Ten załącznik 4a_cz1 zawiera kopie powiązanych tematycznie artykułów naukowych A1-A3 (3 spośród 6) wchodzących w skład cyklu stanowiącego osiągniecie naukowe:

A1 Młyński R., Kozłowski E. Impulse noise measurement in view of noise hazard assessment and use of hearing protectors, International Journal of Occupational Safety and Ergonomics, 2023, 29(2), 528–537, DOI:10.1080/10803548.2023.2174700

A2 Młyński R., Kozłowski E., Usowski J., Jurkiewicz D. Evaluation of exposure to impulse noise at personnel occupied areas during military field exercises. Archives of Acoustics, 2018, 43(2), 197–205, DOI:10.24425/122367

A3 Młyński R., Kozłowski E., Adamczyk J. Assessment of impulse noise hazard and the use of hearing protection devices in workplaces where forging hammers are used. Archives of Acoustics, 2014, 39(1), 73-79, http://acoustics.ippt.pan.pl/index.php/aa/article/view/1523

Kopie pozostałych artykułów wchodzących w skład tego cyklu, oznaczonych jako A4-A6, zamieszczono w osobnym załączniku 4a_cz2.

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Impulse noise measurement in view of noise hazard assessment and use of hearing protectors

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ABSTRACT
Experience shows the occurrence of situations when the measurements of impulse noise parameters are made with measurement equipment unsuitable for such conditions. The results of using such equipment were compared with the results of using equipment with a sufficiently large upper limit of the measurement range. The analysis was carried out on the example of noise generated during shots from a Mossberg smooth-bore shotgun and AKM rifle, as well as produced in the forge. The use of the unsuitable equipment allowed to indicate the exceeding of the exposure limit value of the peak value of the signal (L_{Cpeak}), but this is not always possible when determining the energy properties of the signal ($L_{EX,8h}$). While the inadequate properties of the measurement equipment will generally not prevent the conclusion that noise in a particular workplace is hazardous to hearing, the results of measurements cannot be used to select hearing protectors.

KEYWORDS
impulse noise; noise measurements; exposure to noise; earmuffs; hearing protector selection

1. Introduction

In the case of exposure to noise, it is important to determine its parameters in order to carry out an assessment of noise hazards. In many cases, it is also necessary to obtain the data necessary for the selection of hearing protectors. The problem of obtaining reliable results may occur when measuring the impulse noise parameters. The value of impulse noise parameters often exceeds the dynamic range upper limit of commonly used standard sound level meters.

An employer is obliged to perform the assessment of noise hazards. The results of such an assessment may indicate the need for that employer to take certain measures to reduce exposure to noise. The assessment is carried out on the basis of specific criteria, i.e., limit values for noise parameters. These issues are described both in European legislation, i.e., Directive 2003/10/EC [1], and in Polish national regulations [2]. While the principles of hearing conservation recommend noise reduction at the source as the first step, engineering and administrative controls are the next steps when the former is not possible [3,4]. In the case of impulse noise produced during the use of firearms, firearm suppressors [5] may be such engineering noise control measures. The effectiveness of noise reduction in this way is not always sufficient [6]. On the other hand, the application of technical means limiting exposure to impulse noise in industry, according to our earlier observations, is not always possible [7]. In the absence of their sufficient effectiveness or applicability, it is essential to use hearing protectors. These can be both passive hearing protectors and hearing protectors equipped with electronic systems to support the perception of relevant ambient sounds. Reviews of the various types of hearing protectors have been published by others [8,9]. Hearing protectors should be properly selected [1,10] by assessing their effectiveness in reducing noise. The proper assessment of the effectiveness of noise reduction by hearing protectors requires specific selection methods. Selection methods for hearing protectors are, in turn, based on knowledge of the specific parameters characterizing noise in places where hearing protectors are to be used [11].

There is practical evidence that measurements of noise parameters, under conditions of high sound pressure level values, are performed with measurement equipment which is not suitable for such conditions, i.e., standard sound level meters. When the noise signal saturates the upper limit of a sound level meter, an overload is indicated and the displayed sound pressure level is incorrect. However, in the case of noise exposure assessment, despite the incorrect result, information is obtained that the noise exposure limit value is exceeded, as required by Directive 2003/10/EC [1]. The situation is worse when there is a need to select hearing protectors. The use of measurement data obtained in an inadequate manner for obvious reasons must result in incorrectly determined values for the parameters of noise present under hearing protectors. As a result, this may lead to erroneous assessment of hearing protectors as to whether they can sufficiently reduce exposure to noise.

The measurement of high-level impulse noise such as gunfire can only be accurately conducted with the use of specialized equipment [12,13]. The purpose of this article is to discuss how incorrect measurement of impulse noise parameters with the use of sound level meters affects the noise hazard assessment and the selection of hearing protectors.

2. Noise parameters and their measurements

2.1. Parameters applied for the assessment of noise hazard

The assessment of noise hazard is carried out based on the comparison of the values of selected parameters with the relevant criterion values, i.e., exposure limit values. Directive

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2003/10/EC [1] contains exposure limit values relating to two noise parameters: *C*-weighted peak sound pressure level ($L_{C\text{peak}}$) and *A*-weighted noise exposure level normalized to an 8-h working day, otherwise known as the daily noise exposure level ($L_{EX,8h}$). The maximum values for these parameters have been set as 140 and 87 dB, respectively. According to the Polish regulations [2], the exposure limit values are $L_{C\text{peak}} = 135$ dB and $L_{EX,8h} = 85$ dB. In addition, the Polish regulations specify a criterion value for the *A*-weighted maximum sound pressure level: $L_{A\max} = 115$ dB. However, in the case of exposure to impulse noise, the assessment using this parameter practically duplicates the assessment made with $L_{C\text{peak}}$. Due to the essential duality of the assessment of the impulse noise instantaneous values using the $L_{A\max}$ and $L_{C\text{peak}}$ parameters, the $L_{C\text{peak}}$ parameter will be taken into account in further analysis. For the parameter $L_{EX,8h}$, its value is based on the exposure time and the *A*-weighted equivalent sound pressure level ($L_{A\text{eq}}$).

The $L_{A\max}$ parameter – although, as mentioned, used to assess exposure to noise in Poland – is not used in the process of selecting hearing protectors. For the instantaneous value of the signal, the impulse noise selection methodology, i.e., 'Method for assessing the sound attenuation of a hearing protector for impulsive noise' included in the informative Annex B of the relevant Standard No. EN 458:2016 [11], includes the use of the $L_{C\text{peak}}$ parameter. Due to the fact that the article deals with two aspects related to the measurement of noise parameters, i.e., the assessment of exposure to impulse noise and the selection of hearing protectors, the conducted analysis was based on the two mentioned parameters ($L_{EX,8h}$, $L_{C\text{peak}}$), which are taken into account in the noise exposure assessment in Directive 2003/10/EC [1] and at the same time are considered in the selection of hearing protectors for impulse noise [11]. The analysis was supplemented with other parameters used in the selection of hearing protectors. Details in both of these areas, i.e., assessment of noise hazard and selection of hearing protectors, will be described later in the article.

2.2. Problems with the measurement of impulse noise parameters when assessing noise hazard

Standard No. ISO 9612:2009 [14] for the determination of occupational noise exposure includes the requirement that the sound level meters used shall meet the requirements for IEC 61672-1 [15], class 1 or class 2 instrumentation. In accordance with the provisions of Directive 2003/10/EC [1], the measurement equipment used for the assessment of noise hazard should make it possible to measure the noise parameters taken into account in the assessment and determine whether, among others, the exposure limit values for these parameters have been exceeded. When measuring the parameters of impulse noise, it may happen that the sound pressure level characterizing this noise will exceed the dynamic range upper limit of the sound level meter. Table 1 presents examples of the limits of the possibilities of measuring noise parameters by type of approved sound level meters. These data, which are included in the sound level meter user manuals, include $L_{C\text{peak}}$, which, as a parameter related to the instantaneous value of the signal, is particularly applicable to characterize the properties of impulse noise. The upper limit of the measurement range is also determined for $L_{A\text{eq}}$, which is also used in the assessment of noise hazard.

