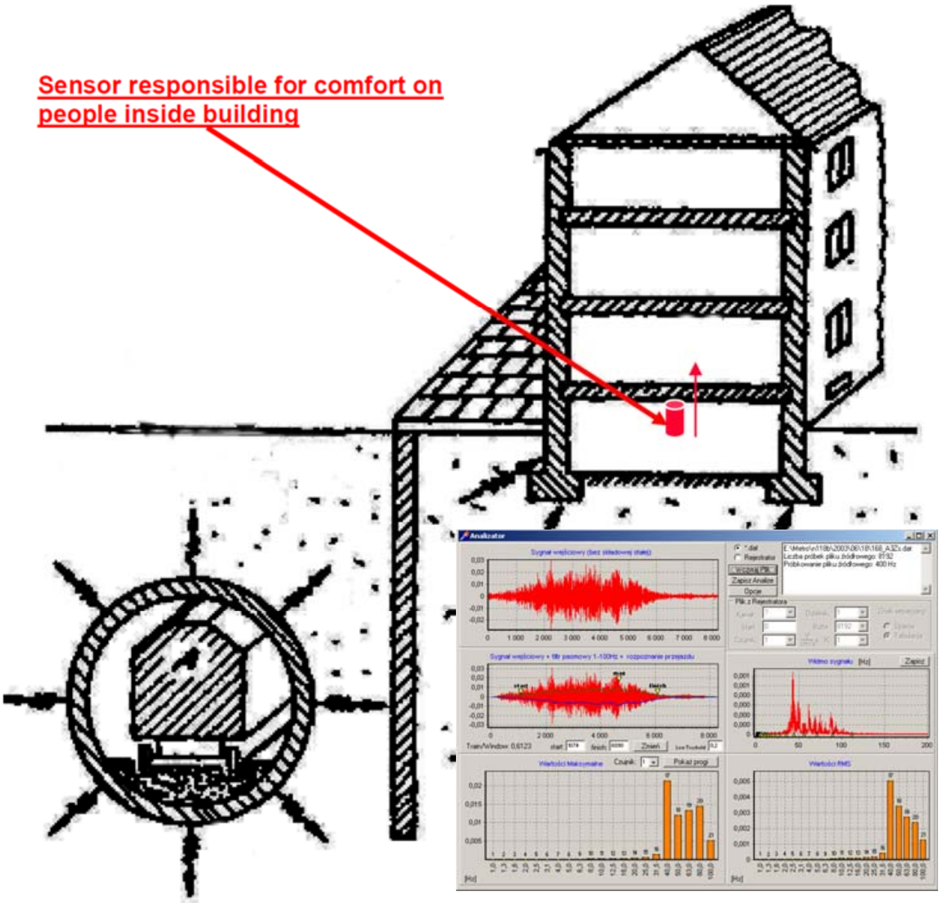

Figure 1. Schematic of sensor positioning in Warsaw Metro and part of control panel of analysis of comfort on people inside buildings

Below there is an example of some measurements of vibrations of building which was located in the neighborhood of vibration stripes (on road). This solution was in aim to minimize speed of passing of heavy lories coming from near stone-pit. Some vibrograms were recorded and analyzed (see Figure 2 and Figure 3). Figures below shows recorded vibrogram and result of analysis. For each measurement the same procedure was applied.

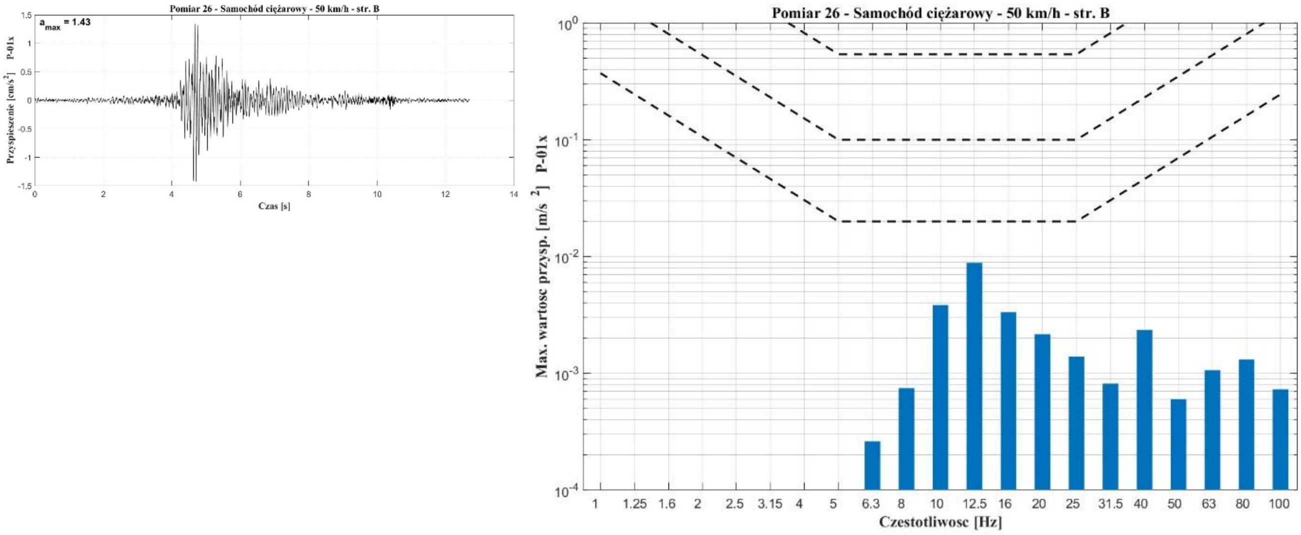

Figure 2. Measurement 26: left side vibrogram and right side third octave band analyze result; lorry pass by analysis of the impact of vibrations on the building structure in the horizontal direction X, in accordance with [4] (the building is subject to rough assessment according to SWD-I) – results for the measurement from Table 1

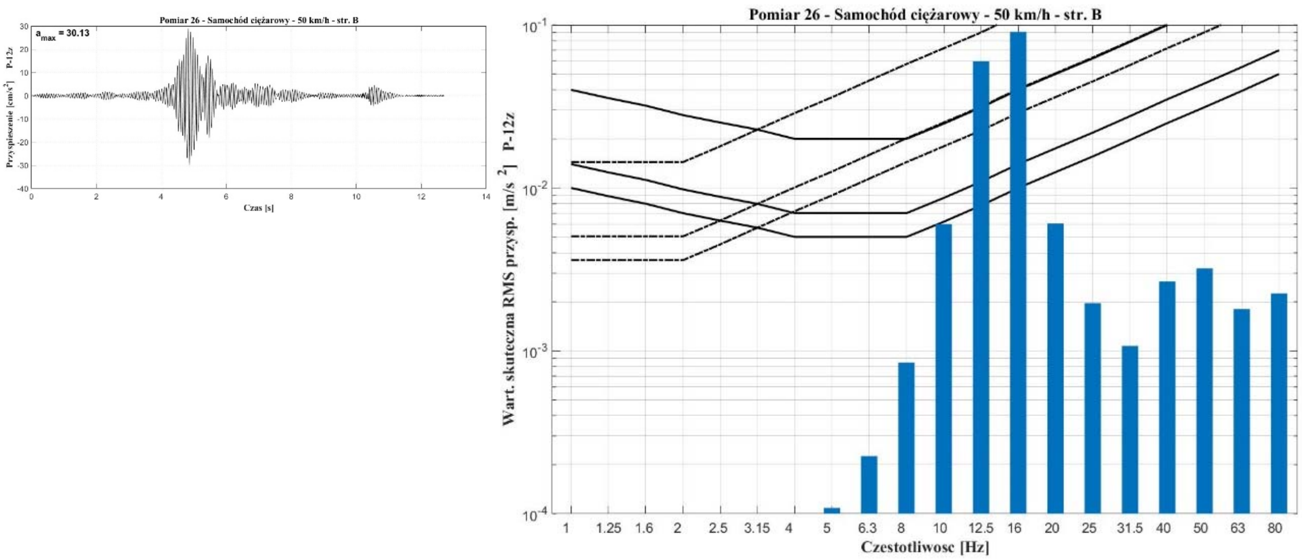

Figure 3. Measurement 26: left side vibrogram and right side third octave band analyze result; lorry pass by analysis of the impact of vibrations on people in the building vertical direction Z according to [5] – results for the measurement from Table 2

Selected results were shown in Table 1 (impact on buildings) and Table 2 (influence on people inside buildings).

Table 1. BVPR (Building Vibration Perceptivity Ratio) index for all measurements in the building under study

DESCRIPTION	P-01x		P-02y	
	Cubic on construction			
	f [Hz]	BVPR	f [Hz]	BVPR
Measurement 3 Heavy truck 38 km/h lane B	12.50	0.27	12.50	0.19
Measurement 6 Light truck 40 km/h lane B	20.00	0.07	16.00	0.05
Measurement 7 Light truck 43 km/h lane B	12.50	0.09	12.50	0.08
Measurement 9 Light truck 31 km/h lane B	16.00	0.08	12.50	0.06
Measurement 10 Heavy truck 51 km/h lane B	12.50	0.07	12.50	0.05
Measurement 11 Heavy truck 50 km/h lane B	12.50	0.24	12.50	0.19
Measurement 12 Light truck 50 km/h lane B	16.00	0.06	12.50	0.04
Measurement 14 Heavy truck 45 km/h lane B	12.50	0.25	16.00	0.14
Measurement 16 Heavy truck 42 km/h lane B	12.50	0.13	12.50	0.08
Measurement 17 Heavy truck 48 km/h lane B	12.50	0.23	12.50	0.25
Measurement 19 Light truck 48 km/h lane B	16.00	0.08	16.00	0.06
Measurement 20 Heavy truck 38 km/h lane B	10.00	0.26	10.00	0.17
Measurement 21 Light truck 52 km/h lane B	16.00	0.04	16.00	0.04
Measurement 22 Light truck 42 km/h lane B	20.00	0.07	16.00	0.03
Measurement 23 Heavy truck 30 km/h lane B	12.50	0.17	16.00	0.11
Measurement 24 Heavy truck 45 km/h lane B	12.50	0.30	12.50	0.17
Measurement 26 Heavy truck 50 km/h lane B	12.50	0.44	12.50	0.28
Measurement 27 Heavy truck 45 km/h lane B	12.50	0.24	12.50	0.17
Measurement 30 Heavy truck 43 km/h lane B	12.50	0.31	12.50	0.18
Measurement 33 Light truck 48 km/h lane B	12.50	0.29	12.50	0.17
Measurement 34 Light truck 54 km/h lane B	12.50	0.02	12.50	0.02
Measurement 35 Heavy truck 54 km/h lane B	12.50	0.32	12.50	0.27
Measurement 36 Heavy truck 54 km/h lane B	12.50	0.34	12.50	0.23
Measurement 37 Heavy truck 51 km/h lane B	12.50	0.27	12.50	0.19
Measurement 39 Heavy truck 51 km/h lane B	20.00	0.17	12.50	0.12
Measurement 41 Light truck 46 km/h lane B	12.50	0.04	12.50	0.03
Measurement 42 Heavy truck 51 km/h lane B	12.50	0.27	12.50	0.18
Measurement 43 Heavy truck 52 km/h lane B	12.50	0.40	12.50	0.30
Measurement 45 Heavy truck 46 km/h lane B	12.50	0.32	12.50	0.38
Measurement 47 Light truck 44 km/h lane B	20.00	0.02	16.00	0.02
Measurement 50 Heavy truck 37 km/h lane B	12.50	0.29	12.50	0.16
Measurement 52 Heavy truck 36 km/h lane B	12.50	0.35	12.50	0.20
Maximum value		**0.44**		**0.38**

The last line shows the maximum value of the BVPR index, which was recorded during the Measurements for the horizontal direction x and y, respectively. A value below 1 means the results without exceeding the A-limit, i.e. vibrations are classified as imperceptible by the building structure.

Table 2. HVPR (Human Vibration Perceptivity Ratio) indicator for all Measurements in the tested building – yellow fields indicate the results exceeding the threshold of perceptibility of vibrations by humans (WODL value above 1)

Description	**P-04x**		**P-06z**		**P-10x**		**P-12z**	
	Disc no 1 Gnd floor Living Room				**Disc no 2 Attic Room**			
	f [Hz]	**HVPR**	**f [Hz]**	**HVPR**	**f [Hz]**	**HVPR**	**f [Hz]**	**HVPR**
Measurement 3 Heavy truck 38 km/h lane B	8	0.02	16	1.8	12.5	0.12	12.5	7.97
Measurement 6 Light truck 40 km/h lane B	16	0.02	16	1.19	16	0.05	12.5	2.17
Measurement 7 Light truck 43 km/h lane B	12.5	0.03	16	0.75	12.5	0.04	12.5	4.05
Measurement 9 Light truck 31 km/h lane B	16	0.02	16	1.31	16	0.06	12.5	3.03
Measurement 10 Heavy truck 51 km/h lane B	63	0.01	12.5	0.42	63	0.01	12.5	3.11
Measurement 11 Heavy truck 50 km/h lane B	12.5	0.05	16	2.09	16	0.11	16	7.54
Measurement 12 Light truck 50 km/h lane B	12.5	0.01	16	0.87	16	0.04	16	2.13
Measurement 14 Heavy truck 45 km/h lane B	12.5	0.05	16	1.38	16	0.09	12.5	6.5
Measurement 16 Heavy truck 42 km/h lane B	8	0.04	16	0.83	8	0.07	12.5	2.47
Measurement 17 Heavy truck 48 km/h lane B	12.5	0.07	16	1.62	16	0.08	12.5	7.95
Measurement 19 Light truck 48 km/h lane B	16	0.02	16	1.79	16	0.06	16	3.4
Measurement 20 Heavy truck 38 km/h lane B	10	0.06	12.5	0.52	10	0.17	12.5	1.78
Measurement 21 Light truck 52 km/h lane B	16	0.01	16	0.81	80	0.01	16	2.59
Measurement 22 Light truck 42 km/h lane B	12.5	0.01	20	0.59	16	0.03	16	2.22
Measurement 23 Heavy truck 30 km/h lane B	12.5	0.04	16	2.02	16	0.11	16	8.14
Measurement 24 Heavy truck 45 km/h lane B	12.5	0.07	16	1.51	10	0.07	16	4.21
Measurement 26 Heavy truck 50 km/h lane B	12.5	0.09	16	2.58	16	0.11	16	9.08
Measurement 27 Heavy truck 45 km/h lane B	12.5	0.05	16	2.07	16	0.12	16	7.56
Measurement 30 Heavy truck 43 km/h lane B	12.5	0.09	16	1.14	10	0.11	16	3.04
Measurement 33 Light truck 48 km/h lane B	12.5	0.09	16	1.28	12.5	0.08	12.5	6.07
Measurement 34 Light truck 54 km/h lane B	6.3	0.01	16	0.26	16	0.01	12.5	1.2
Measurement 35 Heavy truck 54 km/h lane B	12.5	0.09	12.5	1.62	12.5	0.11	12.5	12.01
Measurement 36 Heavy truck 54 km/h lane B	12.5	0.12	12.5	2.12	12.5	0.11	12.5	13.59
Measurement 37 Heavy truck 51 km/h lane B	12.5	0.07	16	1.41	16	0.09	12.5	7.27
Measurement 39 Heavy truck 51 km/h lane B	12.5	0.05	16	1.07	16	0.05	16	2.9
Measurement 41 Light truck 46 km/h lane B	12.5	0.01	16	0.3	16	0.01	12.5	0.49
Measurement 42 Heavy truck 51 km/h lane B	12.5	0.08	16	2.42	16	0.09	12.5	8.66
Measurement 43 Heavy truck 52 km/h lane B	12.5	0.12	16	2.69	12.5	0.12	12.5	15.5
Measurement 45 Heavy truck 46 km/h lane B	12.5	0.11	16	2.5	12.5	0.13	12.5	11
Measurement 47 Light truck 44 km/h lane B	16	0.01	20	0.26	16	0.02	16	0.95
Measurement 50 Heavy truck 37 km/h lane B	12.5	0.09	12.5	1.27	10	0.14	12.5	6.58
Measurement 52 Heavy truck 36 km/h lane B	12.5	0.1	16	1.86	12.5	0.07	12.5	5.92
Maximum value		**0.12**		**2.69**		**0.17**		**15.5**

Color legend:

HVPR > = 4
4 > HVPR > = 1.4
1.4 > HVPR > = 1

The last line shows the maximum value of the HVPR index, which was recorded during the measurements for the horizontal x, y and vertical z directions. A value below 1 means the results without exceeding the threshold of human vibration perception. Such values were recorded mainly for the vertical sensor in the attic (last column).

Despite such high values measured for the impact of vibrations by people in the building (Table 2), none of the measurements reported exceeding the threshold of perceptibility of vibrations by the building structure (Table 1).

Based on the observation of many thousands of measurement results, it can be concluded that so far there has not been a situation where the BVPR value above 1 was observed, and the impact of vibrations on people would not be exceeded (HVPR). The occurrence of such a result may indicate the occurrence of anomalies most often caused by the wrong location of the sensor, chafing plaster or the location of the sensor to assess the comfort of people directly on the ground, etc.

To sum up, the ***basic parameter of environmental assessments concerning transport vibrations (investments in transport infrastructure) should be the assessment of the impact of these vibrations on people in buildings***, made in accordance with [5]. Measurements of the impact of vibrations on the building structure should then not be the sole basis for such an assessment.

5. Conclusions

Due to the provisions of the Act [3], it seems to be unjustified from the point of view of environmental assessments – testing only the impact of vibrations on the structure of buildings. ***The negative effects of vibration on people in a building will occur much sooner, before it is manifested on the building structure***. The provisions of the law in force in Poland oblige the investor to ensure comfort due to vibrations also for people in the buildings, and not only for the building structure, which was demonstrated on the basis of a thorough analysis of the current legal situation.

On the basis of the presented materials, it can be concluded that the provisions of the law ***allow for the correct selection of the parameter that should be used to assess the environmental impact of transport vibrations***, but often people who perform environmental assessments and reports and make environmental decisions ***lack knowledge*** in this regard. This may lead to possible claims of users and building owners, and, consequently, may be the basis for obtaining compensation in the event of exceeding the limits of the vibration comfort due to humans.

Thus, incorrectly formulated requirements as to the scope of environmental assessments in relation to the impact of vibrations do not sufficiently protect the interests of the Investor of the transport infrastructure, or the users of the neighboring buildings.

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Chapter 12

Vibration transmissibility of resilient materials when loaded by a simulating mass and when gripped by the operator's hand

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Abstract
Anti-vibration gloves are made of resilient materials. International standard ISO 13753:2002 describes a method of measuring the vibration attenuation of a sample of such material. The method determines the transmissibility of the material when loaded by a mass providing a compression equivalent to gripping force exerted by the hand. The standard ISO 10819:2013 describes a laboratory method for evaluation of the vibration transmissibility of glove at the palm of the hand, which grips and pushes a test handle. This paper presents comparative results of resilient material measurements using both international standards.

Keywords: anti-vibration gloves, resilient materials, Hand-arm Vibration

1. Introduction

Anti-vibration gloves are the type of personal protective equipment most commonly used to protect against vibrations acting on the employee's upper extremities [1-3]. International ISO 10819:2013 standard describes a method of measuring vibration transmissibility of gloves worn by operators participating in tests and specifies precise evaluation criteria of anti-vibration properties thereof [4]. Resilient material constitutes the main structural component of anti-vibration gloves [4, 5]. In order to evaluate efficiency of vibration attenuation of such material, the ISO 10819:2013 standard proposes a method presented in the ISO 13753:2002 standard, which implies a means of evaluation of materials suitable for manufacture of anti-vibration gloves based on tests utilising a load of mass simulating gripping pressure used to replace an operator participating in the test [5]. The authors of the relevant publication have conducted a comparison of test results obtained for anti-vibration gloves (under ISO 10819:2013) with test results obtained for material samples which these gloves were made of (under ISO 13753:2002). The purpose of this comparison was to determine suitability of test results for resilient materials as correlation of anti-vibration properties of gloves made of such materials.

2. Tested objects

Eight types of selected anti-vibration gloves (designated with numbers 1 to 8) were subjected to the tests of vibration transmissibility of gloves used by operators. The gloves differ in the type of material used to reduce vibrations as well as in the thickness of their vibration-damping pads. Additionally, the type of material used in on the outer surface differs from glove type to type. A series of tests was performed for each type of gloves. Five gloves of each type were tested. The tested gloves are presented in Figure 1.

Figure. 1. Anti-vibration gloves used for tests

Tests of vibration transmissibility by resilient materials were conducted for 8 types of samples cut from 8 types of anti-vibration gloves tested, and specifically from the palm covering part of the glove. Three samples of each material were tested. Average thicknesses of samples tested are presented in Table 1.