Table 1. Examples of class 1 sound level meters (according to IEC 61672-1 [15]) with type approval often used in Poland and their upper limits of measuring ranges.

Manufacturer and model of sound level meter with a given microphone	Upper limit of the $L_{C\text{peak}}$ measurement range (dB)	Upper limit of the $L_A/L_{A\text{eq}}$ measurement range (dB)
Brüel & Kjær 2250 with 4189 microphone	142.7	139.7
Norsonic Nor 140 with Nor 1225 microphone	140.0	137.0
Sonopan DSA 50 with WK-21 microphone	138.0	135.0
Svantek SVAN 979 with GRAS 40AE microphone	140.0	137.0

Note: Information based on product data/instruction manuals. L_A = *A*-weighted sound pressure level; $L_{A\text{eq}}$ = *A*-weighted equivalent sound pressure level; $L_{C\text{peak}}$ = *C*-weighted peak sound pressure level.

Table 2. Exemplary values of parameters of impulse noise generated in the forge and during firing of firearms.

Impulse noise source	$L_{C\text{peak}}$ (dB)
Forgers' workplace	148.9
PM-98 Glauberyt submachine gun at a distance of 1.1 m	151.4
Glock 17/Walther P99 pistol at a distance of 1.1 m	153.3
Mossberg 590 smooth-bore shotgun at a distance of 1.1 m	158.1
ZU-23-2K anti-aircraft gun (at crew position)	158.3
Anti-tank guided missile (at operator position)	160.7

Note: Values based on other studies of the authors' team [7,17,18]. $L_{C\text{peak}}$ = *C*-weighted peak sound pressure level.

Noise with high peak sound pressure levels can occur in both industrial and recreational settings. The peak sound pressure level produced by high-powered firearms can even exceed 172 dB [16]. An example of an industrial noise source that generates noise exceeding the exposure limit value for $L_{C\text{peak}}$ is a forging hammer. The parameters of noise present at work in the forge were included by the team of authors in one of their previous studies [7], where the possibility of reducing this noise by using hearing protectors was analyzed. In another study, the team of authors described issues related to the selection of hearing protectors for shooting instructors [17]. An inherent element of these two works were the measurements of noise parameters in the places where people use the selected hearing protectors. The next study presents the results of the measurements of noise parameters occurring during military field exercises [18]. Table 2 presents some sample results of noise parameter measurements taken from the three aforementioned works. The results shown in this table were obtained using measurement equipment whose dynamic range upper limit does not limit the ability to characterize the noise produced by the sources considered and is 174 or 184 dB. A GRAS 67SB transducer (GRAS Sound & Vibration A/S, Denmark) or Brüel & Kjær 4941 microphone (Brüel & Kjær, Denmark) was used. A signal from the transducer/microphone was supplied to a Brüel & Kjær 3052-A-030 input module or Brüel & Kjær PULSE 3560 C measurement unit. The waveforms of this signal were recorded, which enabled further analysis with the use of Brüel & Kjær Pulse Reflex or Brüel & Kjær LabShop software, during which noise parameters were determined.

In Table 2, impulse noise is characterized by $L_{C\text{peak}}$, which, as already mentioned, is a parameter used to assess noise hazard. Data available in the literature most often refer to another noise parameter, i.e., (unweighted) peak sound pressure level, and other types of weapons. Moreover, they were obtained at other distances from the noise source. Despite all these differences, the available data are comparable or even exceed the values presented in Table 2. For example, in the case of C7 rifle shots, at a distance of 30 cm from the shooter, L_{peak} was 154.7 dB [19]. In the case of AR-15 rifle shots, at a distance of 4 m it was even 168 dB [20]. The L_{Cpeak} values presented in Table 2 exceed the upper limit of the L_{Cpeak} measurement range presented in Table 1 for each of the four sound level meters. Thus, measurement of the parameters of noise generated by the sources presented in Table 2 with a standard sound level meter will result in a message about the measurement range distortion and the displayed indication will be erroneous. This will not give a reliable value of L_{Cpeak}. Information on exceeding the measuring range of the instrument, for obvious reasons relating to the correct use of the measurement equipment, makes it necessary to reject the results obtained from the noise parameters measured in this case. Using each of the four sound level meters presented in Table 1, it is only possible to determine that the L_{Cpeak} limit value has been exceeded. This means that the aforementioned requirement in Directive 2003/10/EC [1], which states that the measurement equipment must be capable of detecting the fact that the permissible noise parameters have been exceeded, is met. It should be kept in mind that such measurement data, i.e., erroneous measurement results, will make it impossible to determine correctly the indicators used to show how far the limit value for a certain noise parameter is exceeded.

2.3. Noise parameters for the selection of hearing protectors

The problem of exposure to noise in the workplace is often associated with the need for hearing protectors. As mentioned in Section 1, hearing protectors should be properly selected [1,10]. Depending on the calculation method of selection of hearing protectors [11], it is necessary to know the specific noise parameters to use. When selecting hearing protectors to be used in the presence of impulse noise, it is necessary to characterize the instantaneous values of acoustic impulses using the L_{Cpeak} parameter. The selection must also involve determining L_{Aeq} under a hearing protector. The use of the 'octave band method' for this purpose will require measurement of the sound pressure level in octave bands (L_p). When using the 'HML method' for selecting hearing protectors, it is necessary to measure L_{Aeq} as well as the C-weighted equivalent sound pressure level (L_{Ceq}). The name of the HML method is related to the fact that the calculation uses the *H*, *M*, and *L* values representing the attenuation of hearing protectors: *H* = high-frequency attenuation value, *M* = medium-frequency attenuation value, *L* = low-frequency attenuation value [21]. In the case of the 'SNR method', it is necessary to obtain a result of the L_{Ceq} measurement. The name of the SNR method is related to use of the SNR value in the calculations, which expresses the attenuation of the hearing protector with only one number: single number rating [21]. As the octave band method is the most accurate of these methods, it is recommended to use it first [11]. In this situation, it is necessary to use measurement equipment with an option of analysis in octave bands.

As already mentioned, in the case of a noise hazard assessment one can accept the lack of correct noise values in certain situations when the technical capabilities of the sound level meter are not sufficient. On the other hand, with regard to the data required for the selection of hearing protectors, information on the mere fact of exceeding the noise limit values is no longer sufficient. The use of calculation methods for the selection of hearing protectors requires the availability of correctly determined noise parameter values [11]. Thus, measurement equipment with an insufficient dynamic range upper limit will not provide the data necessary for the correct selection of hearing protectors.

3. Methods

3.1. Method for illustrating the consequences of the use of standard sound level meters for impulse noise

As already mentioned in Section 1, experience shows that measurements of noise parameters, under conditions of high sound pressure level values, are carried out with standard sound level meters, with too low a value of the dynamic range upper limit. The further part of this study describes the effects of using measurement equipment not adapted to measure the parameters of characterized noise.

For this purpose, a simulation was conducted to determine the values of noise parameters by means of a sound level meter, using previously recorded noise waveform. The diagram illustrating the procedure adopted to show the effects of using sound level meters in the case of impulse noise is shown in Figure 1.

The noise waveforms occurring when firing the Mossberg smooth-bore shotgun and the AKM rifle and during metal processing with a forging hammer were recorded using measurement equipment whose dynamic range upper limit does not limit the possibility of noise characterization, i.e., with a GRAS 67SB transducer connected to a Brüel & Kjær 3052-A-030 input module. Original and modified noise waveforms were analyzed in two situations e.g., when the dynamic range upper limit was 139.7 and 135.0 dB. These were the highest and lowest values of this limit among the data presented in Table 1. The noise waveforms recorded in real conditions have been modified to reflect the effect of a signal trimmed due to the limited measuring range of the sound level meter. Examples of noise waveforms for the recorded signal and signals after modification are shown in Figure 2.