Table 1. Thicknesses of the tested samples

Type of gloves	The average thickness in the palm section, mm
1	2.0 ± 0.1 mm
2	6.3 ± 0.1 mm
3	6.3 ± 0.1 mm
4	5.5 ± 0.1 mm
5	7.3 ± 0.1 mm
6	8.1 ± 0.1 mm
7	7.0 ± 0.1 mm
8	6.3 ± 0.1 mm

3. Tests of anti-vibration gloves

3.1. Test method

As per the method specified in the ISO 10819:2013 standard, mean corrected values of vibration transmissibility for gloves intended to protect against vibrations are determined: $\overline{T}_{(M)}$ and $\overline{T}_{(H)}$. These are determined during simulation of vibrations on a test handle by specifically profiled testing vibration signal comprising vibrations in the frequency range of 25-200 Hz ($\overline{T}_{(M)}$) and 200–1250 Hz ($\overline{T}_{(H)}$). Vibration transmissibility values are then calculated based on the results of measurements of acceleration of vibrations at the test handle and operator's hand.

3.2. Measurement system and test conditions

Measurement of vibration transmissibility by selected gloves was performed on a test bench meeting the requirements of ISO 10819:2013. A diagram of the test bench is presented in Figure 2.

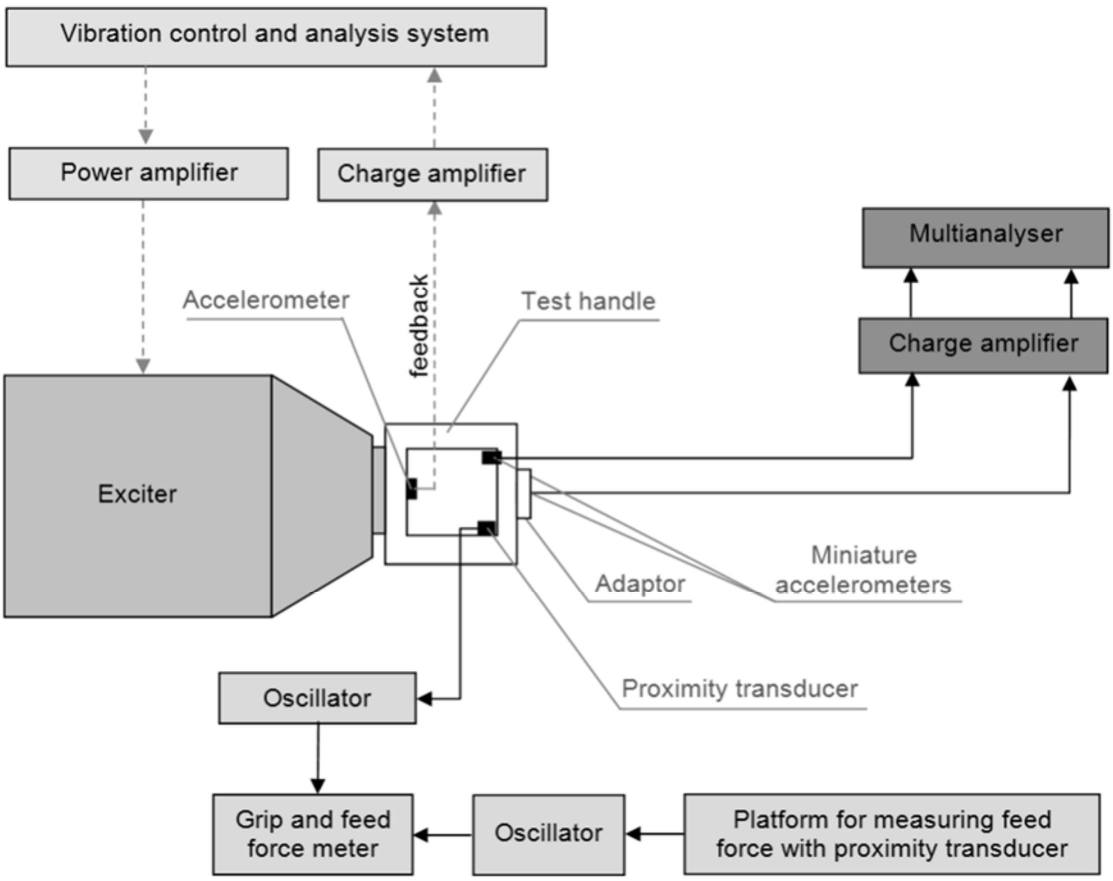

Figure. 2. Diagram of test bench used to test vibration transmissibility by gloves in accordance with ISO 10819

The test bench the glove examination was conducted on includes the following measurement instruments:

- vibration exciter, type V721, by Ling Dynamic Systems,
- power amplifier, type PA2000, by Ling Dynamic Systems,
- 2 vibration transmitters, type 4374, by Brüel & Kjær,
- vibration transmitter, type 4384V, by Brüel & Kjær,
- load amplifier, Nexus type 2692, by Brüel & Kjær,
- load amplifier, Nexus type 2692-0S, by Brüel & Kjær,
- vibration control and analysis system VibPilot, by m+p International,
- PULSE multianalyser system, type 3560C, by Brüel & Kjær,
- thermo-hygrometer, type LB-103, by LAB-EL.

Vibration acceleration in the excitation direction (one direction of measurement) was measured both on test handle (reference point) as well as operator's hand using an adapter. Vibration transmissibility values of the gloves were determined based on results of measurements of acceleration of vibrations. Before testing the gloves, measurements of vibration transmissibility of the handle-operator's hand configuration without glove for each of the 5 operators participating in the tests were made. Five pieces of each type of gloves were tested, where each piece of gloves was tested by a different operator. Each measurement was repeated three times. Measurements were performed under constant grip force value of: 50N ± 8N and feed force of 30 ± 5N at air temperature in the range of 22-24°C.

4. Tests of resilient materials

4.1. Test method

The method of testing resilient materials as in placing a sample of material on a vibration exciter plate and pressing from the top by specified in ISO 13753:2002 consists a load of mass. During the measurement, the values of vibration acceleration a_1 on the exciter plate and vibration acceleration a_2 at surface of the load are measured together with measurement of phase difference between registered signals. Based on the measured vibration acceleration values as well as the value of hand-arm impedance (specified in ISO 13753:2002), values and characteristics of vibration transmissibility for the materials tested are determined.

4.2. Measurement system and test conditions

The measurements are performed on a test bench meeting the requirements of ISO 13753:2002. A diagram of the test bench is presented in Figure 3.

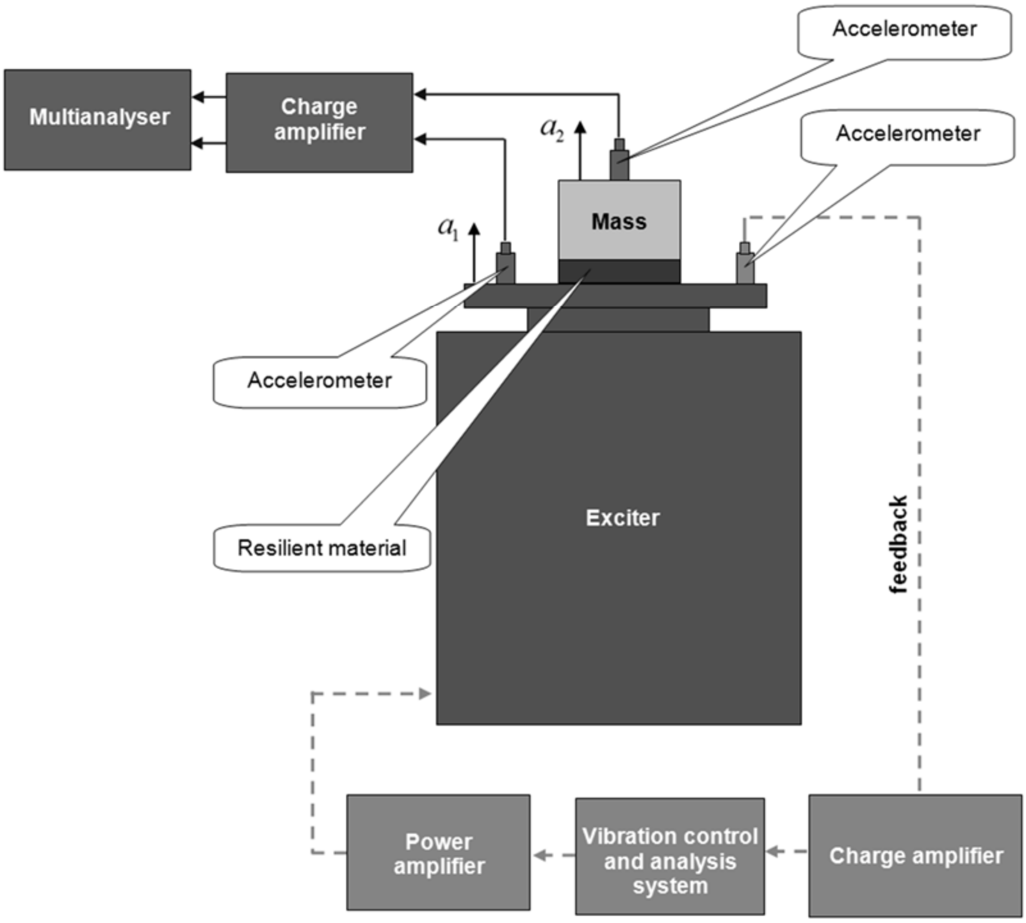

Figure 3. Diagram of test bench used to test resilient materials

The test bench for material samples tests includes the following measurement instruments:

- vibration exciter, type V721, by Ling Dynamic Systems,
- power amplifier, type PA2000, by Ling Dynamic Systems,
- accelerometer, type 4371V, by Brüel & Kjær,
- accelerometer, type 4384, by Brüel & Kjær,
- accelerometer, type 4384V, by Brüel & Kjær,
- charge amplifier, Nexus type 2692, by Brüel & Kjær,
- charge amplifier, Nexus type 2692-0S, by Brüel & Kjær,
- vibration control and analysis system VibPilot, by m+p International,
- PULSE multianalyser system, type 3560C, by Brüel & Kjær,
- thermo-hygrometer, type LB-103, by LAB-EL.

A 4294-002 calibrator by Brüel & Kjær was used for calibration of vibration measurement equipment. During measurements, ambient temperature was 23.9 ± 0.1°C, while relative humidity of air was 22.0 ± 1%. Tests were performed using a standardised cylindrical weight of radius of 45 mm and weight of 2.5 kg (Figure 4). A broadband noise of frequency range of 8-800 Hz and power spectral density of 0.08 $m^2s^{-4}Hz^{-1}$ was used as the vibration test signal.

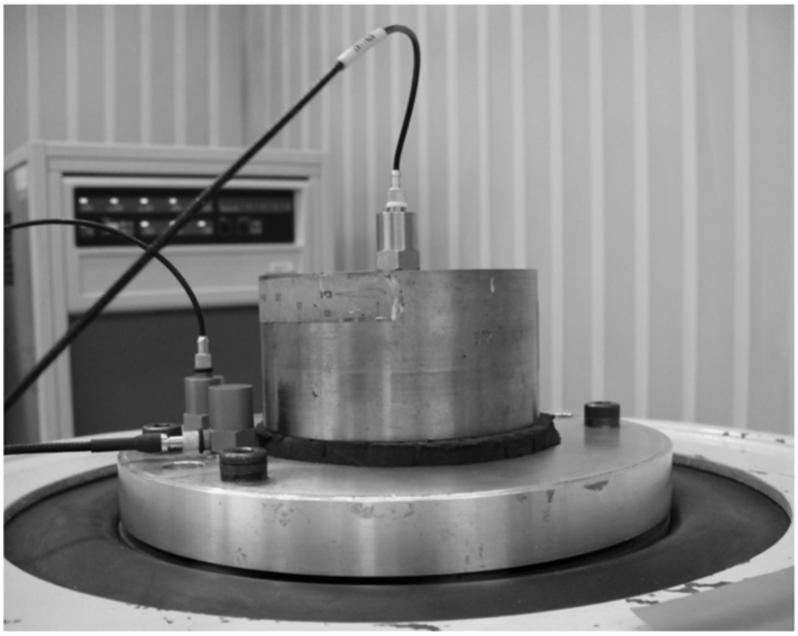

Figure 4. Sample of resilient material during measurement

5. Test results

Mean corrected values of transmissibility: $\overline{T}_{(M)}$ and $\overline{T}_{(H)}$ for the tested gloves as well as standard deviations and coefficients of variation values are presented in Table 2, whereas test results (as average values of vibration transmissibility of samples of resilient materials from the tested gloves) are presented in Table 3. Figure 5 shows frequency characteristics of vibration transmissibility of tested material samples.

Table 2. Mean corrected transmissibility, standard deviation and coefficient of variation for tested gloves in frequency range Δf_M and Δf_H

	Frequency range Δf_M			Frequency range Δf_H		
Type of gloves	$\overline{T}_{(M)}$	**Standard deviation** $s_{T(M)}$	**Coefficient of variation** $C_{V,T(M)}$	$\overline{T}_{(H)}$	**Standard deviation** $s_{T(H)}$	**Coefficient of variation** $C_{V,T(H)}$
1	0.920	0.028	0.030	1.015	0.044	0.044
2	0.756	0.031	0.041	0.583	0.025	0.043
3	0.703	0.039	0.056	0.507	0.027	0.053
4	0.721	0.038	0.052	0.573	0.039	0.069
5	0.811	0.043	0.053	0.741	0.080	0.108
6	0.794	0.050	0.063	0.650	0.033	0.051
7	0.693	0.049	0.071	0.470	0.041	0.088
8	0.707	0.043	0.061	0.534	0.063	0.119

Table 3. The values of transmissibilities calculated for tested materials

Frequency Hz	**Transmissibility (mean)**							
	Sample no.							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
10	1.02	1.02	1.02	1.06	1.04	1.04	1.05	1.02
12.5	1.02	1.02	1.02	1.06	1.04	1.05	1.06	1.02
16	1.02	1.02	1.02	1.07	1.03	1.04	1.03	1.02
20	1.00	1.02	1.02	1.02	1.01	1.01	0.98	1.02
25	0.98	1.01	1.02	0.96	0.96	0.94	0.92	1.01
31.5	0.93	0.99	0.99	0.88	0.89	0.85	0.83	0.99
40	0.89	0.95	0.95	0.81	0.83	0.77	0.75	0.95
50	0.86	0.92	0.92	0.89	0.82	0.80	0.76	0.93
63	0.87	0.92	0.91	0.83	0.87	0.77	0.72	0.92
80	0.89	0.92	0.91	0.77	0.84	0.74	0.68	0.92
100	0.88	0.91	0.90	0.64	0.77	0.67	0.63	0.91
125	0.85	0.89	0.88	0.54	0.68	0.58	0.55	0.89
160	0.82	0.89	0.87	0.48	0.62	0.53	0.50	0.88
200	0.75	0.84	0.82	0.40	0.53	0.46	0.44	0.83
250	0.66	0.74	0.71	0.37	0.46	0.40	0.39	0.73
315	0.57	0.64	0.62	0.39	0.42	0.38	0.38	0.63
400	0.51	0.57	0.55	0.49	0.43	0.43	0.42	0.57
500	0.50	0.56	0.55	0.69	0.49	0.53	0.53	0.54

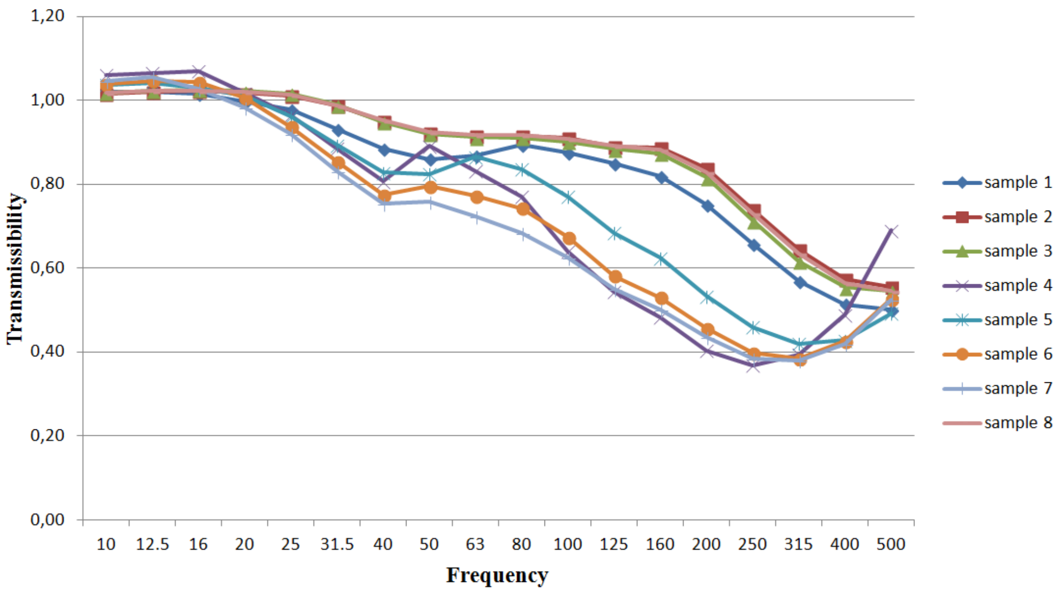

Figure 5. Transmissibility as a function of frequency calculated for tested materials

6. Conclusions

In accordance with ISO 10819, in order to be considered anti-vibration, gloves must fulfil a number of criteria. Basic requirement is that: $\overline{T}_{(M)} \leq 0.9$ and $\overline{T}_{(H)} \leq 0.6$. This requirement is met by 5 types of gloves from among the 8 tested types (gloves No 2, 3, 4, 7 and 8).

As concerns resilient materials (evaluated as per ISO 13753:2002), if vibration transmissibility for the tested material exceeds 0.6 in the whole frequency range, it is concluded that under real conditions such material does not provide attenuation for the same frequency range. Based on an analysis of the results, it was noted that none of the samples met this requirement.

Tests of material used in glove 8 would indicate that it is effective for two frequencies only: 400 and 500 Hz. However, the results obtained for this glove show that it meets all criteria of classification as anti-vibration glove. In the case of gloves 5 and 6 (not classified as anti-vibration), the material these are made of should be effective starting from frequency of 125 Hz.

The main reason for discrepancies between results of resilient materials and results of tests of gloves made of such materials may be the manner of putting a load on the samples. Pressure exerted on a tested sample by a standard loading weight (amounting to about 0.004 MPa) is almost 9 times lower than the pressure exerted by an operator (0.035 MPa). Therefore, mass of the weight should be increased so that the pressure force exerted by the weight should be as close as possible to the grip and feed force of an operator's hand. The results presented herein will be used for further tests to be conducted by Central Institute for Labour Protection – National Research Institute.

Acknowledgements

This paper was based on the results of a research task carried out within the scope of the first stage of the National Programme "Improvement of safety and working conditions" partly supported in 2014-2016 – within the scope of state services – by the Ministry of Labour and Social Policy. The Central Institute for Labour Protection – National Research Institute was the Programme's main coordinator.

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Chapter 13

Whole-body vibration hazard at workstations associated with the processing of mineral raw materials

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Abstract
The article presents the results of whole-body vibration (WBV) research at 30 workstations associated with the processing of mineral raw materials. Measurements of mechanical vibration acceleration were carried out at selected workstations located in the places where the person supervising the machine/equipment works. Based on the results of the measurements, daily exposures to whole-body vibration and multiplication factors of exceeding the permissible exposure limit for vibration were determined. The assessment showed that the researched workstations may be the cause of occupational risk. The risk was large at 7 workstations. At 6 workstations the daily exposure values exceeded 0.5 the threshold limit value (TLV) (medium risk); at 6 workstations did not exceed 0.5 TLV (low risk). At 11 workstations occupational risk was estimated as a negligible (daily exposure values do not exceed 0.2 TLV). Obtained research results indicate the need to carry out control measurements and WBV assessment at workstations associated with the processing of mineral raw materials.