The recorded waveforms of the signal (i.e., the original) and the waveforms after modification were used to determine the values of noise parameters, in accordance with the definitions of these parameters and the rules contained in Standard No. ISO 9612:2009 [14]. The original noise waveform was used as a basis to determine reference data. The noise parameters were determined using program procedures designed to be run in MATLAB R2019a version 9.6.0.1174912. The proper performance of the prepared procedures has been demonstrated by their validation with calibrated measurement equipment based on the Brüel & Kjær 3052-A-030 input module and Brüel & Kjær LabShop. The determined values of the noise parameters, in the case of original and modified waveforms, were used to calculate the differences between them in order to show what the consequences of incorrect use of the measurement equipment may be. The obtained values of noise parameters were also used to show the influence of incorrect measurement results on the selection and evaluation of hearing protectors. The parameters determined included L_{Cpeak}, L_{Aeq}, $L_{EX,8h}$

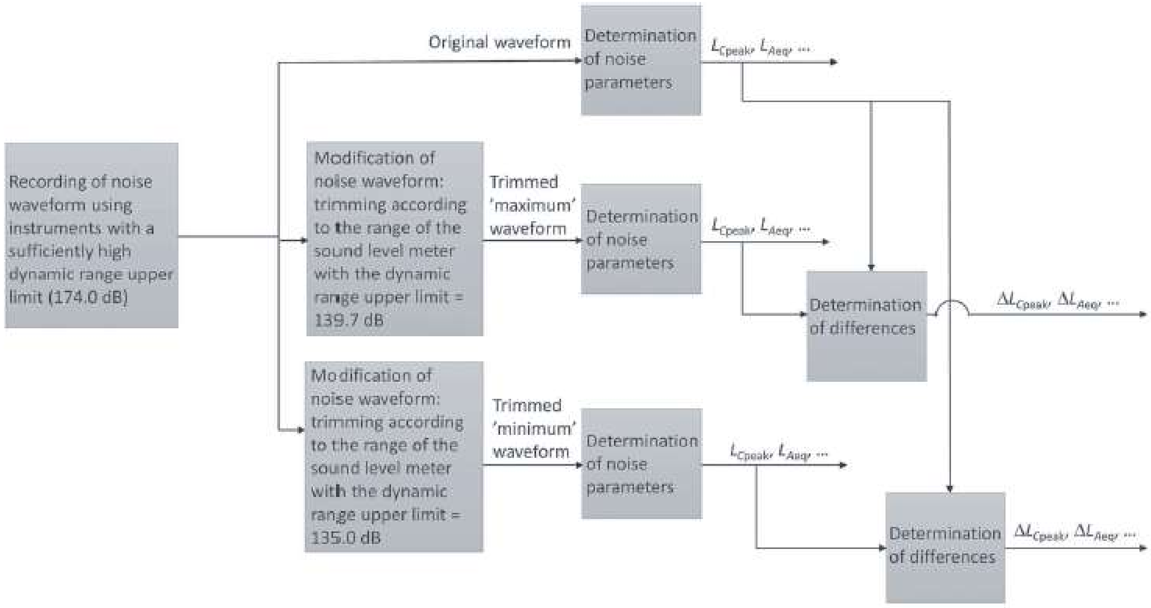

Figure 1. Procedure adopted to show the effects of using sound level meters in the case of impulse noise parameter measurements. Δ = difference; L_{Aeq} = *A*-weighted equivalent sound pressure level; L_{Cpeak} = *C*-weighted peak sound pressure level.

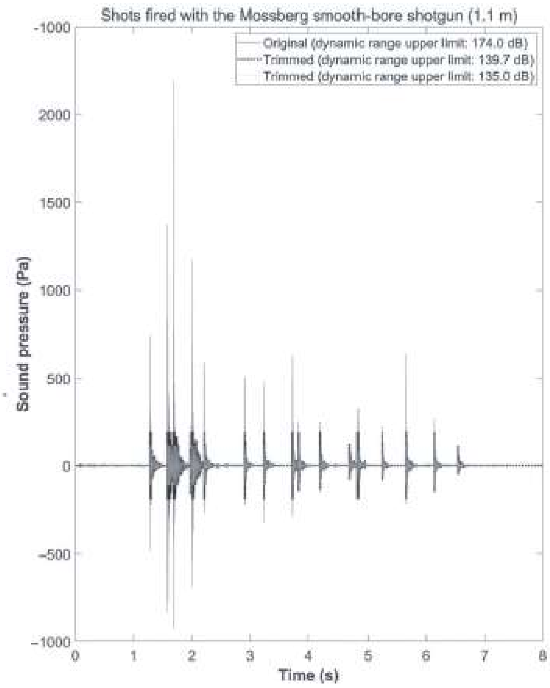

Figure 2. Original and trimmed waveforms of shots from the Mossberg smooth-bore shotgun with different dynamic range upper limit values of the measurement equipment.

and L_{Ceq}. Additionally, the results of the determination of L_p were presented.

All signal waveforms included in the analysis were representative in accordance with the principles of noise exposure assessment [14] and corresponded to the principles of selection of hearing protectors [11]. For each of the sources, an exemplary cycle of activities was used, representative for a specific place of residence of the person who performs these activities. The results obtained included an exemplary working day. All of the signals included in the analysis corresponded in terms of their duration to situations that took place in real conditions. At the same time, all activities that should be analyzed in the case of individual places of residence of a person were taken into account. Details on the selection of representative signals for analysis are provided in the cited paper on selection of hearing protectors for use in a shooting range [17]. For example, one full representative cycle of the task includes not only shooting, but also giving instructions, loading weapons and other preparatory activities, unloading weapons, checking their condition, etc. For example, in the case of the Mossberg shotgun, three-shot exercises were included, each of which consisted of several shots and the activities accompanying this shooting. In the case of the AKM rifle, the analysis included exercises consisting of 50 shots.

3.2. Method for illustrating the consequences of the incorrect selection of hearing protectors

In the case of exposure to impulse noise, two parameters of that noise are considered when selecting hearing protectors [11]. It shall be checked whether the use of a hearing protector will cause the *C*-weighted peak sound pressure level under the hearing protector (L'_{Cpeak}) to be sufficiently lowered, i.e., below the exposure limit value, which, as mentioned earlier, is 135 dB. At the same time, appropriate conditions must be met for the value of the *A*-weighted equivalent sound pressure level of noise under a hearing protector (L'_{Aeq}). It is necessary to ensure that the value of 80 dB is not exceeded for this parameter, as demonstrated by the analysis of the data in Standard No. ISO 1999:1990 [22] concerning the expected hearing permanent threshold shift due to noise exposure. In addition, due to the perception of sound signals, hearing protectors should be selected in such a way that the L'_{Aeq} value is not less than 65 dB, as defined in Standard No. EN 458:2016 [11]. This condition is associated with the effect of overprotection, which can lead to a failure to hear, e.g., a warning signal and, consequently, even an accident. The overprotection phenomenon may be dangerous wherever the reception of sounds that can be treated as useful is important for safety reasons. In the case of using firearms, including, e.g., exercises at the shooting range, it is important to receive commands. In addition to warnings, in the case of the shooting instructor's work, verbal communication between the instructor and the trained person is also important. Then, too much sound attenuation can affect the difficulty in communication between people.

Once the L'_{Aeq} value has been determined, the hearing protectors can be assessed for proper hearing protection for their users. This assessment consists of classifying the result of the L'_{Aeq} calculation into one of three categories: sufficient protection, insufficient protection or overprotection. The protection is sufficient if L'_{Aeq} is within the range from 65 to 80 dB. Insufficient protection means that L'_{Aeq} is higher than 80 dB. Overprotection is observed if L'_{Aeq} is below 65 dB. It is important to note that in the final evaluation of hearing protectors that provide proper hearing protection due to the L'_{Aeq} value, it is also necessary to consider whether they sufficiently limit the L'_{Cpeak} value.

The limited value of the dynamic range upper limit (data presented in Table 1) in the case of measurement of impulse noise parameters with a standard sound level meter will result in the indication of the measured L_{Cpeak} value reaching 143 dB at most. Using such results to calculate the value of this parameter under hearing protectors (L'_{Cpeak}) for each hearing protector will lead to a conclusion of sufficient noise reduction. Obviously, in all cases where the actual L_{Cpeak} value will differ significantly from the indicated value, because the dynamic range upper limit of the sound level meter is exceeded, this conclusion may be false. The further part of the study will show how the potential failure to ignore the information about exceeding the sound level meter's measuring range can affect the selection of hearing protectors carried out due to the L'_{Aeq} parameter, i.e., using L_p, a parameter not associated with peak signal level.

The selection covered 15 different hearing protectors with different sound attenuation values represented by SNR values between 21 and 37 dB in the user manuals of these protectors. The SNR has been defined in Standard No. ISO 4869-2:2018 [21] on estimation of the effective A-weighted sound pressure level when hearing protectors are worn. Determination of the L'_{Aeq} value was conducted using the octave band method. The data on L_p determined in the case of a correctly recorded (original) noise waveform and the data determined assuming that they come from sound level meters with insufficiently high dynamic range upper limit were used.

4. Results

4.1. Consequences of the use of standard sound level meters for impulse noise

The results of determining the values of the L_{Cpeak}, L_{Aeq}, $L_{EX,8h}$ and L_{Ceq} parameters in the case of noise generated during shots from a Mossberg smooth-bore shotgun and an AKM rifle and during metal processing with a forging hammer are presented in Tables 3–5, respectively. Each table gives the results of the analysis of the original noise waveform, i.e., without exceeding the dynamic range upper limit of 174.0 dB. The results of the analysis carried out in the case of modified noise waveforms with the assumption of limiting the dynamic range upper limit to 139.7 and 135.0 dB have also been included.

Tables 3–5 also present the values of the differences between the original and modified noise parameters. For the L_{Aeq} and $L_{EX,8h}$ parameters, values of these differences will be the same, as the $L_{EX,8h}$ parameter is determined on the basis of the L_{Aeq} parameter, after taking into account the exposure time, which is related to 8 h [14].

When determining the value of the $L_{EX,8h}$, two other activities with a lower sound pressure level were taken into account, in addition to the activities related to the operation of forging hammer when acoustic impulses are generated (L_{Aeq} = 109.5 dB). The L_{Aeq} values measured during two other activities are 84.3 and 45.0 dB and are correct when using a sound level meter. In practice, the impact of these two other activities, apart from the direct operation of the hammer, slightly affects the value of $L_{EX,8h}$ and this impact does not exceed 0.8 dB.

The rating of noise hazard in the shooting trainer's workplace indicated not only that the permissible value concerning the signal's instantaneous values, i.e., the L_{Cpeak} parameter, was exceeded, but also that the permissible value of the $L_{EX,8h}$

Table 3. Results of the analysis of the original and modified noise waveforms associated with shots from the Mossberg smooth-bore shotgun at a distance of 1.1 m from the shooter (shooting trainer's position).

Waveform	L_{Cpeak} (dB)	ΔL_{Cpeak} (dB)	L_{Aeq} (dB)	$L_{EX,8h}$ (dB)	ΔL_{Aeq} ($\Delta L_{EX,8h}$) (dB)	L_{Ceq} (dB)	ΔL_{Ceq} (dB)
Original, DRUL = 174.0 dB	158.3	–	103.8	90.2	–	105.6	–
Trimmed, DRUL = 139.7 dB	142.2	16.1	100.2	86.6	3.6	102.0	3.6
Trimmed, DRUL = 135.0 dB	137.6	20.7	98.3	84.7	5.5	100.1	5.5

Note: Δ = difference; DRUL = dynamic range upper limit; L_{Aeq} = A-weighted equivalent sound pressure level; L_{Ceq} = C-weighted equivalent sound pressure level; L_{Cpeak} = C-weighted peak sound pressure level; $L_{EX,8h}$ = A-weighted noise exposure level normalized to an 8-h working day (daily noise exposure level).

Table 4. Results of the analysis of the original and modified noise waveforms associated with shots from the AKM rifle at a distance of 1.1 m from the shooter (shooting trainer's position).

Waveform	L_{Cpeak} (dB)	ΔL_{Cpeak} (dB)	L_{Aeq} (dB)	$L_{EX,8h}$ (dB)	ΔL_{Aeq} ($\Delta L_{EX,8h}$) (dB)	L_{Ceq} (dB)	ΔL_{Ceq} (dB)
Original, DRUL = 174.0 dB	148.9	–	105.4	85.6	–	107.2	–
Trimmed, DRUL = 139.7 dB	140.4	8.5	102.9	83.1	2.5	105.0	2.2
Trimmed, DRUL = 135.0 dB	135.9	13	100.9	81.1	4.5	103.0	4.2

Note: Δ = difference; DRUL = dynamic range upper limit; L_{Aeq} = A-weighted equivalent sound pressure level; L_{Ceq} = C-weighted equivalent sound pressure level; L_{Cpeak} = C-weighted peak sound pressure level; $L_{EX,8h}$ = A-weighted noise exposure level normalized to an 8-h working day (daily noise exposure level).

Table 5. Results of the analysis of the original and modified noise waveforms associated with the noise generated during metal processing in the forge.

Waveform	$L_{C\text{peak}}$ (dB)	$\Delta L_{C\text{peak}}$ (dB)	$L_{A\text{eq}}$ (dB)	$L_{EX,8h}$ (dB)	$\Delta L_{A\text{eq}}$ $\Delta L_{EX,8h}$ (dB)	$L_{C\text{eq}}$ (dB)	$\Delta L_{C\text{eq}}$ (dB)
Original, DRUL = 174.0 dB	148.3	–	109.5	107.5	–	114.1	–
Trimmed, DRUL = 139.7 dB	141.8	6.5	108.2	106.2	1.3	112.3	1.8
Trimmed, DRUL = 135.0 dB	137.6	10.7	106.6	104.6	2.9	110.4	3.7

Note: Δ = difference; DRUL = dynamic range upper limit; $L_{A\text{eq}}$ = *A*-weighted equivalent sound pressure level; $L_{C\text{eq}}$ = *C*-weighted equivalent sound pressure level; $L_{C\text{peak}}$ = *C*-weighted peak sound pressure level; $L_{EX,8h}$ = *A*-weighted noise exposure level normalized to an 8-h working day (daily noise exposure level).

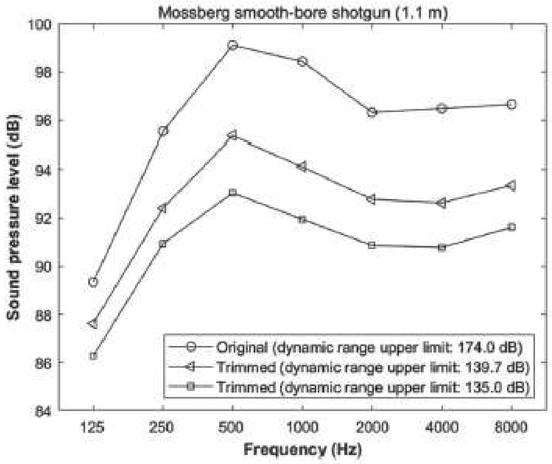

Figure 3. Sound pressure levels in octave bands for the original and trimmed waveforms of shots from the Mossberg smooth-bore shotgun, with different dynamic range upper limit values of the measurement equipment.