Keywords: whole-body vibration, vibration measurements, occupational safety, mineral raw materials

1. Introduction

Mechanical vibrations acting on the whole body of a worker through the feet (when standing) or through the pelvis, back or flanks (when in a sitting or lying position) are called whole-body vibrations (WBV). Prolonged exposure to vibration can lead to permanent, irreversible lesions involving primarily the skeletal system (low back pain) and internal human organs. Whole-body vibration, even with low amplitudes, is often a nuisance to humans, causing not only discomfort but also reducing their psychomotor skills [1-4]. Based on recent data contained in the reports on the activities of the National Labour Inspectorate, it is possible to estimate that over 100.000 people in Poland are employed at workstations associated with the processing of mineral raw materials (crushing, grinding, sifting, etc.) [5]. Underestimation of the total number of people exposed to vibrations is associated with the issue of inadequate identification of exposure to whole-body vibration in workstations associated with the processing of mineral raw materials. Currently, the measurement of mechanical vibrations from machinery and equipment used in the processing of mineral raw materials is usually carried out to determine and monitor their technical condition. Evaluation of whole-body vibrations on this type of workstations is not performed at all or is carried out to a very limited extent. This is due, in large part, to the lack of recognition of the main sources of the exposure of workers to vibrations; sometimes due to the need to use custom instrumentation, as well as the limited possibilities of an additional person (apart from the operator) being at this type of workstation. So, an occupational risk assessment must be prepared by employers in accordance with directive 2002/44/EC [6] on the minimum health and safety requirements regarding the exposure of workers to the risks that arise from vibration. Underestimating the total number of people exposed to vibrations is associated with the problem of insufficient recognition of exposure to WBV at workplaces associated with the processing of mineral raw materials.

2. Testing method

The testing method used by the author is based on the simultaneous registration of time vibration acceleration signals in three directions: x, y and z. The basic value determined to assess worker's exposure to vibration is the daily exposure A(8) based on the dose of vibrations a^2t, which, it is assumed, best reflects the effect of vibration on the human body (PN-EN 14253+A1:2011) [7].

$$D_{total} = \sum_{i=1}^{n} a_i^2 \cdot t_i \ , \frac{m^2}{s^3} \tag{1}$$

where:

a_i – partial vibration acceleration, m/s^2, t_i – duration of partial acceleration, s.

The total vibration dose is determined from the measured values of directional vibration acceleration and is the value indirectly determined in the calculation of the daily exposure to vibration A(8).

The daily exposure to whole-body vibration is determined from the following relationship:

$$A_l(8)_{WB} = k_l \sqrt{\frac{1}{T_0} \sum_{i=1}^{n} a_{wli}^2 \cdot T_i}, \quad \frac{m}{s^2} \tag{2}$$

where:

a_{wli} – the frequency-weighted r.m.s value of the acceleration, determined over the time period T_i, s
l – direction x or y or z, $k_x = k_y = 1.4$ for directions x and y; $k_z = 1$ for direction z, T_0 – reference duration of 8 h (480 min = 28800 s).

The exposure of worker's health to mechanical vibrations is assessed by comparing the determined daily exposures with exposure limit values, specified in the Regulation of the Minister of Family, Labour and Social Policy of 12 June 2018 on the maximum permissible concentration and intensity of agents harmful to health in the working environment [8]. The multiplication factor of exceeding the permissible exposure limit for whole-body vibration is determined from the formula:

$$k_{r,WB} = \frac{A(8)_{WB}}{A(8)_{WB,dop}} \quad (3)$$

where:

$A(8)_{WB}$ – determined value of daily exposure to whole-body vibration, m/s^2, $A(8)_{WB,dop}$ – permissible value of daily exposure to whole-body vibration, m/s^2.

Using the value of the multiplication factor, it is possible to evaluate whether the exposure to vibration is small, medium or large. The occupational risk is *negligible* if the multiplication factor determined for the tested workstation is less than 0.2 (k_r < 0.2), and *small* when the multiplication factor is in the range of 0.2 < k_r < 0.5. The occupational risk is acceptable (medium) if the multiplication factor determined for the workstation is within the range of 0.5 < k_r < 1. The occupational risk is unacceptable (large) if the multiplication factor determined for the workstation is greater than 1, k_r > 1 [9, 10].

3. Measuring instruments

The measurements of the directional components of vibration acceleration were carried out using the following set of instruments:

– Brüel & Kjær PULSE multi-analyser system type 3560C,
– 8-channel Brüel & Kjær charge amplifier type 5974,
– 3 Brüel & Kjær vibration transducers type 4338 or B&K triaxial seat accelerometer type 4322.

This set facilitates the recording of signals over the frequency range of whole-body vibration acting on the worker: 0.9 ÷ 90 Hz from the range from a few mm/s^2 to ca. 1000 m/s^2 without distortion and interference. Figure 1 presents a diagram of the measuring instrumentation set.

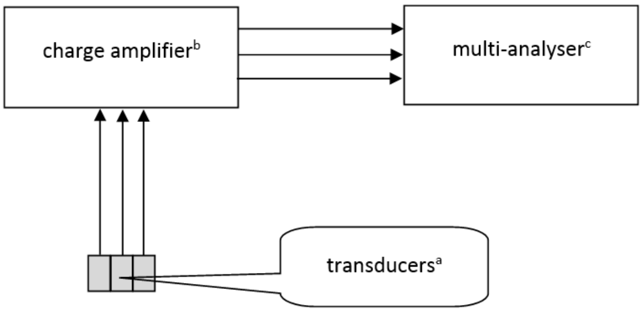

Figure 1. Diagram of the measurement set; a – 3 B&K vibration transducers type 4338 or triaxial seat accelerometer type 4322, b – 8-channel B&K charge amplifier type 5974, c – B&K PULSE multi-analyser system type 3560C

Measurements of mechanical vibration acceleration were carried out at the locations occupied by the people supervising the operation of the machinery or machine. Measurement points were located on the ground next to the machine, on the platform surrounding the device or on seats. Accelerometers were attached to the subgrade using a measuring block with a magnet, double-sided adhesive tape or a two-component glue. Three measurements were carried out at each workstation. The duration of one measurement was 5 minutes. The number and duration of the measurements was sufficient to show that the average value obtained is representative of the vibrations occurring throughout the working day. An example of the location and measurement direction orientation of the measuring points in the tested workstations is shown in Figure 2.

Figure 2. Location of measurement points and measurement directions at sample workstation (jaw crusher)

4. Test results

Daily exposure to vibration at 30 workstations associated with the processing of mineral raw materials was determined within the framework of the conducted tests, based on the recorded values of vibration acceleration. Table 1 shows the highest determined directional components of vibrations, the multiplication factors of exceeding the permissible exposure limit for WBV and evaluated the occupational risk.

Table 1. Daily exposure, the multiplication factors of exceeding the permissible exposure limit for WBV and occupational risk determined on the workstations associated with the processing of mineral raw materials

Workstation No.	Test Object		Daily exposure to vibration* (the largest directional component) *A(8)* m/s^2	Multiplication factor of exceeding the permissible exposure limit for WBV $k_{r,WB}$	Occupational risk
1	Impact crusher – measurement point on a concrete ground near the impact crusher		$A_Z(8) = 0.05$	0.06	negligible
2	Jaw crusher	measurement point on a concrete ground near the control cabinet of the crusher	$A_Z(8) = 0.05$	0.06	negligible
3	Jaw crusher	measurement point on the platform made of steel plates near the crusher	$A_Z(8) = 0.17$	0.21	low
4	Jaw crusher – measurement point on a concrete ground near the control cabinet of the crusher		$A_Z(8) = 0.02$	0.03	negligible
5	Jaw crusher – measurement point on the platform made of steel plates near the crusher		$A_Z(8) = 1.55$	1.94	high
6	Jaw crusher 40-17	measurement point on the platform made of steel plates near the crusher	$A_Z(8) = 0.40$	0.50	medium
7	Jaw crusher 40-17	measurement point on the floor in the vibration-isolated operator's cab	$A_Z(8) = 0.09$	0.11	negligible
8	Cone crusher – measurement point on the platform made of steel plates near the control cabinet of the crusher		$A_Z(8) = 0.42$	0.53	medium
9	Vibrating screen SWR-1 – measurement point on the platform made of steel plates near the vibration isolator		$A_Z(8) = 0.34$	0.43	low
10	Vibrating screen SWR-3	measurement point on the platform made of steel plates near the vibration isolator	$A_Z(8) = 0.32$	0.40	low

Workstation No.	Test Object		Daily exposure to vibration* (the largest directional component) *A(8)* m/s²	Multiplication factor of exceeding the permissible exposure limit for WBV $k_{r,WB}$	Occupational risk
11		measurement point on the platform made of steel plates near the motor-reducer	$A_Z(8) = 1.23$	1.54	high
12		measurement point on the platform made of steel plates near the conveyor	$A_Z(8) = 2.46$	3.08	high
13	Rectangular screen – measurement point on a concrete ground near the screen's engine		$A_Z(8) = 0.81$	1.01	high
14	Rectangular screen – measurement point on the platform made of steel plates near the screen's engine		$A_Z(8) = 1.81$	2.26	high
15	Rectangular screen – measurement point on the platform made of steel plates near the vibration isolator		$A_Z(8) = 0.81$	101	high
16	Mobile screen Metso ST 458 – measurement point on the ground near the screen control panel		$A_Y(8) = 0.03$	0.04	negligible
17	Rectangular screen WPB-821 – measurement point on the concrete ground near the screen		$A_Z(8) = 0.16$	0.20	low
18	Finger sifter – measurement point on the concrete ground near the sifter		$A_Z(8) = 0.15$	0.19	negligible
19	Vibrating screen RHEWUM – measurement point on the platform made of steel plates near the screen		$A_Z(8) = 0.56$	0.70	medium
20	Sand separator – measurement point on the platform made of steel plates near the separator		$A_Z(8) = 0.47$	0.59	medium
21	Ball mill MK-121	measurement point on the platform made of steel plates near the mill	$A_Z(8) = 0.19$	0.24	low
22		measurement point on the concrete ground near the mill	$A_Z(8) = 0.06$	0.08	negligible
23	Vertical mill Gebr.Pfeiffer – measurement point on the concrete ground near the mill		$A_Z(8) = 0.02$	0.03	negligible
24	Vertical mill 521/37 Gebr.Pfeiffer – measurement point on the concrete ground near the mill		$A_Z(8) = 0.02$	0.03	negligible
25	Rotary dryer S-4	measurement point on the platform made of steel plates during draining the concentrate	$A_Z(8) = 0.44$	0.55	medium
26		measurement point on the platform made of steel plates during thermal drying	$A_Z(8) = 0.07$	0.09	negligible
27	Belt feeder – measurement point on the concrete ground near the belt feeder's motor-reducer		$A_Z(8) = 0.12$	0.15	negligible
28	Wheel loader Volvo L350F – measurement point on the loader's seat		$A_Y(8) = 0.73$	0.91	medium
29	Wheel loader CATERPILLAR CAT 988F – measurement point on the loader's seat		$A_Y(8) = 0.73$	0.91	medium
30	Mining dump truck Biełaz 7547 – measurement point on the truck's seat		$A_Z(8) = 0.81$	1.01	high

* Daily exposure to vibration determined over the time period $T_i = 480$ min

The determined values of daily (480 minutes) exposure to vibrations exceed the permissible values (high risk) at 7 workstations; at 6 workstations the daily exposure values exceed 0.5 TLV (medium risk), also at 6 workstations do not exceed 0.5 TLV (low risk). At 11 workplaces occupational risk due to the risk of vibration was estimated to be negligible (daily exposure values do not exceed 0.2 TLV). The uncertainty of measurement analysis is presented in the Table 2.

Table 2. Spreadsheet model showing the uncertainty budget

Source of uncertainty	**Value, m/s²**	**Probability distribution**	**Divisor**	**Standard uncertainty, m/s²**
Calibration of the measurement instruments	0.021	Normal	1	0.021
Calibration of the measurement set	0.002	Normal	$\sqrt{3}$	0.001
Resolution of the measuring instruments	0.028	Rectangular	$\sqrt{3}$	0.016
Location of measurement points and directions	0.010	Normal	1	0.010
Combined standard uncertainty		Assumed normal		0.03
Expanded uncertainty		Assumed normal (k = 2)		0.06

5. Summary and conclusions

The results of whole-body vibration tests at workstations associated with the processing of mineral raw materials indicate the possibility of exceeding the permissible exposure limit values for this type of workstations. In order to enable employers to take action to reduce the exposure to vibration, it is necessary to access the information and materials on the current state of the exposure of workers and the possibilities and methods for reducing vibration.

In the case of workstations associated with the processing of mineral raw materials, one of the most important elements affecting the proper implementation of measurements and the related estimation of daily exposure to vibration is the proper location of the measuring points. The mechanical vibration from machinery and equipment used in the processing of mineral raw materials is transferred to humans most often through seats, floors and platforms. In many cases, such identification of sources is sufficient to assess worker exposure to vibration. However, the situation changes radically, when it is necessary to limit their emissions. The actual elements of the machines do not produce the vibrations directly, but only transmit them to the worker's body; they are secondary sources of vibration. To effectively reduce or eliminate vibration, it is first necessary to identify the primary sources of vibration. The obtained results of tests indicate the need for measurement and evaluation of whole-body vibration at workstations associated with the processing of mineral raw materials.

Acknowledgements

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Chapter 14

Tests of gloves intended for protection against vibration according to EN ISO 10819:2013

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Abstract
Anti-vibration gloves are the most commonly used means of personal protection against hand-arm vibration. The EN ISO 10819:1996 standard specifies the criteria for assessing their anti-vibration properties, also provides the laboratory test method and test bench requirements. In 2013 many changes were introduced to the standard, as a result of which the previously applied test method has become obsolete. The new requirements relate mainly to the extended vibration frequency range in which the measurements are carried out, the increased number of vibration, measurement signals, the test signal and the sequence and number of measurements. This article presents changes in the test methodology of anti-vibration gloves resulting from the requirements introduced in EN ISO 10819:2013.

Keywords: anti-vibration gloves; hand-arm vibration; transmissibility of vibration

1. Introduction

Anti-vibration gloves are a widely used personal protection against hand-arm vibration. Although the structures of devices used by employees are more and more technologically advanced, vibrations generated by tools and machines are still a serious problem [1-3]. In Poland, according to the Statics Poland (GUS) "Work Conditions" (2012-2016) [4-8], the risk of mechanical vibrations in the analyzed period of time remains at a similar level and affects approximately 15-17 thousand people. The actual number of people exposed to vibrations is, however, much higher, since the data on employees only apply to employees employed on the basis of an employment relationship (employment contract), in establishments with a number of employees over 10 persons. Disorders caused by mechanical vibrations involve high costs both by the state (financial costs) and employees themselves (financial and health costs). It is important to prevent the risk of mechanical vibrations by using anti-vibration gloves [3, 9]. The EN ISO 10819:1996 [10] standard specified the criteria for assessing their anti-vibration properties, also provides the laboratory test method and test bench requirements. The aim of this work is to present changes in the method of testing and assessment of anti-vibration gloves used so far in connection with the introduction in 2013 of a new version of EN ISO 10819:2013 [11]. These changes concern both research laboratories involved in measurement and assessment of the vibration transmissibility of gloves as well as designers and constructors of anti-vibration gloves, as well as employers who, in accordance with Directive 2002/44/EC [12], are obliged to ensure protection of employees against negative effects of mechanical vibrations at workstations.

2. Test Method according to EN ISO 10819:1996

The results of tests carried out in accordance with the standard in both EN ISO 10819:1996 and EN ISO 10819:2013 are the factors characterizing vibration transmission through gloves – the frequency-weighted corrected glove vibration transmissibility, however the methods and test conditions given in them differ significantly. In the case of the standard from 1996, the average corrected values of vibration transmissibility coefficients were determined for gloves intended for protection against vibrations: $\overline{T}_{(M)}$ and $\overline{T}_{(H)}$. They were calculated based on the results of vibration acceleration measurements transmitted from the test handle through the glove to the operator's hand. The mean corrected values of vibration transmissibility coefficients were determined during simulation of vibrations on the test handle by two test vibration signals M and H (Figure 1).

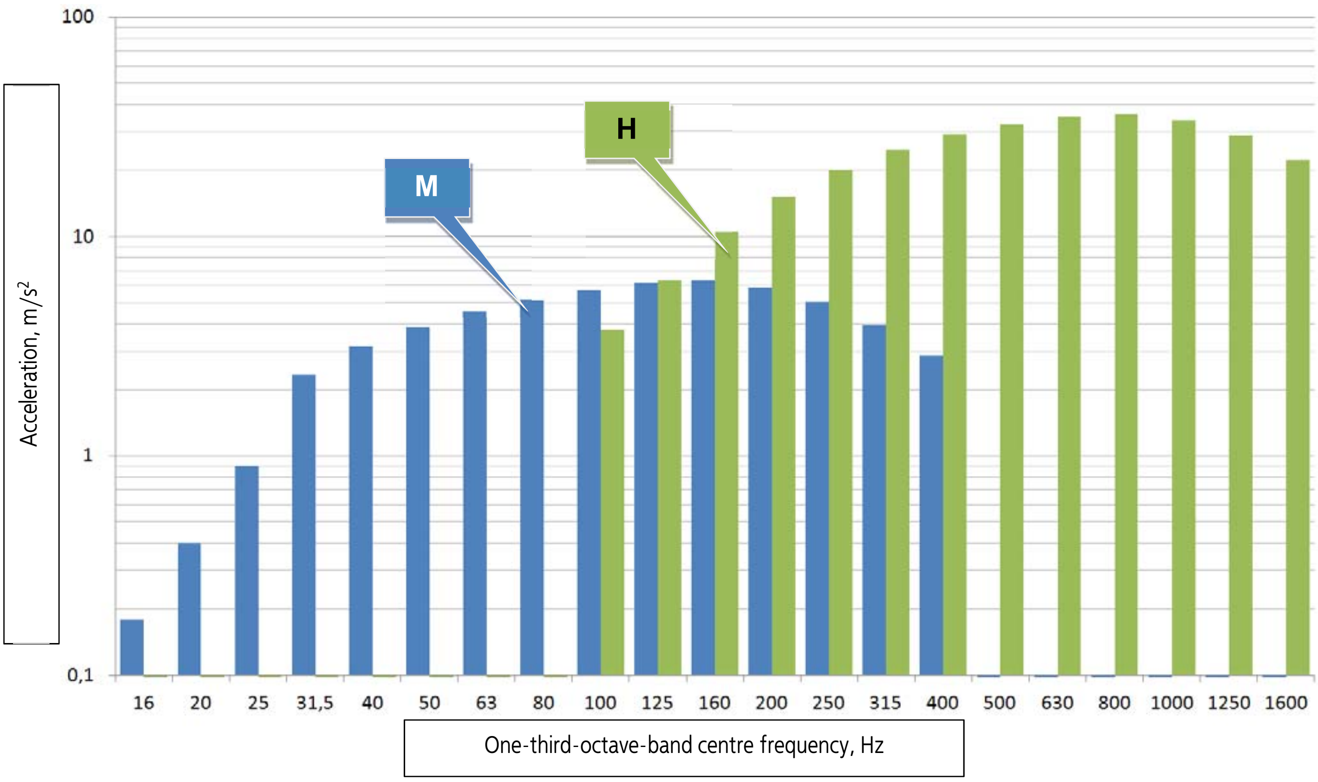

Figure 1. One-third-octave band handle acceleration values for M and H test signals

The test signal M included frequencies in the range of 31.5 ÷ 200 Hz, and the signal H for vibrations in the range of 200 ÷ 1250 Hz. Vibration transmissibility factors were calculated based on the results of vibration acceleration measurements on the test handle and on the operator's hand of the following relationships:

- transmissibility for vibration spectrum *s* measured on a hand without a glove:

$$TR_{sb} = \frac{a_{wsPb}}{a_{wsRb}} \tag{1}$$

where:

TR – frequency-weighted vibration transmissibility, a_{ws} – r.m.s frequency-weighted acceleration for vibration spectrum *s* (s = M or H) (*s* = M lub H), m/s^2, P – subscript denoting measurements taken on the palm of hand, b – subscript denoting measurements taken on a hand without a glove;

- transmissibility for vibration spectrum *s* measured on a gloved hand, i.e. between the glove and the hand

$$TR_{sg} = \frac{a_{wsPg}}{a_{wsRg}} \tag{2}$$

where:

g – subscript denoting measurements taken on a gloved hand;

- corrected vibration transmissibility of glove for vibration spectrum *s*:

$$TR_s = \frac{TR_{sg}}{TR_{sb}} \tag{3}$$

- mean corrected transmissibility of glove for vibration spectrum *s*

$$\overline{TR}_s = \frac{1}{6}\sum_{k=1}^{6} TR_{ks} \tag{4}$$

where:

k = 1, 2, … , 6 (2 measurements x 3 gloves).

According to the methodology described in ISO 10819:1996, tests were carried out for three types of gloves of a given type (one for each operator). One measurement was performed with the participation of each operator without a glove (3 measurements in total), followed by two measurement cycles for test signals M and H (in total 6 measurements for the test signal M and 6 measurements for the signal H). Figure 2 presents a scheme for determining the vibration transmissibility coefficients by the adapter and gloves and calculating the mean corrected transmissibility of glove coefficient, standard deviation and coefficient of variation in accordance with EN ISO 10819:1996.