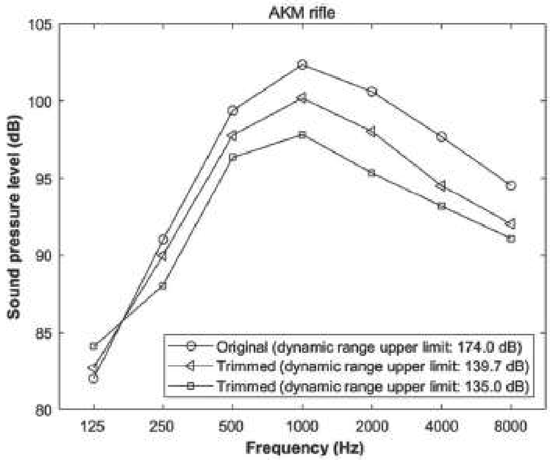

Figure 4. Sound pressure levels in octave bands for the original and trimmed waveforms of shots from the AKM rifle, with different dynamic range upper limit values of the measurement equipment.

parameter, reflecting the signal's energy properties, was too high. For each of the noise parameters, the difference between the value of this parameter determined with a sound level meter with an insufficient value of the dynamic range upper limit and the result obtained with measurement equipment of the appropriate measuring range increases as the dynamic range upper limit of the sound level meter decreases.

The effects of using a sound level meter with the dynamic range upper limit not adjusted to the parameters of impulse noise for L_p are shown in Figure 3. The measurement results relating to noise generated during shots from the Mossberg smooth-bore shotgun are included. Results for the two other noise sources being considered are presented in Figures 4 and 5. The values of the differences in indications determined from the original noise waveform and trimmed waveform (when the dynamic range upper limit is 139.7 or 135.0 dB) are greatest for L_p measured during shots from the Mossberg smooth-bore shotgun, while the smallest are for the noise generated in the forge.

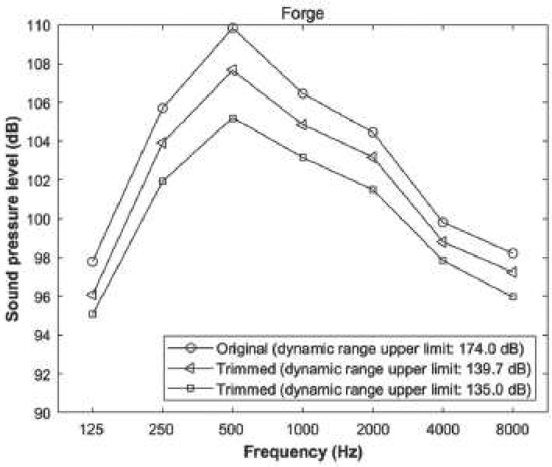

Figure 5. Sound pressure levels in octave bands for the original and trimmed waveforms of noise generated in the forge, with different dynamic range upper limit values of the measurement equipment.

4.2. *Consequences of the use of standard sound level meters for impulse noise*

Figures 6–8 present the results of the determination of $L'_{A\text{eq}}$. The figures show the lines that distinguish the three evaluation areas for hearing protectors, i.e., insufficient protection, sufficient protection and overprotection.

The data presented in Figures 7 and 8 indicate that among the earmuffs, there are both those which, due to their $L_{A\text{eq}}$, provide sufficient protection against noise generated at the workplace in the forge and those whose assessment indicates insufficient protection. In the case of noise generated during shots from the Mossberg smooth-bore shotgun (Figure 6), apart from these two categories, some earmuffs lead to overprotection.

5. Discussion

Commercially available sound level meters and dosimeters are convenient for conducting noise assessments, but recent studies have raised awareness of their limitations [23]. The use of measurement equipment not suitable for the parameters of the measured signal must naturally result in incorrect indications. The results of noise parameter determination obtained in our work on the basis of the waveforms, which was recorded

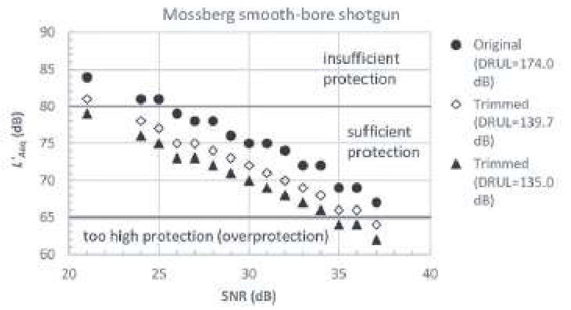

Figure 6. Results of L'_{Aeq} determination for hearing protectors used during shots from the Mossberg smooth-bore shotgun. DRUL = dynamic range upper limit; L'_{Aeq} = *A*-weighted equivalent sound pressure level of noise under a hearing protector; SNR = single number rating.

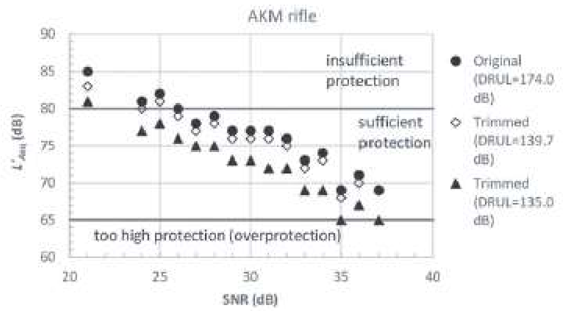

Figure 7. Results of L'_{Aeq} determination for hearing protectors used during shots from the AKM rifle. DRUL = dynamic range upper limit; L'_{Aeq} = *A*-weighted equivalent sound pressure level of noise under a hearing protector; SNR = single number rating.

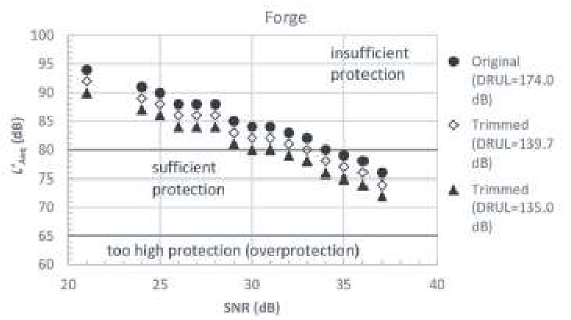

Figure 8. Results of L'_{Aeq} determination for hearing protectors used in the presence of noise generated during metal processing in the forge. DRUL = dynamic range upper limit; L'_{Aeq} = *A*-weighted equivalent sound pressure level of noise under a hearing protector; SNR = single number rating.

correctly, and the modified waveforms according to the measurement range limits considered, were used to assess the noise hazard and to select hearing protectors. In this way it is shown what the consequences can be of using the results of measurements carried out using inappropriate equipment.

The results presented in Tables 3–5 show that the L_{Cpeak} value indicated by sound level meters with an insufficient dynamic range upper limit exceeds the exposure limit value related to this parameter (135 dB), similar to the result obtained in the case of a correctly performed measurement. The assessment of the noise hazard, i.e., finding that the exposure limit value has been exceeded, despite incorrect L_{Cpeak} values, is therefore concurrent in the case of correct and incorrect measurements. It should be noted, however, that when assessing the noise generated during shots from the Mossberg smooth-bore shotgun (Table 3), carried out using the $L_{EX,8h}$ parameter, a sound level meter with a dynamic range upper limit of 135.0 dB resulted in indications which led to the result opposite to the reference measurement. For this meter, a value of $L_{EX,8h}$ amounting to 84.7 dB has been determined, which indicates that the criterion value of 85 dB is not exceeded. The situation of obtaining an incorrect result of noise hazard assessment due to the parameter $L_{EX,8h}$ also occurred in the case of shots from the AKM rifle (Table 4). Concluding on the basis of the results measured by any of the two sound level meters with an insufficiently high value of the dynamic range upper limit indicates that the $L_{EX,8h}$ value (even 3.9 dB below the criterion) is not exceeded, when in fact it is exceeded. The examples shown therefore indicate that the provision in Directive 2003/10/EC [1] that the measurement equipment must enable to determine whether the noise limit values are being exceeded may not be complied with when measuring impulse noise. Despite this, in the end, the assessment of noise in the workplace (not including the problem of selection of hearing protectors) will generally indicate that the noise is dangerous, since, as is known, the assessment also includes a component on the peak value of the signal. In the assessment of noise in the workplace, it is sufficient that there is an exceedance for one of the noise parameters for the noise to be considered hazardous.

It follows from the aforementioned that the measurements of impulse noise parameters should be carried out with the use of equipment that enables the correct indication of relatively high values of the sound pressure level. Therefore, in the case of noise sources considered in this article, the dynamic range upper limit of the equipment used should reach 165 dB. As mentioned in Section 1, the issue of equipment for measuring impulse noise parameters is rarely undertaken in published works. The first example of including this subject is Standard No. ANSI/ASA S12.42-2010 [13] describing methods for the measurement of insertion loss of hearing protectors in continuous or impulsive noise. This standard includes, *inter alia*, indications for the implementation of a transducer for measuring impulse noise parameters. It is required that this transducer (a free-field pressure probe/microphone) should be capable of measuring impulse levels of 180-dB peak sound pressure level. The need for a sufficiently large dynamic range upper limit of measurement equipment for the characterization of impulse noise was also highlighted in the work on the development of a noise dosimeter [12]. This work presents two developed noise dosimeters appropriate for the military. The dynamic range upper limit of these noise dosimeters is 165 and 180 dB.

It is natural that the greater the value of the peak sound pressure level characterizing impulse noise, the greater are the differences between the values of noise parameters determined using sound level meters with insufficiently high dynamic range upper limit in relation to the measurement data obtained correctly. Data presented in Tables 3–5 allow to obtain information about the scale of potential deviations of the results produced with the use of sound level meters in inappropriate impulse noise measurements from the results that can be described as correct. The indication of L_{Cpeak}, if measured with an unsuitable sound level meter, may deviate from the value characterizing the impulses produced when firing a firearm by 13 dB (ΔL_{Cpeak} in the case of the AKM rifle) or by even more than 20 dB (Mossberg smooth-bore shotgun). For the noise that is characteristic of industrial conditions, i.e., produced in a forge, the deviation of the indication of the L_{Cpeak} may reach almost 11 dB. The largest of the numerical values of the analyzed indication differences in the case of parameters related to the energy properties of the signal, i.e., ΔL_{Aeq} ($\Delta L_{EX,8h}$) and ΔL_{Ceq}, are 5.5, 4.5 and 3.7 dB, respectively, in the case of noise from the Mossberg smooth-bore shotgun, from AKM rifle shots and in the forge. The largest deviations of the values obtained by the sound level meter from the reference results, when measuring L_p (Figures 3–5), are 4.3 dB (ΔL_{p1} – the difference in indications determined from the original noise waveform [dynamic range upper limit: 174.0 dB] and the trimmed waveform when the dynamic range upper limit is 139.7 dB) and 6.5 dB (ΔL_{p2} – the difference in indications determined from the original noise waveform [dynamic range upper limit: 174.0 dB] and the trimmed waveform when the dynamic range upper limit is 135.0 dB). Therefore, the referred values of deviations (ΔL_{Cpeak}, ΔL_{Aeq} [$\Delta L_{EX,8h}$], ΔL_{Ceq}, ΔL_{p1}, ΔL_{p2}) confirm that it is sometimes incorrect to make an assumption among people carrying out measurements that the impact of exceeding the dynamic range upper limit of the measurement equipment during impulse noise measurements is negligible.

Although L_{Cpeak} in the case of noise generated during shots with the AKM rifle exceeds the value of this parameter characterizing noise generated in the forge only by 0.6 dB, the discrepancy of the $L_{EX,8h}$ determination in the case of noise in the forge (compared to the parameter determined from the recorded noise waveform) is lower (2.9 dB) than that of the AKM rifle (4.5 dB). The noise in the forge is not only composed of the impulses produced by the forging hammer. Impulses are emitted against the background of the continuous noise generated during the operation of many machines in the forge hall. The energy contained in the peaks of impulses generated in the forge which are not taken into account in the signal analysis by sound level meters with a limited measuring range shall represent a smaller proportion of the total signal energy than that of the impulses associated with gunshots. Hence, the impact on the final value of $L_{EX,8h}$ is smaller than for the noise generated by a firearm.

An integral part of the selection of hearing protectors is the need to know the given parameters of noise that is present in the place where their user is located. The data shown in Figures 6–8 show that the transfer of erroneous noise measurement results to the L'_{Aeq} value determined during the selection process under the hearing protector leads to a different erroneous assessment for some earmuffs. For example, in the case of an earmuff with SNR = 25 dB (Figure 6), the data determined based on the waveform recorded correctly lead to the 'insufficient protection' assessment. In turn, data reflecting the use of sound level meters with an insufficiently high dynamic range upper limit result in 'sufficient protection' assessment. A situation of this kind can be particularly dangerous for the potential user of a hearing protector. If an incorrect noise measurement is ignored and erroneous measurement data are used to select a hearing protector, the results would indicate correct hearing protection. In fact, when the data obtained from a correctly performed measurement are taken into account, the selection indicates insufficient hearing protection. This means that such hearing protectors should not be used to protect hearing in the presence of the noise under consideration. There may also be an incompatible result of the assessment of an earmuff of a slightly different nature. Selection of hearing protectors is also associated with the need to take into account instances of overprotection [24]. For example, in the case of an earmuff with SNR = 37 dB, a selection result based on data obtained using sound level meters indicates overprotection. At the same time, a selection based on properly obtained measurement data indicates sufficient protection. In this case, therefore, it is not reasonable to remove the earmuff from the set of hearing protectors as a result of using incorrect measurement data. Unlike in the previous case, an incorrect assessment will not harm the potential user of hearing protectors.

When hearing protectors are selected for shots from the Mossberg smooth-bore shotgun, the use of measurement data obtained using sound level meters with an insufficient dynamic range upper limit results in an erroneous evaluation of the earmuffs for 6 out of 15 earmuffs examined. At the same time, in three out of the six situations mentioned, incorrect assessment was performed for both sound level meters under consideration. In three of the remaining six erroneous cases, a different rating based on the data obtained correctly occurred only in the case of a sound level meter with a lower dynamic range upper limit (i.e., 135.0 dB). It should also be noted that, in general, a particularly unfavorable assessment (sufficient protection instead of insufficient protection) was given for 3 out of 15 earmuffs. When selecting hearing protectors for the noise generated when firing from the AKM rifle (Figure 7), an incorrect assessment was given for 3 out of 15 earmuffs (with SNR of 24, 25 and 26 dB). In contrast, the evaluation of the results of the selection of hearing protectors for the noise present in the forge was different for 4 out of 15 hearing protectors (with SNR of 30, 31, 32 and 33 dB).

In general, it can therefore be concluded that the selection of hearing protectors with regard to the L'_{Aeq}, parameter, using measurement data obtained with a sound level meter with an insufficient dynamic range upper limit, may result in an incorrect assessment in about 20–40% of the earmuffs. It should be added that the full selection of hearing protectors in the case of impulse noise exposure requires additional analysis due to the value of the parameter L'_{Cpeak}.