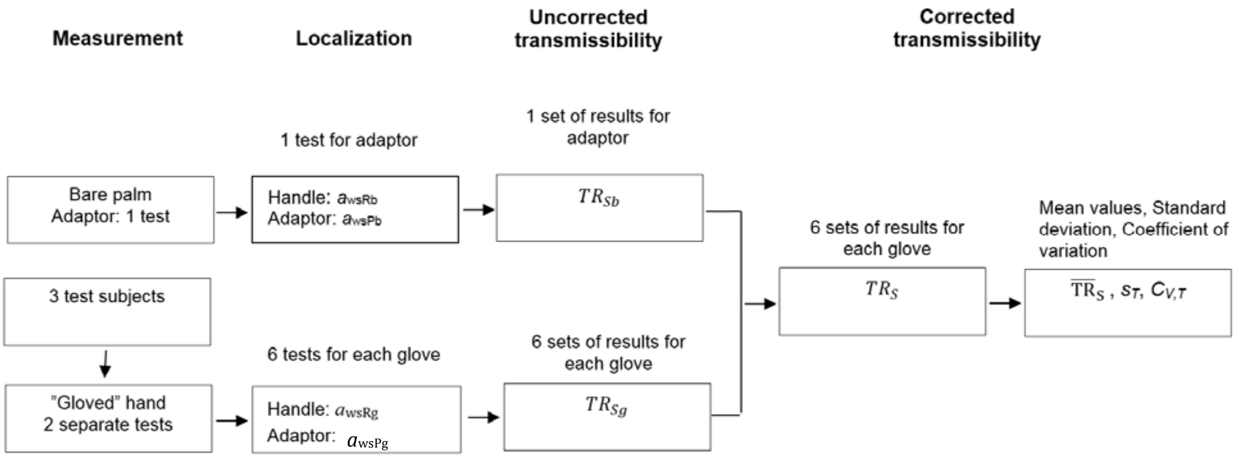

Figure 2. Flow diagram for determining the mean corrected transmissibility values, standard deviations and coefficients of variation according to EN ISO 10819:1996

Gloves were considered anti-vibration when they met both of the following criteria simultaneously: $\overline{TR}_M < 1$ and $\overline{TR}_H < 0{,}6$.

3. Test method according to EN ISO 10819:2013

According to the method given in the new version of EN ISO 10819, only the principle of determining vibration transmission coefficients is similar to the one given in the 1996 standard version. The introduced changes related to test signals apply to both their frequency range and their number. Two signals: M (31.5 ÷ 200 Hz) and H (200 ÷ 1250 Hz) were replaced with one band-filtered noise signal with a frequency range of 25 ÷ 1250 Hz, lowering the lower measuring frequency from 31.5 to 25 Hz. In the amplitude-frequency characteristics of the signal, two parts can be distinguished: the first one with a constant vibration velocity (from 25 Hz to 250 Hz) and the second one (315 to 1650 Hz) with a falling edge. Figure 3 presents the amplitude-frequency characteristics of acceleration of test signal vibrations in one-third bands.

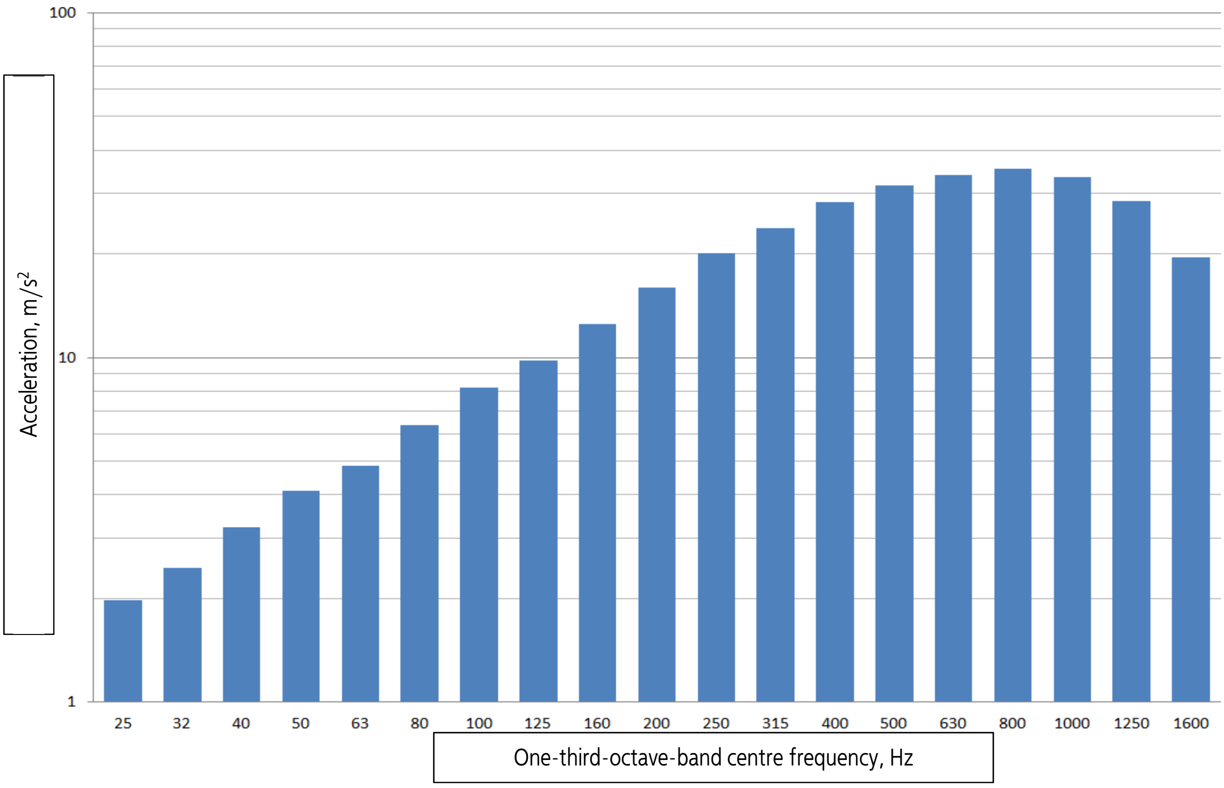

Figure 3. One-third-octave band handle acceleration values

Vibration transmissibility factors are determined for two ranges of one-third-octave bands:

- $\overline{T}_{(M)}$ in the frequency range Δ*f*M: 25 Hz ÷ 200 Hz
- $\overline{T}_{(H)}$ in the frequency range ΔfH: 200 Hz ÷ 1250 Hz.

According to the new version of the standard, the number of specimens of the type glove increased from 3 to 5 (each of the 5 operators participating in the tests one copy). Before testing the gloves one measurement of vibration acceleration in one-thirds of the adapter band fixed to the test handle is carried out. During this measurement the adapter is not held by hand (on the test handle). The unadjusted vibration acceleration values in the one-third-octave bands on the test handle and the measuring adapter are measured simultaneously and used to calculate the vibration transmissibility between the adapter and the handle. Next, using the adapter, for each piece of glove there are separate measurements of the vibration acceleration in the one-third-octave bands inside the gloves with the participation of each of the five operators (15 measurements in total). The unadjusted vibration acceleration in one-third-octave bands is measured simultaneously on the test handle and on the adapter placed on the operator's palm inside the glove, and then used to calculate the vibration transmission factor by the gloves. The vibration transmissibility factors are calculated based on the results of vibration acceleration measurements on the test handle and on the operator's hand of the following relationships:

- one-third-octave band vibration transmissibility for the bare adaptor:

$$T_b(f_i) = \frac{a_{h(Pb)}(f_i)}{a_R(f_i)} \tag{5}$$

where:

$a_{h(Pb)}(f_i)$ – one-third-octave band unweighted acceleration values on the bare adaptor, m/s²,

$$a_{h(Pb)}(f_i) = \sqrt{a^2{}_{h(Pbx)}(f_i) + a^2{}_{h(Pby)}(f_i) + a^2{}_{h(Pbz)}(f_i)} \ \ [\text{m/s}^2] \tag{6}$$

where:

$a_{h(Pbx)}(f_i)$ – value $a_{h(Pb)}(f_i)$ in direction x, m/s², $a_{h(Pby)}(f_i)$ – value $a_{h(Pb)}(f_i)$ in direction y, m/s², $a_{h(Pbz)}(f_i)$ – value $a_{h(Pb)}(f_i)$ in direction z, m/s²,

and

$a_R(f_i)$ – one-third-octave band unweighted accelerations obtained at the handle, m/s², (determined analogously as in the case of the test handle by the vector sum in three directions: x, y, z);

- the frequency-weighted bare adaptor vibration transmissibility, $T_{b(S)}$ for S_M and S_H:

$$T_{b(S)} = \frac{\sqrt{\sum_{i=i_L}^{i_U} [a_{h(Pb)}(f_i)\ W_{hi}]^2}}{\sqrt{\sum_{i=i_L}^{i_U} [a_R(f_i)\ W_{hi}]^2}}, \tag{7}$$

where:

W_{hi} – frequency weighting factors for hand-transmitted vibration for conversion of one-third-octave band magnitudes to frequency-weighted magnitudes;

- the uncorrected glove vibration transmissibility, $T_g(f_i)$, for the ith one-third-octave band:

$$T_g(f_i) = \frac{a_{h(Pg)}(f_i)}{a_R(f_i)} \tag{8}$$

where:

$$a_{h(Pg)}(f_i) = \sqrt{a^2{}_{h(Pgx)}(f_i) + a^2{}_{h(Pgy)}(f_i) + a^2{}_{h(Pgz)}(f_i)} \tag{9}$$

where:

$a_{h(Pgx)}(f_i)$ – value of $a_{h(Pg)}(f_i)$ in direction x, m/s^2, $a_{h(Pgy)}(f_i)$ – value of $a_{h(Pg)}(f_i)$ in direction y, m/s^2, $a_{h(Pgz)}(f_i)$ – value of $a_{h(Pg)}(f_i)$ in direction z, m/s^2;

- the frequency-weighted uncorrected glove vibration transsmissibility, $T_{g(S)}$, for S_M and S_H vibration spectra:

$$T_{g(S)} = \frac{\sqrt{\sum_{i=i_L}^{i_U} [a_{h(Pg)}(f_i)\ W_{hi}]^2}}{\sqrt{\sum_{i=i_L}^{i_U} [a_R(f_i)\ W_{hi}]^2}} \tag{10}$$

- the corrected glove vibration transmissibility, $T(f_i)$, for the ith one-third-octave band:

$$T(f_i) = \frac{T_g(f_i)}{T_b(f_i)} \tag{11}$$

- The frequency-weighted corrected glove vibration transmissibility, $T_{(S)}$:

$$T_{(S)} = \frac{T_{g(S)}}{T_{b(S)}}. \tag{12}$$

Figure 4 presents a scheme for the determination of vibration transmissibility coefficients by the adapter and gloves and the calculation of the average corrected vibration transmission coefficient, standard deviation and coefficient of variation according to EN ISO 10819:2013.

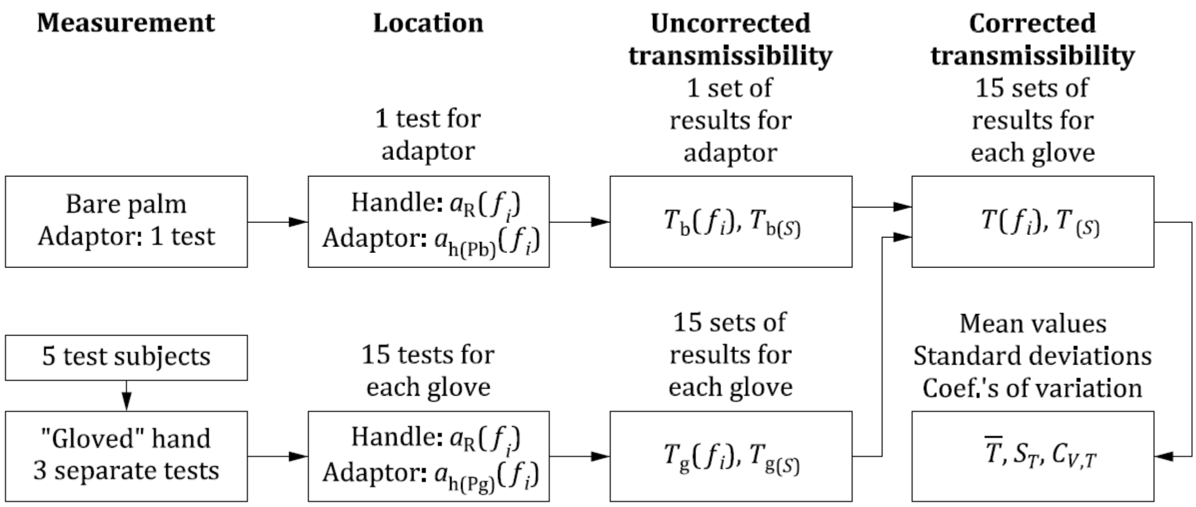

Figure 4. Flow diagram for determining the mean corrected transmissibility values, standard deviations and coefficients of variation according to EN ISO 10819:2013

The criteria for vibration transmission factors by gloves have also changed. Currently, gloves are considered anti-vibration when they meet both of the following criteria:

$$\overline{TR}_M \leq 0{,}9 \text{ and } \overline{TR}_H \leq 0{,}6.$$

4. Summary and Conclusions

On the basis of many years of testing of anti-vibration gloves in real conditions, it was found that many of this type of products not only do not meet the minimum requirements for vibration reduction, but even strengthen them. This brings the opposite effect to the intended one, negatively affecting the employee's health. The effectiveness of protection of anti-vibration gloves depends not only on their design, but also on the conditions in which they are used (the nature of the vibrations emitted by the tool, exerted by the force operator), which is why the correct selection is very important. The changes in the glove testing method introduced in 2013 tightened the requirements for their anti-vibration properties. The lower frequency of the third term band, reduced to 25 Hz, forces designers and manufacturers to introduce new solutions with increased effectiveness of protection against low-frequency vibrations. The criterion for assessing the vibration transmission coefficient has also been stricter, whose previous value of 1 meant only the requirement of no amplification of vibrations in the frequency range 31.5 ÷ 200 Hz. The current criterion value 0.9 means the requirement of vibration reduction in the range of 25 ÷ 200 Hz by at least 10%. Changes in the methodology of testing anti-vibration gloves related to the introduction of a new version of EN ISO 10819 proved to be so significant that they caused the need to rebuild the research station at the CIOP-PIB Mechanical Vibration Laboratory, currently the only laboratory in Poland that measures and evaluates the vibration transmission factor by gloves on the operator's hand. Despite the introduced changes in EN ISO 10819, the laboratory test method does not allow to clearly determine the impact of anti-vibration gloves on the reduction of vibrations in real conditions. Additional tests are still necessary for this estimation. However, the laboratory method allows the elimination of gloves with inadequate anti-vibration properties from the market and their initial selection for tools.

Acknowledgments

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Chapter 15

Polish acoustics based on bibliometric analysis for 2017-2021

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Abstract
The publications on acoustic conditions at workplaces have been indexed for many years in various databases. The most well known are Web of Science Core Collection (WoS CC) and Scopus – both indexing publications from all over the world. This article presents bibliometric data encompassing years 2017-2021 in regard of every type of indexed documents (e.g. article, conference). The data search was conducted in October 2022. The oldest indexed document, affiliated by Polish authors on acoustic comes from 1987 and 1977, respectively in WoS CC and in Scopus. Same dates apply when it comes to acoustic conditions at workplaces (acoustic AND workplace). In addition, search results were prepared in SciVal, in regard of the same period of time (2017-2021). This tool uses data indexed in Scopus.

Keywords: acoustic, noise, workplace, bibliometric analysis, Web of Science CC, Scopus, SciVal, Poland

1. Introduction

According to the bibliological research done in Web of Science Core Collection (WoS CC) and Scopus databases, the oldest document ever indexed in Scopus for acoustic's search comes from 1852 [Leared A. and it's on the mechanism of the acoustic phenomena of the circulation of the blood, with an exposition of a new element in the causation of the first sound of the heart (The Dublin Quarterly Journal of Medical Science. 1852;13(2):338-362. doi:10.1007/BF02943893)]. The total number of all results for query (Title-Abs-Key_Scopus): acoustic is 652.619 publications, with Poland as an affiliation present in 8.490 cases. The oldest of those is dated 1957 (Miodoński J. Columellization and mobilization of the ossicles of the middle ear. Acta Oto-Laryngologica.1957;47(1):64-72. doi:10.3109/00016485709130316), and has been cited once in 2022. The oldest publication indexed in WoS CC [1] for acoustic's search is from 1900 and it's an abstract of a report on the acoustic principles affecting the conduction of sound by the bones of the head, by: Gray AA, Volume 1900, Page 1012-1014, Part 1, Published JAN-JUN 1900. The total number of all results for query (Topic_WoS CC): acoustic is 344.303 publications, and 5086 of them is affiliated to Poland. The oldest text in that pool comes from 1970 and provides an analysis of Nasal vowels in contemporary standard Polish acoustic-phonetics (Jassem W, Volume 24, Issue 4, Page 401-404. doi: 10.1016/0024-3841(70)90093-8).

For the purposes of this chapter, an analysis related to publications affiliated by Polish authors regarding the issues of acoustics also related to the work environment was prepared.

2. Research method

Two bibliographic and abstract databases were used to conduct the searches: Scopus [2] (Elsevier) and Web of Science (Clarivate Analytics).

Scopus is an interdisciplinary bibliographic and abstracting database for the mathematical and natural sciences, technology, medicine and the humanities. It indexes more than 25.000 journal titles, including about 19.000 peer-reviewed journals (out of which about 4.000 are open access), as well as book series, conference reports, etc. It contains more than 81 million bibliographic records, data from more than 7.000 publishers. The man coverage in Scopus pertains primarily to times past 1970, with some pre-1970 records going back as far as 1788.

The Scopus' indexes contain more than 1.5 billion citations. In addition, the database contains more than 17 million profiles of scientists, 80.000 profiles of institutions, including CIOP-PIB (Affiliation ID: 60031598). The database provides information on publications with abstracts, appendix bibliography. The SciVal tool – used to analyse data contained in the Scopus database – is correlated with the Scopus database. This tool allows users to perform comparisons and analysis within institutions, countries, authors, among others. Scopus is updated on the daily basis.

In connection to the article's main title, searches were performed in various variations including the use of such search fields, as: Article title, Abstract, Keywords: e.g. Acoustic And Affiliation country: Poland And Published years: 2017-2021.

Web of Science CC – database is provided on the Web of Science platform (until December 2013 it was offered as Web of Knowledge). The publication records stored therein contain basic bibliographic information, article abstracts, and citation information. In addition, it is possible to reach journal information in the Journal Citation Reports (JCR) database from each of the abovementioned records. The information resource in WoS is an ever-increasing number of records, currently surpassing 170 million (and more than 1.9 billion citations). This tool enables bibliometric analysis based on data indexed in the Web of Science Core Collection (Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Emerging Sources Citation Index databases) and Journal Citation Reports. Number of indexed scientific journals is lesser in comparison to Scopus, however, it's upgraded daily even so. In connection to the article's main title, searches were performed in various variations including the use of such search fields, as: Topic: e.g. Acoustic, Adress (Affiliation country): Poland And Published years: 2017-2021.

3. Acoustic in Scopus 2017-2021

For query: acoustic (Article title – Abstract – Keywords) AND Poland (Affiliation country) AND 2017-2021 (Published years) there are 2295 results. Within them different types of indexed documents can be identified. The articles predominated the search results (1491), trailed by 693 conference papers, 53 reviews, 45 book chapters and 13 others. Table 1 presents information for each year separately: number of publications, number of citations, the most cited publications from that year, and who cited them (country).

Table 1. Results for query in Scopus: Acoustic (Article title – Abstract – Keywords) AND Poland (Affiliation country), published in 2017-2021, for each year separately: the most frequently cited publication and no. of citations, who cited that publication (country and no. of citations from county) the most often (No. of citations, date of search: 15.10.2022)

Year	No. of publications	No. of citations	Most cited for the year _no. of citations*	Who cited mostly_country_ No. of citations
2021	466	1463	Kuntoğlu M, Aslan A, Pimenov DY, et al. A review of indirect tool condition monitoring systems and decision-making methods in turning: Critical analysis and trends. Sensors (Switzerland). **2021**;21(1):1-33. doi:10.3390/s21010108 **cited 79**	• Turkey = 19 • China = 18 • Poland = 16
2020	470	6016	Aghanim N, Akrami Y, Ashdown M, et al. Planck 2018 results: VI. Cosmological parameters. Astronomy and Astrophysics. **2020**;641. doi:10.1051/0004-6361/201833910 **cited 2742**	• United States = 872 • China = 421 • United Kingdom = 402
2019	494	2996	Glowacz A. Fault diagnosis of single-phase induction motor based on acoustic signals. Mechanical Systems and Signal Processing. **2019**;117:65-80. doi:10.1016/j.ymssp.2018.07.044**cited 210**	• China = 116 • India = 29 • United States = 16
2018	447	3806	Gągol M, Przyjazny A, Boczkaj G. Wastewater treatment by means of advanced oxidation processes based on cavitation – A review. Chemical Engineering Journal. **2018**;338:599-627. doi:10.1016/j.cej.2018.01.049 **cited 418**	• China = 186 • India = 69 • Poland = 42
2017	388	3347	Kirby MA, Pelivanov I, Song S, et al. Optical coherence elastography in ophthalmology. Journal of Biomedical Optics. **2017**;22(12). doi:10.1117/1.JBO.22.12.121720 **cited 104**	• United States = 66 • China = 21 • Poland = 11

The most cited publication (2742 times) for the analysed period (2017-2021) is: Aghanim N, Akrami Y, Ashdown M, et al. Planck 2018 results: VI. Cosmological parameters. Astronomy and Astrophysics. 2020;641. doi:10.1051/0004-6361/201833910. The search results provide information about affiliations of authors so the user is able to discover which institution/s they represent. Figure 1 presents Top_10 institutions and number of publications per institution.

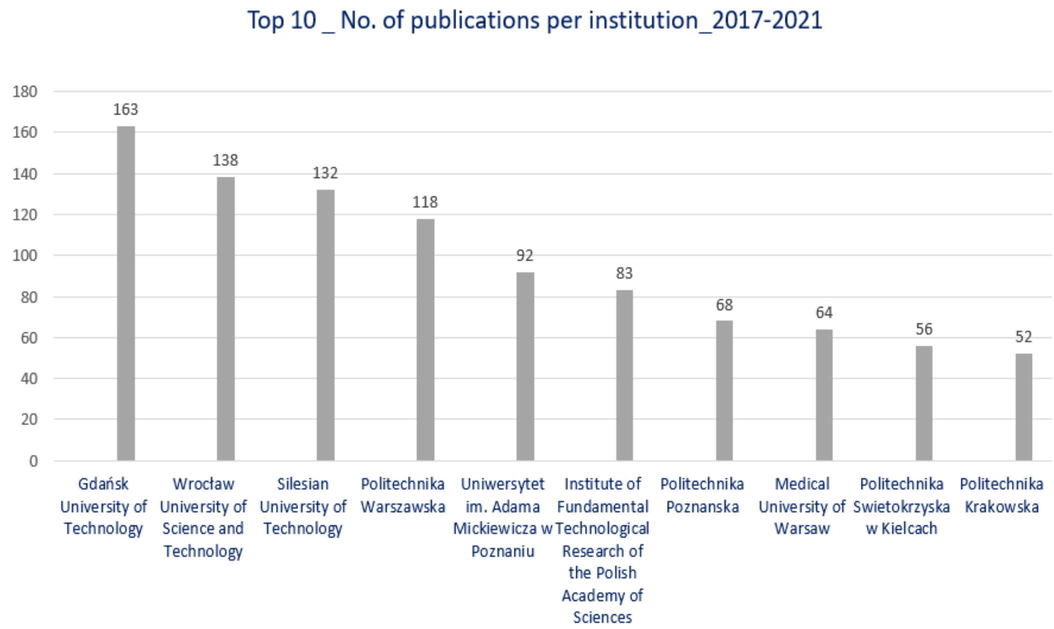


Figure 1. Top 10 Institutions_afiliations, number of publications per institution for 2017-2021, results for query in Scopus: TITLE-ABS-KEY (acoustic) AND Affiliation country (Poland)

3.1. Acoustic AND workplace

Work environment is one of the aspects of research and analysis when it comes to publications indexed in Scopus database. In this instance another query was used: Acoustic AND workplace (Article title, Abstract, Keywords) for all country affiliations.

The results for that query is 271 publications (mostly articles: 140 112 conference papers, 10 reviews, 6 book chapters and others) came back as a result. The most cited publication: Le, TN, Straatman LV, Lea J, et al. Current insights in noise-induced hearing loss: A literature review of the underlying mechanism, pathophysiology, asymmetry, and management options. Journal of Otolaryngology – Head & Neck Surgery. 2017;46(1). doi:10.1186/s40463-017-0219-x – was cited 179 times (result for 15.10.2022).

Within the results obtained, data on institutions (Top-10), authors (Top-10) and scientific journals (Top-10) are presented. The chart below (Figure 2) presents Top 10 institutions with numbers of publications per affiliation.

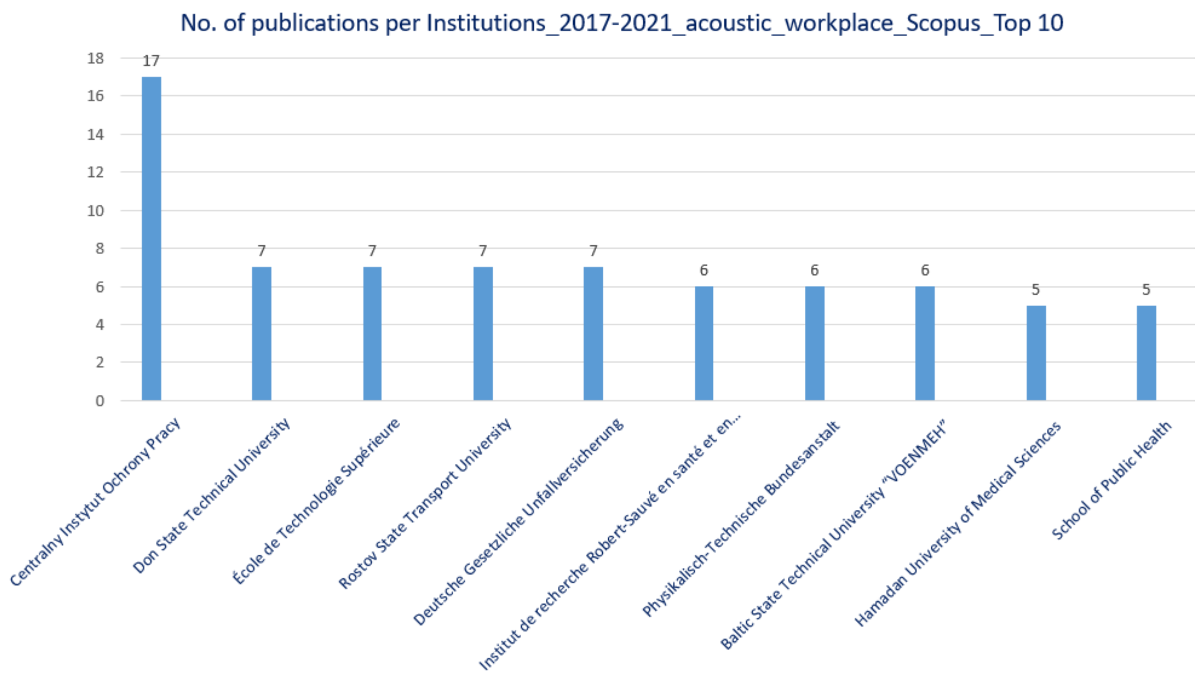


Figure 2. Institutions_afiliations, number of publications per institution for 2017-21, results for query in Scopus: TITLE-ABS-KEY (acoustic AND workplace), for All Affiliation country

Another information, based on results in Scopus, concerns authors and number of publications per author (Figure 3).

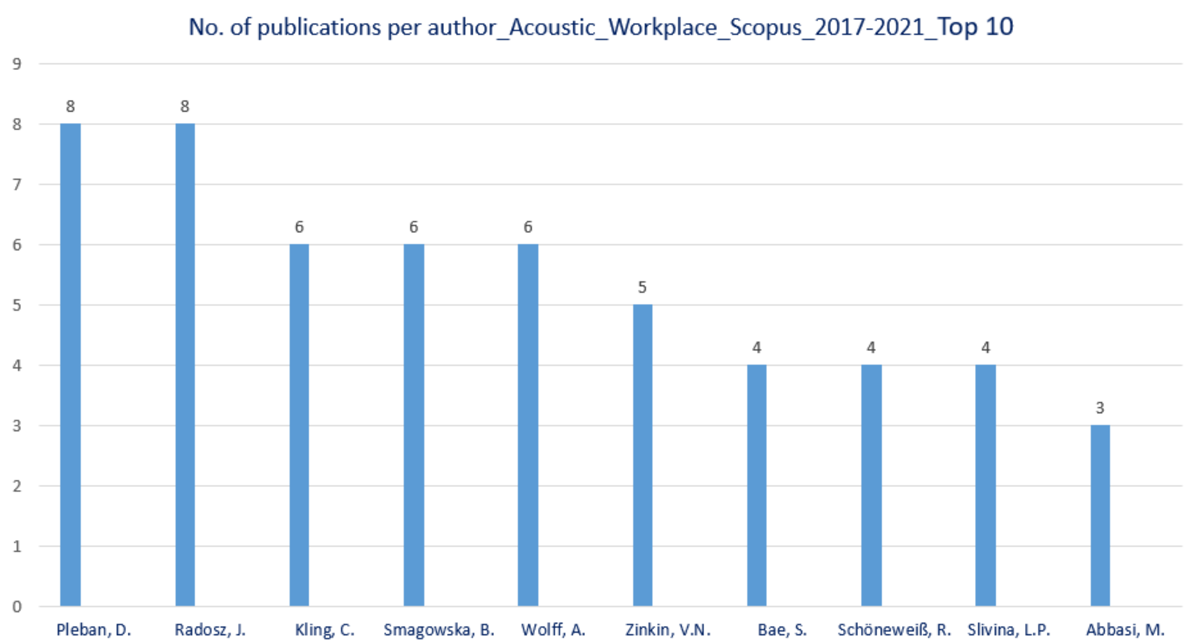


Figure 3. Authors and number of publications per author, results for query in Scopus: TITLE-ABS-KEY (acoustic AND workplace), for All Affiliation country, publication years 2017-2021

Another information, based on results in Scopus, concerns scientific journals and number of publications per journal (Figure 4).

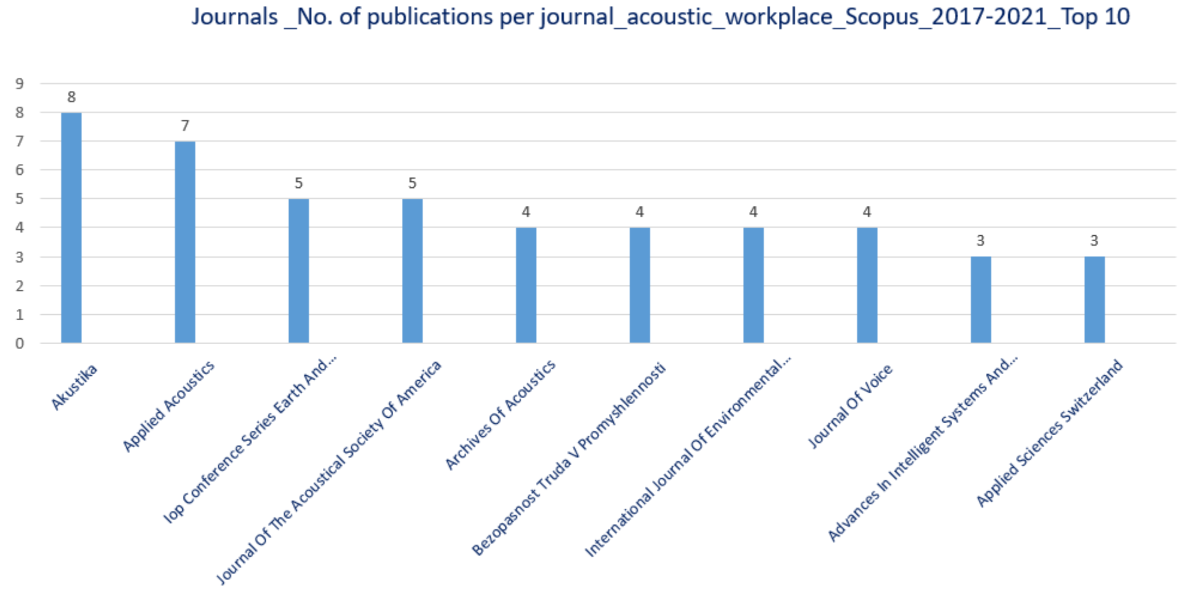


Figure 4. The scientific journals and number of publications per journal, results for query in Scopus: TITLE-ABS-KEY (acoustic AND workplace), for All Affiliation country, publication years 2017-2021

With retaining the all the previous queries in Scopus, one additional query was added: "affiliation of authors: Poland". With this in place a search was repeated and resulted in information on 30 publications indexed. The 15 of them was cited, and got 85 citations.

The most cited publication has got 31 citations: Chen C, Yilmaz S, Pisello AL, et al. The impacts of building characteristics, social psychological and cultural factors on indoor environment quality productivity belief. Building and Environment. 2020;185. doi:10.1016/j.buildenv.2020.107189.

Table 2 presents 15 cited documents – Scopus is updated every day, so the actual number of citations can be different each another search (result for: 15.10.2022).

Table 2. Results for query in Scopus: Acoustic AND Workplace (Article title – Abstract – Keywords), published 2017-2021, the most frequently cited publications (Top_15), Open Access or not (Open Access = 1, No OA = 0)

No.	Publication indexed in Scopus_Acoustic AND Workplace _2017-2021_Poland	No. of citations	Open Access = 1 No OA = 0
1.	The impacts of building characteristics, social psychological and cultural factors on indoor environment quality productivity belief In: Chen C-F, Yilmaz S, Pisello AL, et al.Building and Environment. 2020;185:107189.	31	1
2.	Active structural acoustic control of an active casing placed in a corner In: Chraponska A, Wrona S, Rzepecki J, et al. Applied Sciences (Switzerland). 2019;9(6):1059.	12	1

No.	Publication indexed in Scopus_Acoustic AND Workplace _2017-2021_Poland	No. of citations	Open Access = 1 No OA = 0
3.	Selection of earmuffs and other personal protective equipment used in combination In: Kozlowski E, Mlynski R. International Journal of Environmental Research and Public Health. 2019;16(9):1477.	7	1
4.	The Hearing Threshold of Employees Exposed to Noise Generated by the Low-Frequency Ultrasonic Welding Devices In: Dudarewicz A, Zaborowski K, Rutkowska-Kaczmarek P, et al. Archives of Acoustics. 2017;42(2):199-205.	6	1
5.	Acoustic conditions in open plan office – application of technical measures in a typical room [Warunki akustyczne w pomieszczeniach biurowych open space – zastosowanie środków technicznych w typowym pomieszczeniu] In: Mikulski W. Medycyna Pracy. 2018;69(2):153-165.	5	1
6.	Exposure to infrasonic noise in agriculture [Open Access] In: Bilski B. Annals of Agricultural and Environmental Medicine. 2017;24(1):86-89.	5	1
7.	Occupational risk assessment related to ultrasonic noise In: Pleban D, Smagowska B, Radosz J. INTER-NOISE 2018 – 47th International Congress and Exposition on Noise Control Engineering: Impact of Noise Control Engineering; 2018.	4	0
8.	Reducing the harmful effects of noise on the human environment. Sound insulation of industrial skeleton enclosures in the 10-40 kHz frequency range In: Mikulski W. Journal of Environmental Health Science and Engineering. 2020;18(2):1451-1463.	3	1
9.	Determination of ultrasonic noise exposure in the workplaces In: Pleban D, Radosz J, Smagowska B. 25th International Congress on Sound and Vibration 2018, ICSV 2018: Hiroshima Calling 4; 2018. pp. 2474-2480.	3	0
10.	Home sources of low frequency noise [Domowe źródła hałasu niskoczęstotliwościowego] In: Zagubień A, Wolniewicz K. Rocznik Ochrona Srodowiska. 2017;19:682-693.	3	0
11.	Workplaces in wind farms and in their vicinity – Recommendations for wind turbine noise reduction In: Pleban D, Radosz J, Smagowska B. 24th International Congress on Sound and Vibration, ICSV 2017; 2017.	2	1
12.	An assessment of acoustic properties of a large-capacity open-plan office room according to a 3-level rating scale – a case study [Ocena w skali trzystopniowej właściwości akustycznych biurowego pomieszczenia open space o dużej kubaturze – opis przypadku] In: Mikulski W. Medycyna pracy. 2021;72(4):375-390.	1	1

No.	Publication indexed in Scopus_Acoustic AND Workplace _2017-2021_Poland	No. of citations	Open Access = 1 No OA = 0
13.	Noise in the mining work environment – Causes, effects and threats In: Mocek P. IOP Conference Series: Earth and Environmental Science. 2020;609(1):012075.	1	1
14.	IoT-based system for monitoring and limiting exposure to noise, vibration and other harmful factors in the working environment In: Morzynski L. INTER-NOISE 2019 MADRID – 48th International Congress and Exhibition on Noise Control Engineering; 2019.	1	0
15.	Measurement of Earmuffs Attenuation at High Audible Frequencies In: Kozłowski E, Młyński R. Archives of Acoustics. 2017;42(2):249-254.	1	1

The contents of Table 2 show that the most of the cited documents are Open Access. This information is an argument for publishing in Open Access model for higher citation rates, but also for an easier access (sic!) to the full text of article.

Another information obtained in the results – presents authors of publications and the number of articles attributed to them (Figure 5):

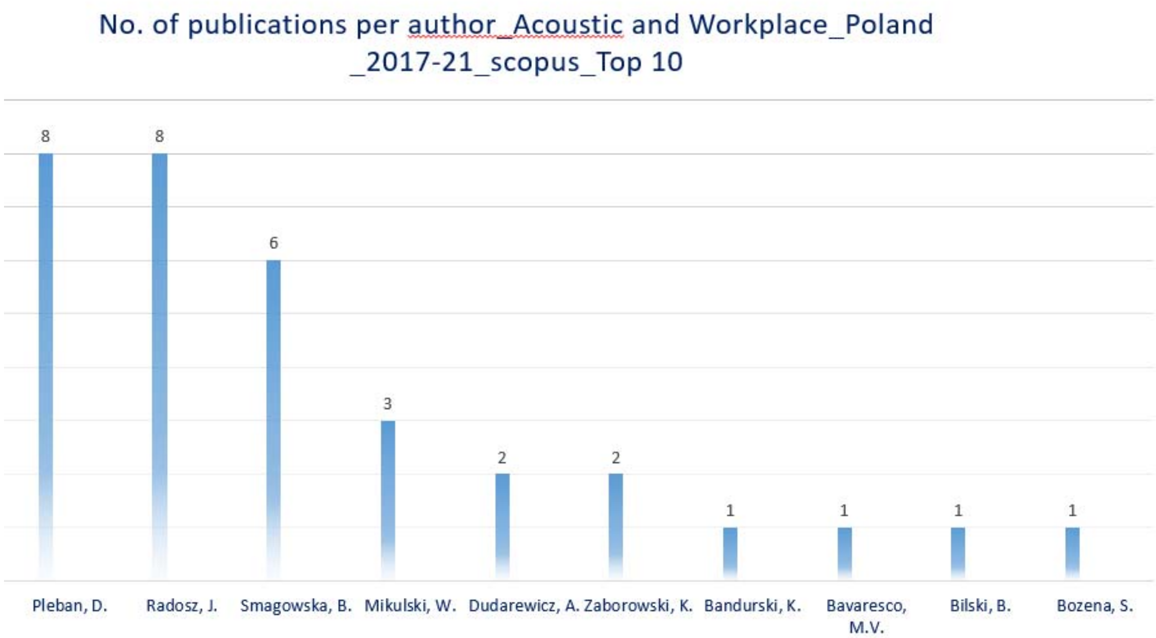


Figure 5. Top_authors, number of publications per author for 2017-21, results for query in Scopus: TITLE-ABS-KEY (acoustic AND workplace) AND Affiliation country (Poland)

As in the case of authors – the results received information on institutions (Affiliation) and the number of documents assigned to them, as shown in the figure below (Figure 6).