In summary of the discussed measurement problems in the case of noise with sound pressure level values exceeding the dynamic range upper limit of the sound level meter, it can be said that the occupational health and safety services, the employer and employees, during the assessment of noise parameters in the workplace, although they will not receive a precise measurement result, will obtain information about the occurrence of exceeded values of permissible noise parameters. At the same time, the article shows (Tables 3 and 4) that an insufficient high dynamic range upper limit can, unfortunately, in some cases result in a failure to demonstrate an exceedance of the noise parameter value related to the energy properties of the signal ($L_{EX,8h}$). This poses a potential problem when evaluating noise in a workplace where impulse noise is present. Moreover, this problem is potentially very significant because practically all sound level meters that have type approval, i.e., can be used to evaluate noise parameters in the workplace, have a high dynamic range upper limit close to about 140 dB. Fortunately, however, this evaluation also includes peak signal values. In every situation where a noise assessment due to the $L_{EX,8h}$ parameter failed, the exceedance was shown by the L_{Cpeak} parameter. Thus, in the end, although standard sound level meters are characterized by a high dynamic range upper limit of about 140 dB and will not always allow to obtain numerical data characterizing noise, their use can be conditionally accepted in practice. This acceptance is possible when there is sufficient information about the exceedance of any of the assessed noise parameters. The situation is different in the case of the selection of hearing protectors. The selection of a hearing protector that properly protects hearing requires the determination of the value of noise parameters. At the same time, the proper selection of a hearing protector means, on the one hand, verifying that it sufficiently reduces noise in terms of hearing protection, and on the other means avoiding overprotection due to the provision of safe working conditions. This is primarily about being able to hear certain important sounds, such as auditory danger signals. In a situation where data are needed to carry out the selection of hearing protectors, noise parameters should be measured using measuring equipment suitable for testing noise at high sound pressure levels. Manufacturers of measurement equipment offer measurement microphones suitable for this purpose, which can be part of specialized measurement systems or can be used in place of standard microphones with which sound level meters are equipped.

6. Conclusions

The study presents the effects of the use of sound level meters to measure the parameters of impulse noise in a situation where the dynamic range upper limit of equipment was not large enough in relation to the parameters of characterized noise. The analysis was carried out on the example of noise generated during shots from the Mossberg smooth-bore shotgun and AKM rifle, as well as produced in the forge. The use of the sound level meter to assess the hazard of impulse noise, despite erroneous measurement results, allowed to indicate the exceeding of the exposure limit value of the parameter related to the instantaneous signal properties (L_{Cpeak}). The situation was different in the case of the parameter reflecting the energy properties of the signal, i.e., $L_{EX,8h}$. The use of a sound level meter in the case of impulse noise led, in part of the cases, to the result that the exposure limit value of this parameter was not exceeded, where it was actually exceeded. Consequently, the results of the article indicate that the provision of Directive 2003/10/EC [1], stating that the measurement equipment used to assess the noise hazard must make it possible to determine the fact that the limit values for noise parameters have been exceeded, may not be met when the properties of impulse noise are characterized. Fortunately, noise assessment in the workplace takes into account both the parameter reflecting the energy properties of the signal ($L_{EX,8h}$) and the parameter related to the instantaneous signal properties (L_{Cpeak}). This helps to prevent lack of recognition of the presence of a noise hazard for hearing.

While the inadequate properties of the measuring equipment will generally not prevent the general conclusion that noise in a particular workplace is hazardous to hearing, the results of measurements obtained with this equipment cannot be used to select hearing protectors. The selection of earmuffs to be used in the presence of impulse noise, due to the parameter reflecting the signal energy properties (L'_{Aeq}), using measurement data obtained with a sound level meter with an insufficient dynamic range upper limit, may result in an incorrect assessment in about 20–40% of the earmuffs.

The conclusions of the analyses carried out therefore show that the use of a standard sound level meter for impulse noise assessment in a workplace with relatively high sound pressure levels is only conditionally acceptable. However, obtaining data for the selection of hearing protectors requires the use of equipment with a sufficiently large upper limit of the measuring range. Improper measurements not only can lead to an incorrect results, but also can result in inadequate hearing protection for employees forced to use hearing protectors.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Evaluation of Exposure to Impulse Noise at Personnel Occupied Areas During Military Field Exercises

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The tests reported in this paper were carried out to evaluate the exposure of soldiers to noise at operator and control positions during military field exercises. The tests were conducted during firing from a T-72 tank, a BWP-1 Infantry Fighting Vehicle, antitank guided missiles, a ZU-23-2K anti-aircraft gun, and a 2S1 GOZDZIK howitzer. The evaluation of noise exposure showed that the limit values of sound pressure level, referred to by both Polish occupational noise protection standards and the Pfander and Dancer hearing damage risk criteria developed for military applications, were repeatedly exceeded at the tested positions. Despite of the use of tank crew headgear, the exposure limit values of sound pressure level were exceeded for the crew members of the T-72 tank, the BWP-1 infantry fighting vehicle, and the 2S1 GOZDZIK howitzer. The results show that exposure of soldiers to noise during military field exercises is a potentially high hearing risk factor.

Keywords: impulse noise; noise exposure; hearing damage risk criteria; weapon.

1. Introduction

Impulse noise stands out from all other sounds reaching humans in being especially hazardous to hearing. The consequences of human exposure to acoustic impulses may be instantaneously destructive even as a consequence of short exposure (Mrena *et al.*, 2004). Impulsive noise associated with firing weapons is a significant hazard due to high levels of acoustic impulses. Data from the Otolaryngology Clinic at the Military Institute of Medicine in Warsaw where, in 2013, due to acute acoustic trauma emerged after firing weapons, 27 soldiers were hospitalised is an example demonstrating the scale of the danger posed by impulse noise. Each one of the 27 patients suffered a sudden noise induced hearing loss which emerged during firing, with a characteristic hearing impairment seen as a noise notch occurring at 4 kHz. Each patient was subjected to multidirectional treatment which included hyperbaric chamber treatment, steroid treatment (Corhydron, Encorton, or Dexaven), and vascular treatment (Adavin, Nootropil, Cocarboxylaza, Nivalin). The treatment resulted in a hearing improvement for only 17 patients from the group, whereas 11 patients still suffered from tinnitus. These data confirm that impulse noise is a practically high hearing risk factor. Thus, situations in which hearing may be at risk should be recognised. Impulse noise specification and evaluation of exposure to this noise are issues which have been receiving attention for decades (Buck, 2009). The evaluation is strictly related to the necessity of determining impulse noise parameters and their subsequent comparison with the exposure limit values. Parameters related to a signal level may be used to evaluate exposure to impulse noise, as, for example, in a work environment assessment (Directive 2003/10/EC, 2003; National Institute for Occupational Safety and Health [NIOSH], 1998; Occupational Safety and Health Administration [OSHA], 1992). Polish occupational noise protection standards are in force by Minister of Labour and Social Policy Regulation (2014). Soldiers in Poland, in the conditions of military field exercises, are covered by these standards.

The most similar to these regulations is the French hearing damage risk criterion developed for military applications (Dancer, Franke, 1995). Both amplitude parameters related to the signal level and time parameters taking into account impulse duration may also be employed in evaluation of exposure to impulse noise (Buck, 2009). This approach is used in the USA, Dutch, and German hearing damage risk criteria developed for the army (Ward, 1968; Smoorenburg, 1982; Pfander, 1994) on the basis of observations of a temporary threshold shift in soldiers exposed to impulse noise. The amplitude and time characteristics of impulse noise are significant when considering hazards posed by it (Lwow *et al.*, 2011). A special type of approach to the evaluation of effects of exposure to impulses on humans is auditory hazard assessment algorithm for the human (AHAAH) which is the subject of the USA MIL standard (Amrein, 2015). This algorithm is based on an electro-acoustic ear model, where an impulse noise waveform is used as input data characterising impulse noise (Price, 2012). In the event of exposure to impulse noise, possibilities for reducing the influence of the noise on hearing using hearing protectors are also considered (Buck, 2009; Lenzuni, 2012; Młyński, Kozłowski, 2013). There are many works which include measurement results for impulse noise generated by specific sources, e.g. pistols or rifles (Lwow *et al.*, 2011; Lenzuni, 2012). In contrast to these works, the purpose of this study is not to characterise impulse noise sources but to evaluate exposure of soldiers at operator positions during training area exercises and soldiers present during the exercises at control (including observer, paramedic, etc.) positions located at some distance from the operator positions to impulse noise.