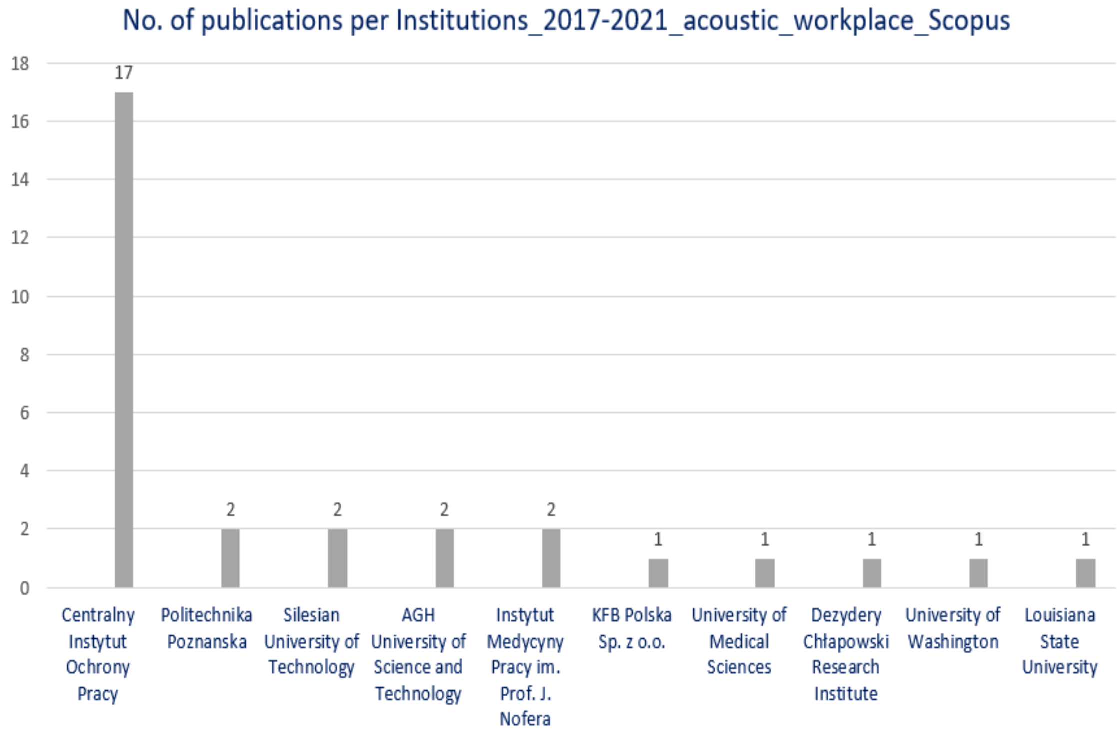


Figure 6. All institutions_afiliations, number of publications per institution for 2017-2021, results for query in Scopus: TITLE-ABS-KEY (acoustic AND workplace) AND Affiliation country (Poland)

4. Acoustic in Web of Science_2017-2021

The way of conducting search for documents in the WoS CC database mirrored one used previously in regard of Scopus. The same questions were used.

For query: Acoustic (Topic) And Poland (Adress) 1.598 results were obtained. The lower number of documents in results is due to fewer indexed scientific journals, books and other documents. The articles dominated among the indexed documents are articles (1258), followed by 310 proceeding papers, 48 review articles, 7 book chapters and 5 editorial materials. Just like in the Scopus search, also in here publications on every aspects of acoustic can be found.

The most cited publication for 2017-2021 (the same publication in WoS CC) is: Aghanim, N, Akrami Y, Ashdown M, et al. Planck 2018 results: VI. Cosmological parameters. Astronomy and Astrophysics. 2020;641. doi:10.1051/0004-6361/201833910 – and was cited 2926 times. This score is higher than in Scopus.

Table 3 presents general information about result in WoS CC, for query: Acoustic AND Poland AND 2017-2021 (result for: 15.10.2022).

Table 3. Results for query Wos CC: Acoustic (Topics) AND AND Poland (Adress), published in 2017-2021, for each year separately: most cited frequently cited publication and no. of citations, who cited that publication (country and no. of citations from county) the most often (No. of citations, date of search: 15.10.2022)

Year	No. of publications	No. of citations	Most cited for the year _no.of citations*	Who cited mostly_country_ No. of citations
2021	348	1.332	Ventilation Diagnosis of Angle Grinder Using Thermal Imaging Glowacz, A Apr 2021 | 21 (8) _cited 84	• China = 343 • Poland = 312 • United States = 103
2020	352	5.398	Planck 2018 results: VI. Cosmological parameters Aghanim, N; Akrami, Y; (...); Zonca, A Sep 11 2020 |641 _cited 2926	• United States = 1.448 • China = 924 • Germany = 716
2019	315	2.344	Fault diagnosis of single-phase induction motor based on acoustic signals Glowacz, A Feb 15 2019 | 117 , pp.65-80 _cited 184	• China = 572 • Poland = 543 • United States = 297
2018	323	2.746	Wastewater treatment by means of advanced oxidation processes based on cavitation – A review Gagol, M; Przyjazny, A and Boczkaj, G Apr 15 2018 | 338, pp.599-627 _cited 384	• China = 833 • Poland = 705 • United States = 295
2017	260	2.806	Diagnosis of the three-phase induction motor using thermal imaging Glowacz, A and Glowacz, Z Mar 2017 |81, pp.7-16 _cited 146	• Poland = 705 • China = 517 • United States = 368

In search results the information about affiliation of authors, which institutions represent mostly, can be accessed. Figure 7 presents Top_10 institutions and number of publications, regarding each of them.

Select All ☑	Field: Affiliations	Record Count	% of 1598
☑	POLISH ACADEMY OF SCIENCES	193	12.078%
☑	AGH UNIVERSITY OF SCIENCE TECHNOLOGY	179	11.202%
☑	FAHRENHEIT UNIVERSITIES	122	7.635%
☑	GDANSK UNIVERSITY OF TECHNOLOGY	105	6.571%
☑	WROCLAW UNIVERSITY OF SCIENCE TECHNOLOGY	96	6.008%
☑	SILESIAN UNIVERSITY OF TECHNOLOGY	89	5.569%
☑	WARSAW UNIVERSITY OF TECHNOLOGY	73	4.568%
☑	ADAM MICKIEWICZ UNIVERSITY	66	4.130%
☑	INSTITUTE OF FUNDAMENTAL TECHNOLOGICAL RESEARCH OF THE POLISH ACADEMY OF SCIENCES	62	3.880%
☑	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	48	3.004%

Figure 7. Top 10 Institutions_afiliations, number of publications per institution for 2017-21, results for query in WoS CC: TITLE-ABS-KEY (acoustic) AND Affiliation country (Poland)

4.1. Acoustic AND workplace

According to the aspect of the working environment and acoustics were made search in WoS CC. For that was used query: Acoustic AND Workplace (Topic [Article title, Abstract, Keywords]), publication years 2017-2021, for all affiliations (all countries) – that brought 112 results.

The illustration below (Figure 8) presents affiliations (country) Top_10 – with number of publications assigned to the particular affiliation.

Select All ☑	Field: Countries/Regions	Record Count	% of 112
☑	USA	25	22.321%
☑	RUSSIA	16	14.286%
☑	CANADA	12	10.714%
☑	ITALY	11	9.821%
☑	GERMANY	9	8.036%
☑	POLAND	9	8.036%
☑	AUSTRALIA	8	7.143%
☑	IRAN	6	5.357%
☑	ENGLAND	4	3.571%
☑	FINLAND	4	3.571%

Figure 8. All institutions_afiliations, number of publications per institution for 2017-2021, results for query in WoS CC: TITLE-ABS-KEY (acoustic AND workplace), (data of search: 15.10.2022)

The very same query brings yet another information and it shows what journals authors mostly chose to publish. The illustration below (Figure 9) presents Top 10 scientific journals with the numbers of articles published in each and every one of them.

Select All ☑	Field: Publication Titles	Record Count	% of 112
☑	AKUSTIKA	8	7.143%
☑	APPLIED ACOUSTICS	6	5.357%
☑	BUILDING AND ENVIRONMENT	4	3.571%
☑	ADVANCES IN INTELLIGENT SYSTEMS AND COMPUTING	3	2.679%
☑	APPLIED SCIENCES BASEL	3	2.679%
☑	JOURNAL OF CORPORATE REAL ESTATE	3	2.679%
☑	JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA	3	2.679%
☑	BUILDING RESEARCH AND INFORMATION	2	1.786%
☑	BUILDINGS	2	1.786%
☑	CURRENT POLLUTION REPORTS	2	1.786%

Figure 9. The scientific journal with number of publications per journal, in results for query in WoS CC: TITLE-ABS-KEY (acoustic AND workplace), publication years 2017-2021, (data of search: 15.10.2022)

4.2. Acoustic AND workplace_Poland

Another query in WoS CC with another search field was: (Adress [Affiliation country]) Poland. When combined with previous parts in read as: Acoustic AND Workplace (Topic [Article title, Abstract, Keywords]), publication years 2017-2021, Adress (Affiliation): Poland.

Total number publications in WoS CC – as a results for query: Acoustic AND Workplace (TITLE-ABS-KEY), years of publication 2017-2021, Adress [affiliation country]: Poland – is 9, 7 of them was cited 44 times.

Most cited publication: Chen CF, Yilmaz S, Pisello AL, et al. The impacts of building characteristics, social psychological and cultural factors on indoor environment quality productivity belief. Building and Environment. 2020;185. doi:10.1016/j.buildenv.2020.107189 – has got 31 citations.

Another Question was about affiliations of authors. The answer is presented on a chart from WoS CC (Figure 10).

Select All ☑	Field: Affiliations	Record Count	% of 9
☑	CENTRAL INSTITUTE FOR LABOUR PROTECTION NATIONAL RESEARCH INSTITUTE	2	22.222%
☑	POZNAN UNIVERSITY OF TECHNOLOGY	2	22.222%
☑	BYDGOSZCZ UNIVERSITY OF SCIENCE TECHNOLOGY	1	11.111%
☑	KOSZALIN UNIVERSITY OF TECHNOLOGY	1	11.111%
☑	LAWRENCE BERKELEY NATIONAL LABORATORY	1	11.111%
☑	LOUISIANA STATE UNIVERSITY	1	11.111%
☑	LOUISIANA STATE UNIVERSITY SYSTEM	1	11.111%
☑	NATIONAL TAIWAN UNIVERSITY	1	11.111%
☑	POZNAN UNIVERSITY OF MEDICAL SCIENCES	1	11.111%
☑	SILESIAN UNIVERSITY OF TECHNOLOGY	1	11.111%

Figure 10. All institutions_afiliations, number of publications per institution for 2017-2021, results for query in WoS CC: TITLE-ABS-KEY (acoustic AND workplace) AND Affiliation country (Poland)

As a result for the same query, Table 4 presents 6 cited documents – WoS CC is updated every day, so the actual number of citations can be different in each another search (result for: 15.10.2022).

Table 4. Results for query in WoS CC: Acoustic AND Workplace (Topic) and Poland (Adress), published 2017-2021, the most frequently cited publications (Top_6), Open Access or not (Open Access = 1, No OA = 0) (No. of citations, date of search: 15.10.2022)

No.	**Publication indexed in WoS CC _Acoustic AND Workplace_2017-21_Poland**	**No. of citations**	**Open Access = 1 No OA = 0**
1.	The impacts of building characteristics, social psychological and cultural factors on indoor environment quality productivity belief In: Chen CF, Yilmaz S, Pisello AL, et al. Building and Environment. 2020;185. doi:10.1016/j.buildenv.2020.107189	31	1
2.	Active structural acoustic control of an active casing placed in a corner In: Chraponska A, Wrona S, Rzepecki J, et al. Applied Sciences (Switzerland). 2019;9(6):1059.	7	1
3.	Exposure to infrasonic noise in agriculture In: Bilski B. Annals of Agricultural and Environmental Medicine. 2017;24(1):86-89.	4	1
4.	Home sources of low frequency noise [Domowe źródła hałasu niskoczęstotliwościowego] In: Zagubień A, Wolniewicz K. Rocznik Ochrona Srodowiska. 2017;19:682-693.	3	0
5.	Measurement of Earmuffs Attenuation at High Audible Frequencies In: Kozłowski E, Młyński R. Archives of Acoustics. 2017;42(2):249-254.	2	1
6.	An assessment of acoustic properties of a large-capacity open-plan office room according to a 3-level rating scale – a case study [Ocena w skali trzystopniowej właściwości akustycznych biurowego pomieszczenia open space o dużej kubaturze – opis przypadku] In: Mikulski W. Medycyna pracy. 2021;72(4): 375-390.	1	1

Affiliation of Poland means that even one author of publication has Polish institutional address. Another information obtained in the results (9 records) presents the journals (Publication Titles in WoS CC) in which the articles (with numbers, articles per journal) were published (Figure 11):

Select All ☑	Field: Publication Titles	Record Count	% of 9
☑	APPLIED SCIENCES BASEL	2	22.222%
☑	ANNALS OF AGRICULTURAL AND ENVIRONMENTAL MEDICINE	1	11.111%
☑	ARCHIVES OF ACOUSTICS	1	11.111%
☑	BUILDING AND ENVIRONMENT	1	11.111%
☑	E MENTOR	1	11.111%
☑	MEDYCYNA PRACY	1	11.111%
☑	OCCUPATIONAL SAFETY AND HYGIENE VI	1	11.111%
☑	ROCZNIK OCHRONA SRODOWISKA	1	11.111%

Figure 11. All journals – in results for query in WoS CC: TITLE-ABS-KEY (acoustic AND workplace) AND Affiliation country (Poland), publication years 2017-2021

The Web of Science database offers a greater number of information available through the results received – including, among others: Authors, Publication Years, Document Types, Web of Science Categories, Affiliations, Publishers, Funding Agencies, Grant Numbers, Open Access, Editorial Notices, Editors, Group Authors, Research Areas, Countries/Regions, Languages, Conference Titles, Book Series Titles, Web of Science Index.

5. Another tool Scopus_SciVal: Acoustic_Poland

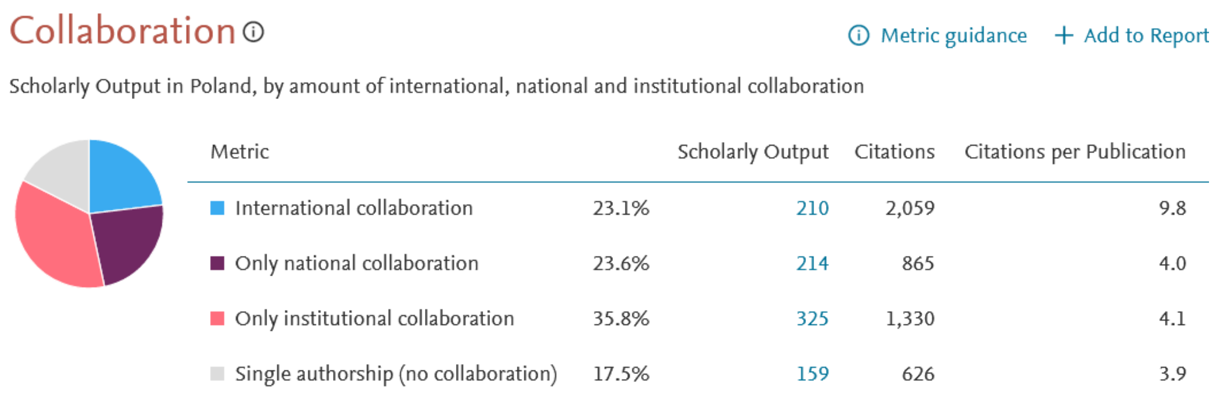
Another tool for searching and analysing publication data collected in Scopus is SciVal (Elsevier). SciVal tool provides access to information on achievements and work done for more than 7.500 institutions in 220 countries around the world, that have been indexed in the Scopus. SciVal enables multi-element analysis and visualization – including the scientific activities of the author, universities and research institutions. The tool allows users to create reports on the achievements of scientific institutions, comparative analysis with other units, countries, evaluation of potential collaborators and partners in the country and the world, as well as analysis of trends in the world of science.

During the data collection regarding the main theme of this article, categories named "research areas" as well as "Acoustics and Ultrasonics (Physical Sciences)" were chosen [3]. Having done that, the query was formulated: research areas: Acoustics and Ultrasonics, country Poland, years 2017-2021.

General – Overall research performance – answer was: 908 publications (23.5 % of them are OA) (Figure 12).

Figure 12. Part of view from SciVal – results for query: research areas: Acoustics and Ultrasonics, country: Poland, years: 2017-2021 (date of search: 15.10.2022)

Collaboration – in SciVal it indicates how many publications have international, national, or institutional co-authorship, and how many have a single authorship. That results show (Figure 13) and confirm that international cooperation contributes to greater visibility and higher number of citations than national, or institutional.



Metric		Scholarly Output	Citations	Citations per Publication
International collaboration	23.1%	210	2,059	9.8
Only national collaboration	23.6%	214	865	4.0
Only institutional collaboration	35.8%	325	1,330	4.1
Single authorship (no collaboration)	17.5%	159	626	3.9

Figure 13. Part of view from SciVal – results for query: research areas: Acoustics and Ultrasonics, country: Poland, years: 2017-2021 (date of search: 15.10.2022)

Institutions – the most active Institutions in Research Area, by number of publications. Table 5 presents the top of 10 (98 of the 270) Institutions in Poland that have publications in: Acoustics and Ultrasonics, for 2017-2021. Scholarly output presents the number of publications per institution.

Table 5. Results in SciVal for query, research areas: "Acoustics and Ultrasonics", country: Poland, years: 2017-2021, institutions (Top-10), scholarly output of the institution, no. of citations publications affiliated by institution and no. of authors (No. of citations, date of search: 15.10.2022)

No.	Institution ID In Scopis (SciVal)	Institution	Scholarly Output	Citations	Authors
1	327062	Polish Academy of Sciences	188	1040	205
2	327002	AGH University of Science and Technology	152	838	126
3	703315	Institute of Fundamental Technological Research of the Polish Academy of Sciences	113	412	74
4	327008	Gdańsk University of Technology	88	585	65
5	327040	Wrocław University of Science and Technology	68	281	69
6	327023	Silesian University of Technology	51	263	72
7	327001	Adam Mickiewicz University in Poznań	46	175	55
8	327038	Warsaw University of Technology	46	155	58
9	717784	Central Institute for Labour Protection	42	72	18
10	327006	Cracow University of Technology	30	317	25

Citation Count – total citation impact, that show how many citations have this entity's publications received. The total number of citations received by publications in Poland is 4.880 (detailed information can be found in the Table 6 and in the chart in Figure 14.

Table 6. Results in SciVal for query, research areas: "Acoustics and Ultrasonics", country: Poland, years: 2017-2021, no. of citations for each year

Year	No. of citations
2021	362
2020	425
2019	1270
2018	1363
2017	1460
all	4 880

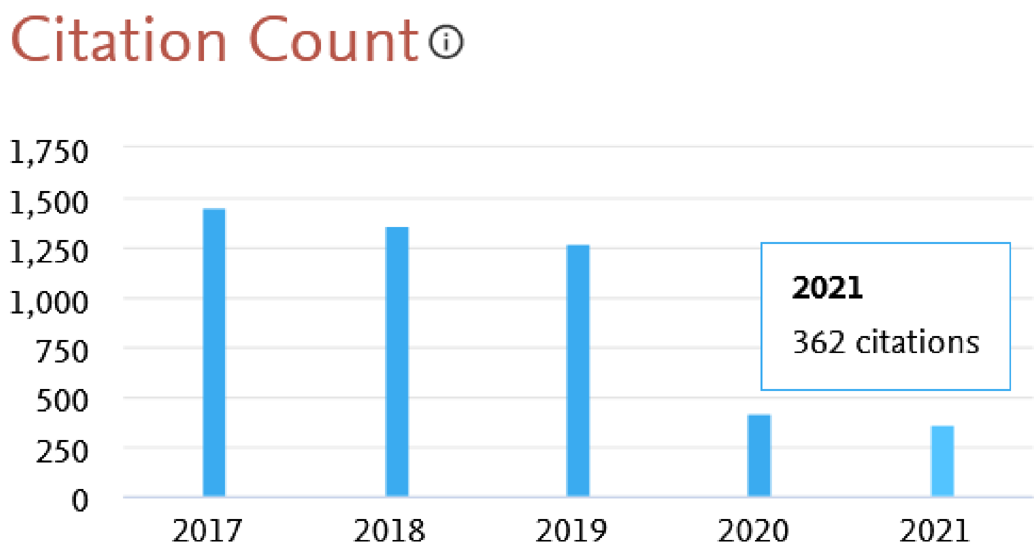


Figure 14. Part of view from SciVal – results for query: research areas: Acoustics and Ultrasonics, country: Poland, years: 2017-2021 (date of search: 15.10.2022)

Views Count – indicates the total usage impact of an entity: how many views have this entity's publications received? That number in SciVal is generated on the basis of the usage data in Scopus. That metric is the sum of abstract views and clicks on links leading to full-texts of articles on the publisher's website. They tot up all period numbers of Scopus views, which – in regard of the abovementioned query, is 18.357 (Figure 15), for each year: 2021 = 1.998, 2020 = 2518, 2019 = 4505, 2018 = 4675, 2017 = 4661.

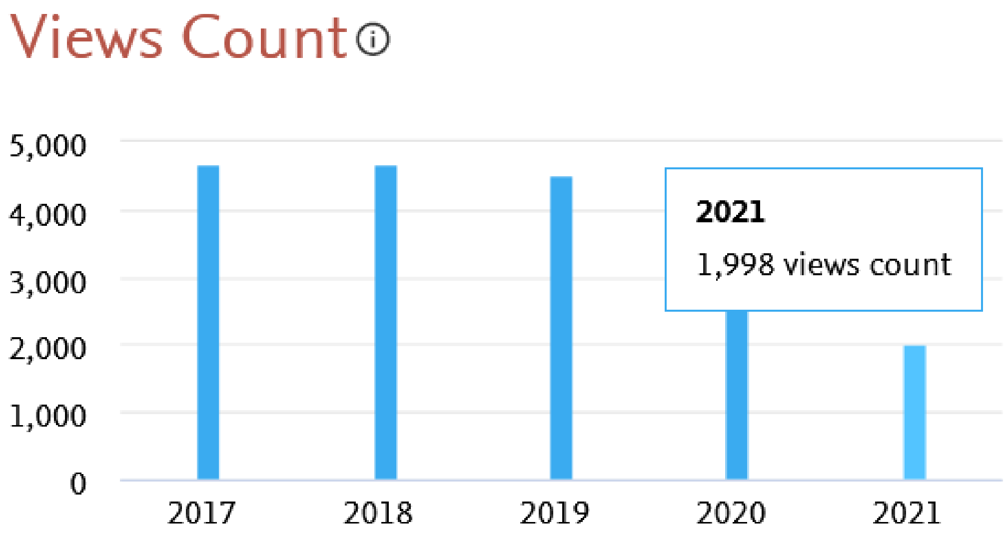


Figure 15. Part of view from SciVal – results for query: research areas: Acoustics and Ultrasonics, country: Poland, years: 2017-2021 (date of search: 15.10.2022)

Authors – this tab shows Scholarly Output in SciVal, which in turn provides data on: how many publications has a specific author indexed in Scopus; Citations tell users how many citations has that author got as well as his or her h-index value (Table 7).

Table 7. Authors_Top 10 – results for query in SciVal – research areas: Acoustics and Ultrasonics, country: Poland, years: 2017-2021 (date of search: 15.10.2022)

Name	Scholarly Output	Citations	Citations per Publication	H-index
Nowicki, Andrzej	24	72	3	24
Kostek, Bozena	23	48	2.1	16
Pawełczyk, Marek	20	107	5.4	17
Lewandowski, Marcin	17	35	2.1	13
Radosz, Jan	17	50	2.9	7
Wrona, Stanisław	17	81	4.8	11
Pleban, Dariusz	17	36	2.1	6
Kamisiński, Tadeusz	16	19	1.2	10
Pilch, Adam	16	30	1.9	10
Secomski, Wojciech	15	44	2.9	12

6. Another resources for acoustic

Apart from Scopus and Web of Science, there are several other bibliographic databases that can be used to search for publications in the field of acoustics.

One of them is **BazTech** database – established in 1998 and has indexed up to this day 550 thousand+ articles published in 752 journals (72% of them are full-text). BazTech has been launched as a bibliographic and abstract database, however as it has been registering more and more full-text articles from Polish scientific technical journals,it is opined it's been getting closer and closer in shape and form to a full-text citation database [4].

A basic search in Baztech with a query: acoustic [akustyka] gives 1180 results on October 7, 2022 (Figure 16):

Figure 16. Partly view from BazTech database, result for query: akustyka, 1180 records (date of search: 7.10.2022)

Another database, international this time, is **IEEE Xplore**. That digital library – is a research database which provides access to journal articles, conference proceedings, technical standards, and related materials on computer science. The database contains material published by the Institute of Electrical and Electronics Engineers (IEEE) and other partner publishers. IEEE Xplore provides access to more than 5 million documents. The database is subscribed for a fee and provides access to the full-text of IEEE content published since 1988 with select content published since 1884 from: IEEE journals, transactions, and magazines, including early access documents, IEEE conferences, IET conferences, IEEE published standards, IEEE Standards Dictionary Online, IEEE Virtual Journals. The content in IEEE Xplore is more than:

- 260 journals,
- 4 million conference papers,
- 12.000 technical standards,
- 6.000 books.

Approximately each month 25.000 new documents are added to IEEE Xplore [5].

Below (Figure 17) is an example of the results obtained in the base for the question: acoustic, unlimited for affiliations, publication types and years of publication. Query in All fields (e.g.: author, title, journal, abstract) – brought 103.034 results.

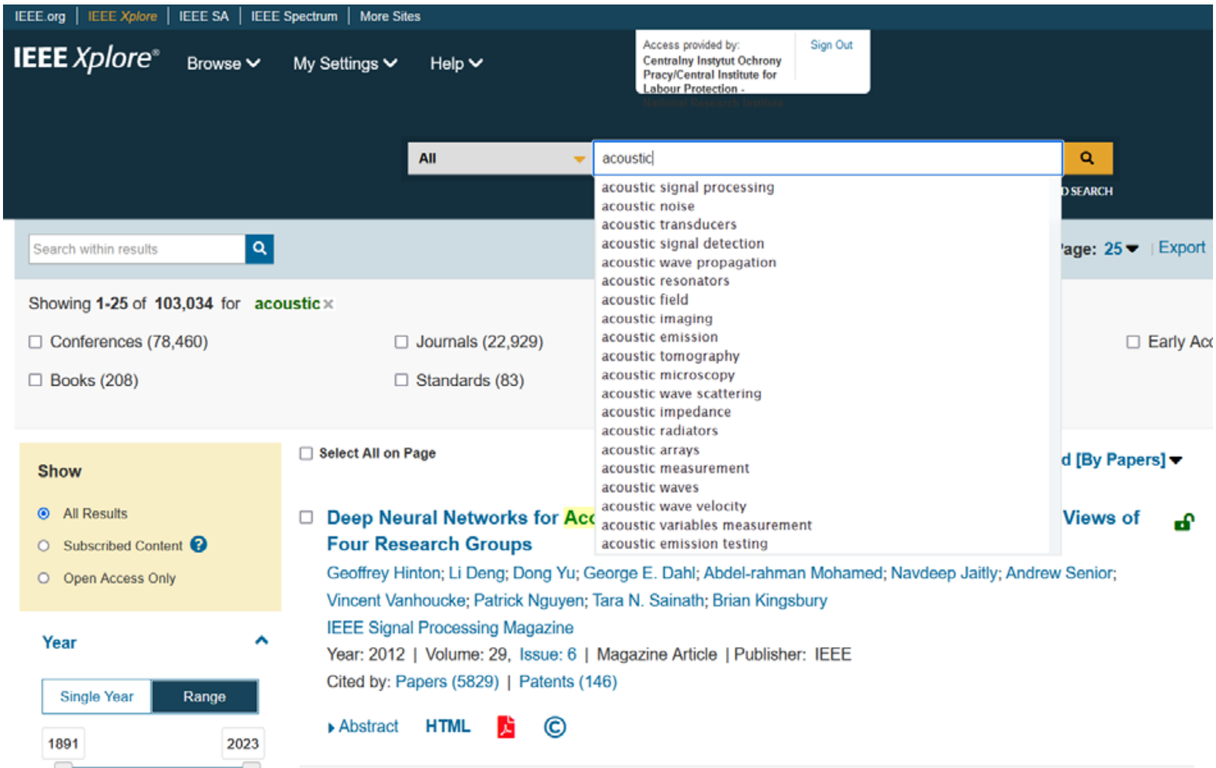


Figure 17. Partly print screen from IEEE Xplore, results for query: acoustic (date of search: 17.10.2022). As the first most cited by: Papers (5829), by Patents (146)

7. Conclusions

Topics in acoustics as well as acoustics and the working environment are represented in the WoS CC and Scopus databases, which index the publication output of researchers. The results presented do not illustrate the entire of work, but only that indexed in that databases. The keywords selected for searches may also not illustrate the entire body of work on acoustics. Conducted searches show the presence of Polish researchers in the international community. As a point of interest, it is worth mentioning that both WoS CC and Scopus provide some results also for the search term Accustic, but for the purposes of this study, the term Acoustics was the leading one. Some general conclusions below:

- publications in the field of acoustics were included in the results of searches in Scopus and Web of Science for years 2017-2021,
- articles published by Polish authors are cited and noticed by scientists from other countries, as evidenced by which countries they are cited from (e.g. United States, China),
- the results – for Acoustic AND Workplace (Scopus) – obtained confirm that the most of cited documents are Open Access (Table 1),
- research results published in 2017 tend to have more citations than in 2021 – confirming the general rule, the need for time to get noticed and cited,
- the predominant type of document indexed in the databases – are articles (for all types of searches).

8. Acknowledgements

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References

[1] Results for query: ACOUSTIC in Topic in WoS WoS CC = 344.303 records eb of Science Core Collection for:
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Chapter 16

Speech perception by level-dependent hearing protectors users in impulse noise conditions

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Abstract
The aim of this study was to check the functionality of level-dependent hearing protectors in impulse noise conditions in terms of speech perception by their users. Measurements were conducted in semi-anechoic chamber under acoustic conditions that reflect the situation present at shooting range. Impulse noise previously recorded in real conditions and 20-word lists were emitted from loudspeaker sets. The study included nine different level-dependent hearing protectors, including eight earmuffs and one earplug. Each hearing protector was tested by 25 people in both passive and level-dependent mode. Two out of nine models of hearing protectors provide better speech intelligibility in level-dependent than in passive mode, on average by nearly 10 percentage points. The changes between operating modes were not statistically significant for the remaining seven hearing protectors. In level-dependent mode, there is little differentiation in speech intelligibility values between hearing protectors. In passive mode, the speech intelligibility values are more differentiated. Higher attenuation is associated with poorer speech intelligibility. The use of level-dependent hearing protectors is not restricted by any significant impairment of speech intelligibility in the presence of impulse noise. Among hearing protectors operating in level-dependent mode there are those that do not impair speech intelligibility in the presence of acoustic impulses, compared to passive protection, but also those that improve it.

Keywords: noise, hearing protectors, impulse noise, earplugs, earmuffs

1. Introduction

Due to the insufficient effectiveness of technical means and organisational solutions to reduce impulse noise [1], the only way to protect against this type of noise is usually to use hearing protectors. These devices reduce the noise reaching an employee's ears, but at the same time they may affect the perception of sounds, which carry important information for the employee. The most common reactions of employees are those that indicate that the use of hearing protectors worsens this perception. However, research shows that the deterioration in sound perception during the use of hearing protectors is not obvious and occurs on a case-by-case basis. Moreover, some available literature indicates that the use of hearing protectors even improves speech intelligibility in certain conditions. Examples of works in this field are discussed below.

One of the OSHA (Occupational Safety and Health Administration) studies [2] points out that hearing protectors may interfere with the process of verbal communication by staff. This study indicated that the problem is particularly important in the case of many elderly people working for many years in noisy conditions, who have an hearing loss and might have problems with understanding verbal instructions or auditory danger signals, which may even lead to an accident. Other study [3] already indicated that even though hearing protectors had no significant effect on speech intelligibility for people with good hearing, in the case of people with hearing loss they had a negative effect on the quality of communication. Authors of next study [4] also showed that hearing protectors with low attenuation can have very little effect on speech intelligibility in noise. Further research has shown that hearing protectors can even improve speech intelligibility. For example Howell and Martin [5] found that hearing protectors do not degrade speech intelligibility for the listener and may even effect a slight improvement. Dastpaak et al. [6] have determined that in the presence of noise, earplugs increase the speech intelligibility. This increase is greater with 25 NRR (noise reduction rating – parameter expressing the noise reduction of hearing protectors with a single number) than with 32 NRR earplugs. Other studies, apart from confirming that the use of certain types of hearing protectors affects speech intelligibility, also point to sound level as a factor affecting speech intelligibility. For example, Hashimoto et al. [7] have shown that the use of hearing protector with little low-frequency attenuation has resulted in a lower deterioration of speech intelligibility presented at A-weighted sound pressure level of 65 dB compared to two hearing protectors with higher attenuation. On the other hand, when speech was presented at an A-weighted sound pressure level of 85 dB, there was no such effect. Fernandes [8] has showed that in the presence of pink noise at the sound pressure level of 60 and 70 dB, hearing protectors reduced speech intelligibility compared to tests without hearing protectors, while for higher sound pressure levels of noise (80 and 90 dB), hearing protectors improved intelligibility. In addition, this study found that the earplugs provide better speech intelligibility than earmuffs. The authors conclude that the overall effect of hearing protectors on speech intelligibility is directly related to their frequency response.

Level-dependent hearing protectors are increasingly being used, both in industrial workplaces and in situations where acoustic impulses are produced by firearms. Such hearing protectors are equipped with an electronic system that transmit the sound to the ear of the user ,which is present outside the protector, after its modification. The use of level-dependent functionality has an influence on the sound pressure level of the sound reaching the hearing, which in the absence of noise improves the perception of useful sounds (speech, warning signals), but in the presence of noise it is not so obvious. According to OSHA studies [2] in certain situations, using level-dependent hearing protectors (fitted with electronic system) may improve the capability of workers to communicate verbally. Electronic system carries sounds at frequencies within the speech band from the environment to the ears of hearing protectors' user. Another study indicated that the use of level-dependent earmuffs in a noisy environment was an improvement as compared to no use of hearing protectors [9]. Speech intelligibility was improved in the case of level-dependent earmuffs compared to non-electronic earmuffs and was also better than in the case of no use of earmuffs [4, 10]. There are also studies that have shown that the use of level-dependent hearing protectors has little or no effect on speech intelligibility [11-13]. However, Abel et al. [14] and Bockstael et al. [15] showed that the amplification of sounds in level-dependent mode even had a negative effect on the recognition of words in noise. The occurrence of difficulties in communication is probably related to the distortion of the signal spectrum and the lack of sufficient preserve of temporal variations by the electronic system. In the other study, depending on the type of solution realizing level-dependent functionality, the lack of change or even deterioration of speech intelligibility after the use of earplugs was shown [16]. All the above mentioned works concern the situation when speech intelligibility was tested in the presence of steady noise. There is no knowledge of the influence of hearing protectors on speech intelligibility in situations of impulse noise, what was included in the scope of this work.

The aim of this work was to check the functioning of level-dependent hearing protectors in the situation of impulse noise. The effect of these hearing protectors on speech intelligibility was tested when they operate in level-dependent mode in relation to passive mode. In addition, it was determined whether the use of different models of hearing protectors in both level-dependent and passive modes affected speech intelligibility.

2. Methods

2.1. Subjects

The studies were conducted with 50 people (24 women and 26 men). The age of subjects ranged from 18 to 42 years old (mean age was 26.4). The subjects hearing met the requirements of EN ISO 4869-1:2018 [17] regarding a subjective method for the measurement of sound attenuation of hearing protectors. This means that the subjects hearing threshold was not greater than 15 dB for frequencies up to 2000 Hz and no more than 25 dB for frequencies above 2000 Hz.

2.2. Hearing Protectors

In the study nine models of level-dependent hearing protectors were taken into account, including eight models of earmuffs and one model of earplugs. The earmuffs studied included: M1÷M8 (designation introduced for the purpose of this study). The M1 and M6 earmuffs were designed for military applications; M2, M5 and M7 earmuffs designed for industrial applications; M3, M4 and M8 earmuffs designed for hunting or sport shooting. The P1 earplugs were designed for industrial applications with polymer tips. Two different sizes of tips of earplugs were provided for subjects. The tests were performed in two hearing protector operation mode: with the level-dependent mode switched off (passive mode) and with the level-dependent mode switched on (with maximum amplification in the sound transmission path).

2.3. Test signals

Two types of sound signals were used in the study. One of them was impulse noise, previously recorded in real conditions, produced during shooting with a Glauberyt machine gun (caliber 9 x 19 mm Parabellum) on an indoor shooting range. To record this signal, the Brüel & Kjær PULSE measurement system (based on Brüel & Kjær 3052-A-030 measurement unit) with G.R.A.A.S. 67SB blast probe and G.R.A.S. 12AK power supply module was used. Each time the impulse noise consisted of two sequential shots. The time interval between shots was 160 ms. Due to the need to ensure safe conditions for conducting the experiment, the C-weighted peak sound pressure level in the place of the subject (during subject's absence from the test stand) did not exceed 120 dB. The exposure limit value for this parameter is 135 dB [18], so that the signal played on the test stand was safe for the subject, even if that person does not wear hearing protectors.

The second of the test signals was a word test [19, 20], part of the polish numerical and verbal test for hearing and auditory training, commonly used to evaluate speech intelligibility. The test consists of 10 lists of 20 phonetically balanced monosyllabic words each. The amplification in the speech path is set so that the A-weighted equivalent sound pressure level measured at the head position of the subject is 66 dB. This corresponds to the voice raised according to the speech level classification in the assessment of speech communication standard [21].

Both signals were reproduced in such a way that there was a coincidence in time between the acoustic impulses and the words to be recognized.

2.4. Experimental setup

The experimental setup was located in a semi-anechoic chamber in the Tech-Safe-Bio Laboratory in Central Institute for Labour Protection – National Research Institute (Warsaw, Poland). The configuration of the experimental setup was designed to reflect an example of the situation that may occur at the shooting range. The main components of the experimental setup were loudspeaker sets designed to reproduce sound signals. The JBL SR4722A loudspeaker set was used to reproduce impulse noise (shots). It was positioned on the right side of the subject, 1.5 m away from centre and at the height of the subject's head. The location of this loudspeaker set on the side of a subject reflected the situation of the impulses generated at shooting range by other shooters. The JBL SR4722A loudspeaker set was powered by the Crown Macro-tech 2400 power amplifiers. The impulse noise shaping assembly, in addition to these power amplifiers, consisted of a Yamaha YDG 2030 graphic equalizer and a JBL DSC 260 limiter.

The speech (word test) was played with the M-Audio BX5 D2 loudspeaker set. The loudspeaker set was located 1.8 m away from the centre and at the height of the subject's head. The loudspeaker set was positioned at the rear right hand side in diagonal direction (angle of 45°). This location of the loudspeaker set was to reflect the real situation consisting in the perception of speech sounds spoken by a shooting instructor. A picture showing the location of the loudspeakers on the test stand is presented in Figure 1.

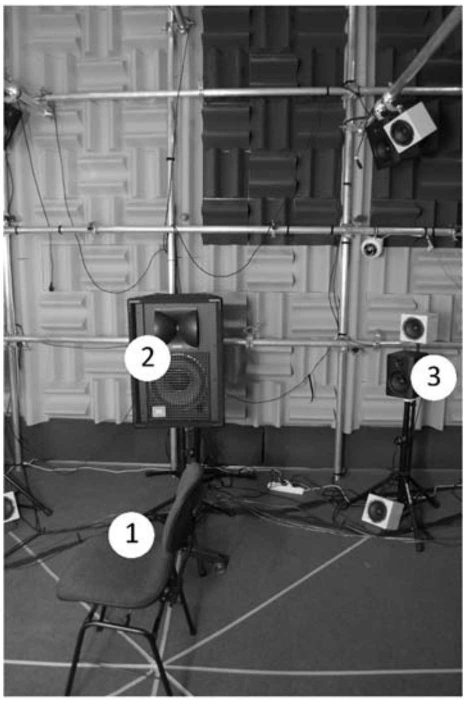

Figure 1. The view of experimental setup: 1 –seat for the subject, 2 – loudspeaker set used to reproduce impulse noise, 3 – loudspeaker set used to reproduce speech

The electrical signal to the inputs of the loudspeaker sets was provided by the MOTU 24I/O audio interface. This interface is controlled by a computer with the MOTU PCI-424 card installed. A sampling frequency of 44100 Hz was used when signals were reproduced. The reproduction of individual sound files during the test was controlled by a computer through DAW (digital audio workstation) application.

2.5. Test Method

The study was based on the word recognition by hearing protectors users. Hearing protectors were divided into two groups of 5 and 4 models. Hearing protectors from both groups were independently used by two equal groups of 25 people. Hearing protectors were worn by individuals in a different (fixed) order. Each time, the hearing protectors were used in two modes: passive and level-dependent. Thus, in each elementary measurement situation (one hearing protector in one of the two modes) tests were conducted using a single 20-word list. Subjects wrote down the content of understood words on forms prepared for this purpose. Then the number of correctly understood words was counted and speech intelligibility was determined. Speech intelligibility was defined as the ratio of the number of correctly understood words in a given elementary measurement situation to the total number of words reproduced in that situation. Before the proper tests, each person underwent a training session during which 20 numbers from a single list were recognized. The other conditions of the training session were identical to those of the appropriate tests.

The conditions for sound reproduction were determined during the preliminary tests so that the measured speech intelligibility values oscillated around 50%. The conditions determined in such a way that the individual results of each subject are not limited by extreme situations, i.e. the possibility of achieving full (100%) speech intelligibility or inability to recognize words (0%). Both of these extreme situations would make it impossible to differentiate between hearing protectors, assuming there are differences between them.

2.6. Statistical Analysis

A statistical analysis of the obtained data were completed to determine which results of speech intelligibility measurements obtained in particular situations should be considered significant. Depending on properties of obtained data, a t-test or Wilcoxon test (equivalent to the Mann-Whitney U test) were used. The calculations were performed using MATLAB R2019a (version 9.6) with the Statistics and Machine Learning Toolbox (MathWorks Inc., Natick, MA, USA).

3. Results and discussion

3.1. Speech intelligibility

The speech intelligibility values determined with participation of subjects using hearing protectors in both passive and level-dependent mode are shown in Figure 2. Each point shown in the graphs in Fig. 2 is the result of a measurement carried out using one of the word lists consisting of 20 words. Analysing the speech intelligibility values presented in Figure 2, it is not possible to determine whether the groups of results related to the passive and the level-dependent mode of hearing protectors are separable.

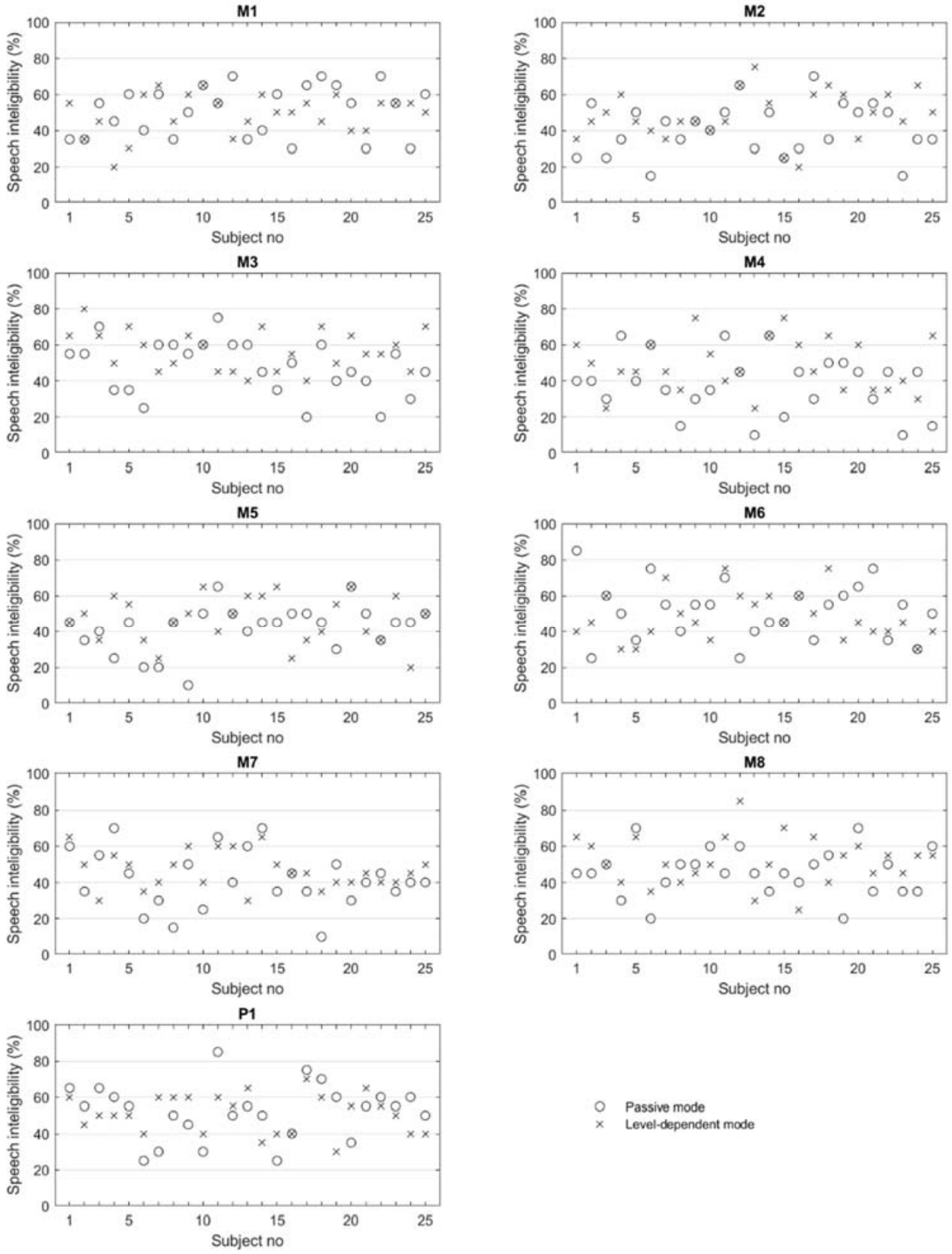

Figure 2. Speech intelligibility values obtained by subjects during the use of the hearing protectors

The outcome of the verification of the hypothesis that data for a specific hearing protector in a specific mode of use has a normal distribution (Lilliefors test) has led to the result that this hypothesis should be discarded in the following four cases: M1 earmuff in both level-dependent and passive mode, M5 earmuff in passive mode, M6 earmuff in level-dependent mode.

Due to the fact that not all series with test results are characterized by a normal distribution and there were cases that the results contain outliers or the test results for equal variances was not positive during selected analyses, instead of parametric tests (t-test), nonparametric Wilcoxon test was used.

Figure 3 shows mean speech intelligibility values, including all subjects. The mean values were determined independently for passive and level-dependent mode. This allows to assess the effect of changing the passive on the level-dependent mode on speech intelligibility and whether the use of individual hearing protectors may affect speech intelligibility. The mean speech intelligibility values shown in Figure 3 for level-dependent hearing protectors range from 46.6% (M5 and M7 earmuffs) to 56.8% (M3 earmuff). When the hearing protectors were in passive mode, the mean speech intelligibility values ranged from 38.4% (M4 earmuff) to 52.2% (P1 earplugs).

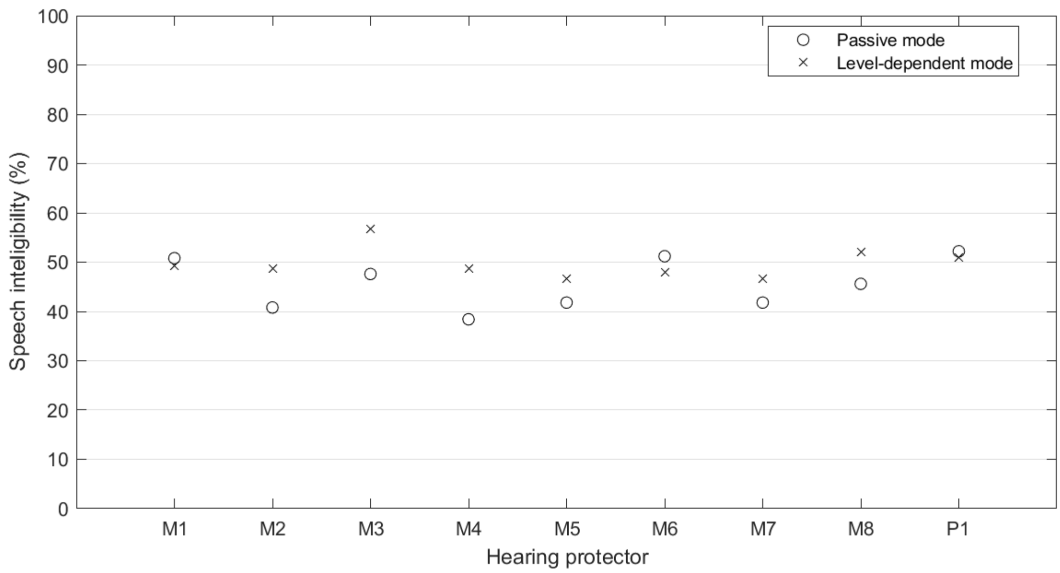

Figure 3. Mean speech intelligibility values including all subjects

3.2. Effect of the mode of use of hearing protectors

The activation of the level-dependent mode resulted in a change in the speech intelligibility values that can be considered statistically significant for two of the 9 hearing protectors included in the study. These are M3 and M4 earmuffs for which increase in speech intelligibility, resulted from changing operation mode to level-dependent was about 10 percentage points. The results of M2 are close to the criterion value (p=0.05), but the *p*-Value is greater than 0.05 and the change in speech intelligibility is not considered statistically significant. The difference between the hearing protectors M3, M4 and the other hearing protectors cannot be easily pointed out, although it is known that each manufacturer uses its own solutions for the construction of the electronic circuit. In one of the works cited earlier [15], it was suggested that both the distortion of the signal spectrum and the lack of sufficient preserve of temporal variations by the electronic system may have a decisive influence on the perception of speech sounds.

As indicated in the introduction, this paper deals with the use of hearing protectors in the presence of impulse noise, which is different from other published papers. The possibilities of direct comparison of the results obtained are therefore limited. It was also not possible to compare the situation in which hearing protectors were used in relation to their non-use, as this was impossible due to tests carried out in the presence of impulse noise (regardless of the fact that formal noise parameters did not indicate that the exposure limit values for the working environment were exceeded). However, an important element of the work was the comparison between the modes of use of hearing protectors, i.e. passive and level-dependent.

The difference between passive and level-dependent mode was indicated in one of the study on speech perception in noise [4]. The authors of mentioned study stated that the use of level-dependent mode may lead to improve intelligibility in relations to passive mode. In one of the papers, the results indicated that the improvement in speech intelligibility associated with the change in the operating mode of earmuffs may reach as much as 50 percent points [10]. In our study statistically important increasing of speech intelligibility after activation of level-dependent mode was also observed in some of the hearing protectors and was no higher than 11 percentage points. No statistically significant deterioration in speech intelligibility was found for the other hearing protectors. However, this is different from the results presented in one of the papers [14], where it was stated that the use of level-dependent mode caused the deterioration of word recognition in noise.

3.3. Level-dependent mode

Table 1 summarizes the differences between the mean values of speech intelligibility when using different hearing protectors in level-dependent mode, calculated on the basis of the values presented in Figure 3. The results of the comparison among hearing protectors can be read from Tab. 1 according to the "each with each" key. This means that the result for a pair of any two hearing protectors included in the test should be read at the intersection of one of the columns and one of the rows. From the values in Tab. 1, it can be concluded that there are cases where there is no difference between the speech intelligibility values of the hearing protectors (M2 and M4 earmuffs; M5 and M7 earmuffs) and there are significant differences of more than 10 pp (M3 and M5 earmuffs; M3 and M7 earmuffs).

Table 1. Differences in speech intelligibility between situations where different hearing protectors are used in level-dependent mode. The values are expressed in percentage points

		Hearing protector							
		M2	M3	M4	M5	M6	M7	M8	P1
Hearing protector	M1	-0.6	7.6*	-0.6	-2.6	-1.2	-2.6	2.8	1.8
	M2		8.2*	0.0	-2.0	-0.6	-2.0	3.4	2.4
	M3			-8.2*	-10.2*	-8.8*	-10.2*	-4.8	-5.8
	M4				-2.0	-0.6	-2.0	3.4	2.4
	M5					1.4	0.0	5.4	4.4
	M6						-1.4	4.0	3.0
	M7							5.4	4.4
	M8								-1.0

* – statistically significant value

In 6 out of 36 situations where hearing protectors were compared with each other, i.e. 17%, the differences in the measured speech intelligibility values were statistically significant. Mean speech intelligibility values that distinguish the use of individual hearing protectors in statistically significant situations ranged from 7.6 to 10.2 percentage points. It should also be noted that all situations where differences in mean speech intelligibility values are statistically significant relate to M3 earmuff. This means that only with this earmuff can speech intelligibility values be expected to be higher than with other hearing protectors, for which the mean speech intelligibility value is approximately 50%. Even less differentiation between the models of level-dependent hearing protectors was found in a work that included 4 devices [12]. Speech intelligibility between different level-dependent hearing protectors differed by 3-5 percentage points.

3.4. Passive mode

Table 2 shows the differences in speech intelligibility between situations where different hearing protectors are used in passive mode. The arrangement of Table 2 and the way of its using is the same as Table 1. Based on the data presented in Table 2, it can be stated that in the case of passive mode, there are more cases of large differences in speech intelligibility between different hearing protectors than in the case of previously analysed level-dependent mode. There are 7 cases where the difference in speech intelligibility exceeds 10 pp. There is also one case where there is no difference in speech intelligibility values between hearing protectors (M5 and M7 earmuffs).

Table 2. Differences in speech intelligibility between situations where different hearing protectors are used in passive mode. The values are expressed in percentage points

		Hearing protector							
		M2	M3	M4	M5	M6	M7	M8	P1
Hearing protector	M1	-10.0*	-3.2	-12.4*	-9.0*	0.4	-9.0	-5.2	1.4
	M2		6.8	-2.4	1.0	10.4*	1.0	4.8	11.4*
	M3			-9.2*	-5.8	3.6	-5.8	-2.0	4.6
	M4				3.4	12.8*	3.4	7.2	13.8*
	M5					9.4*	0.0	3.8	10.4*
	M6						-9.4	-5.6	1.0
	M7							3.8	10.4*
	M8								6.6

* – statistically significant value

In passive mode, the differences in the measured speech intelligibility values were statistically significant in 12 situations in which hearing protectors were compared with each other. This is twice as much as in level-dependent mode. Mean speech intelligibility values that distinguish the use of individual hearing protectors in statistically significant situations range from 9 to 13.8 percentage points. When comparing M1 and M7 earmuffs, despite the fact that the difference in mean speech intelligibility is 9 pp, a large scattering within the group eliminated this case from the statistically significant ones. It should be noted that in contrast to level-dependent mode, three groups of hearing protectors are observed in passive mode. The first group (M1, M6 earmuffs and P1 earplugs) has speech intelligibility values exceeding 50%, the second group (M2, M4, M5 and M7 earmuffs) has speech intelligibility values close to 40%, and the third group has speech intelligibility values between 45% and 50% (M3 and M8 earmuffs). In most cases, statistically significant changes occur between the first and second mentioned group.

The highest speech intelligibility in passive mode was measured in the case of P1 earplugs. The speech intelligibility values associated with the use of P1 earplugs are significantly higher than in the case of 4 out of 8 earmuffs: M2, M4, M5 and M7. This observation is partly consistent with the results of one study, where 2 earplugs and 2 earmuffs were included [8]. In this study it was found that booth earplugs offer greater effectiveness in speech recognition than earmuffs.

3.5. Effect of hearing protector attenuation on speech intelligibility

An important practical feature of hearing protectors is the information how they reduce noise. This property is determined for example by the SNR (single number rating - parameter expressing the sound attenuation of hearing protectors with a single number, similar to the previously mentioned NRR, but used in the European Union) parameter, which is an indicator that considers seven bands with centre frequencies from 125 Hz to 8 kHz. Figure 4 compares the speech intelligibility values with the SNR values of the particular hearing protectors. The comparison includes only earmuffs. The P1 earplugs are not included because their use is different from that of earmuffs. In addition, the M8 earmuff is not included in Figure 4 because the SNR value was not included in its user manual. Figure 4 also shows a line that fits the presented data best in a least-squares sense.

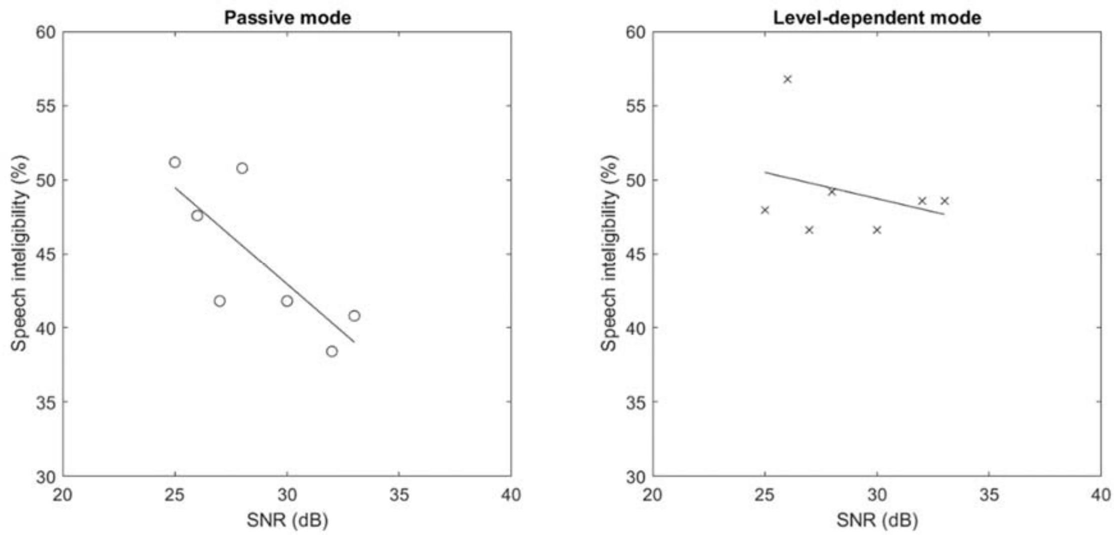

Figure 4. Comparison of the speech intelligibility values with the SNR values for M1-M7 earmuffs used in two modes: left panel – passive mode, right panel – level-dependent mode

The graphs in Figure 4 show a clearly different relationship between speech intelligibility and SNR for passive and level-dependent mode. The slope of the passive mode trend line is much higher (-1.3 %/dB) than in the case of level-dependent mode (-0.35 %/dB). When the earmuffs are used in passive mode, a higher attenuation is associated with a deterioration in the ability to understand speech. The situation is different for level-dependent mode, where speech intelligibility is almost independent of the SNR value. In passive mode, only 2 out of 7 earmuffs provide a speech intelligibility of more than 50% and, at the same time, increasing attenuation leads to increasingly lower speech intelligibility values (less than 40%). In the case of level-dependent attenuation, switching on the electronics results in higher average speech intelligibility values. As mentioned above, these values are aligned between the individual earmuffs, with the exception of the individual case with the distinctly improved speech intelligibility of the other earmuffs.

The results for the passive mode of use of hearing protectors are consistent with the conclusions of one study, where two models of earplugs with different attenuation were considered in the speech intelligibility tests [6]. Although the authors of mentioned study conducted researches in the presence of continuous rather than impulse noise, using monosyllabic words in another language (Persian), they also stated that speech intelligibility depends on the attenuation of the earplugs. The speech intelligibility was higher in the case of earplugs with NRR equalled to 25 dB than for earplugs with 32 dB NRR. The distinction between the two earplugs in the presence of noise was 11-12 percentage points. Among the earmuffs included in our study there were two earmuffs with SNR of 25 and 32 dB. Speech intelligibility between the two earmuffs (Fig. 4, left panel) differs by 12.8 percentage points.

4. Conclusions

The results did not indicate any statistically significant deterioration in speech intelligibility related to the change in the use of hearing protectors from passive to level-dependent mode in impulse noise conditions that may occur at the shooting range. This means that users of level-dependent hearing protectors who choose them for their basic functionality, i.e. the ability to transmit speech sounds at moments of relative silence under these protectors, can also use them in the presence of acoustic impulses without fear of impairing their ability to understand words (as opposed to passive hearing protectors). Furthermore, the results have shown that level-dependent hearing protectors include models that do not impair speech intelligibility (compared to passive protection), but also improve it.

Two out of nine hearing protectors provide better speech understanding used in level-dependent mode than in passive mode, on average by nearly 10 percentage points.

An analysis of the measured speech intelligibility values when using different hearing protectors in level-dependent mode in the presence of impulse noise showed that in the group of nine hearing protectors included, for one of them (M3 earmuff) the speech intelligibility values were 5-10 percentage points higher than for the other hearing protectors, for which the average speech intelligibility value was about 50%. In general, in level-dependent mode, there is little differentiation in speech intelligibility values between hearing protectors.

In passive mode there are three groups of hearing protectors differentiated in terms of speech intelligibility: more than 50%, close to 40% and between 45% and 50%. In most cases, statistically significant differences in speech intelligibility occur between the first and second group of hearing protectors.

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