2. Methods

2.1. Subject of testing

The evaluation of exposure of soldiers to noise during field exercises was carried out in four areas. The first of the areas was a tank shooting range where noise was produced during firing from a T-72 tank. The second area was intended for exercises with the participation of infantry. Operations in area 2 consisting of firing from a BWP-1 infantry fighting vehicle (73 mm gun and PPK MALUTKA anti-tank guided missile), a PPK SPIKE anti-tank guided missile, a shoulder-launched anti-tank rocket-propelled grenade launcher and machine guns. The third area was the place of artillery exercises where 23 mm ZU-23-2K anti-aircraft guns were used. The last area was reserved for the howitzer (122 mm 2S1 GOZDZIK self-propelled howitzer) crews. The special feature of the exercises in the first area was that main noise sources moved around the area. In other areas (2, 3, and 4) main noise sources were placed in fixed locations. Measurements in four areas of exercises were carried out in similar weather conditions in the absence of precipitation at positive temperatures.

The evaluation consisted in measurements of the parameters of noise present at selected operator positions and control positions located in the exercise area. The individual positions included in the evaluation of exposure to noise, taking into account the type of weapon producing acoustic impulses at those positions as well as the distance between the positions and noise sources, are presented in Table 1. A distance

Table 1. Specification of operator and control positions included in the noise exposure evaluation.

Area	Position	Type of weapon	Distance from position to noise source [m]
1	Tank shooting-range controller – observation tower	T-72 tank	150–2050
	Shooting controller – observation tower		150–2050
	Axis observers – observation tower		150–2050
	Tank crew (under headgear)		0
2	BWP-1 crew (under headgear)	73 mm BWP-1 gun	0
	BWP-1 crew (under headgear)	PPK MALUTKA	0
	PPK SPIKE operators	PPK SPIKE	0
	Paramedic	73 mm BWP-1 gun and RGP	65
		PPK MALUTKA	70
	Observers – observation tower	73 mm BWP-1 gun and RGP	70
		PPK MALUTKA	100
	Artillery observers	73 mm BWP-1 gun and RGP	45
		PPK MALUTKA	55
3	Gun crew	23 mm ZU-23-2K anti-aircraft gun	0
	Gun crew fire control		7
	Truck driver		3
	Observers – observation tower		300
4	Howitzer crew (under headgear)	122 mm 2S1 GOZDZIK self-propelled howitzer	0
	Howitzer crew fire control		55

PPK – anti-tank guided missile, BWP – infantry fighting vehicle, RGP – shoulder-launched anti-tank rocket-propelled grenade launcher.

from position to noise source of 0 m is synonymous with the consideration of the operator position. Otherwise (distance other than 0 m) the control position is considered. The applied measurement method took into consideration the use of tank crew headgear by measuring the noise parameters using a miniature microphone placed in a soldier's ear. As it was mentioned earlier, during the measurements in area 1, the exercises entailed tanks performing incursions along axes whilst firing at targets. For measurements in areas 2, 3, and 4 individual noise sources were immobile, set at operator positions. Figure 1 shows the site plan of the area 1 during T-72 tank shooting exercises. Measurements in the observation tower were made in the shooting controller, the tank shooting-range controller rooms and at the location where axis observers were present.

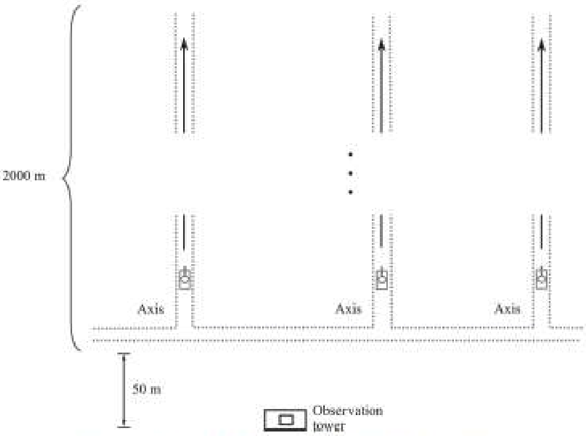

Fig. 1. Site plan of the area 1 during T-72 tank firing.

The arrangement of measurement points in area 2 is shown in Fig. 2. Point "1" indicates the location of BWP-1 when the 73 mm gun firing measurements were taken. The measurement was made using a miniature microphone under the headgear of a soldier inside the vehicle. Point "2" corresponds to the location of the vehicle during PPK MALUTKA firing. This measurement was also taken under the headgear of a soldier. Point "3" corresponds to the location of PPK SPIKE. Measurements at point "4" – taken on the observer tower, those at point "5" registered by the ambulance, and those at point "6" – in the artillery observer position, were repeated twice, i.e. during firing from the gun placed on BWP-1 (where PPK SPIKE, RGP, and machine guns were also fired) and during firing from PPK MALUTKA.

Figure 3 shows the plan of area 3 which was the site for ZU-23-2K anti-aircraft guns firing. The noise parameters measurements were taken at the gun operating position (point "1"), at the gun crew fire control position (point "2"), inside the cabin of the truck on which one of the guns was located (point "3"), and on the observation tower (point "4"). Figure 4 shows the site plan of area 4 during 2S1 GOZDZIK howitzer firing taking into consideration howitzer arrangement and measurement points: "1" – a measurement inside the howitzer (under headgear), "2" – a firing station.

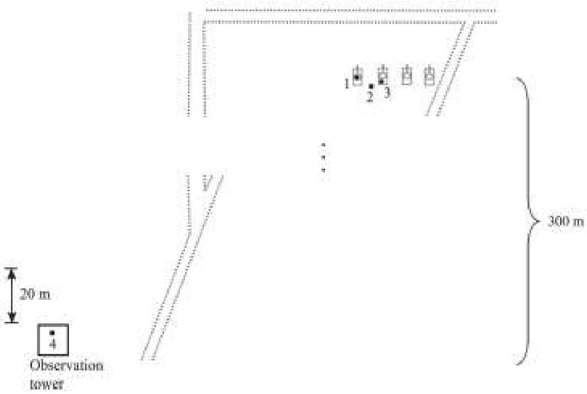

Fig. 3. Site plan of the area 3 during ZU-23-2K anti-aircraft gun firing.

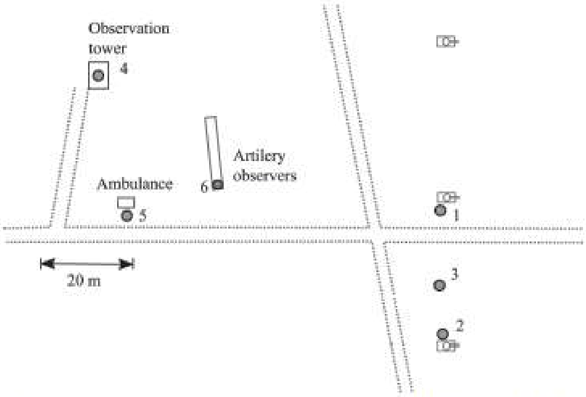

Fig. 2. Site plan of the area 2 during BWP-1 and PPK SPIKE firing.

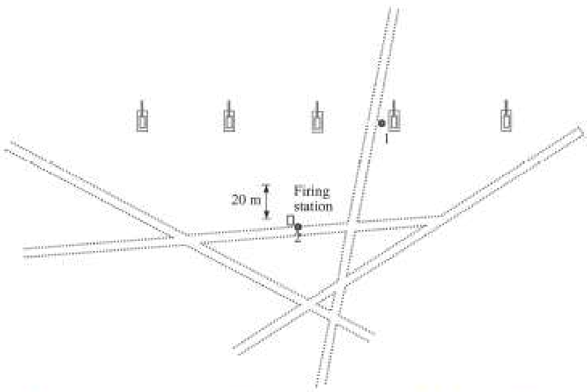

Fig. 4. Site plan of the area 4 during 2S1 GOZDZIK howitzer firing.

2.2. Evaluation of exposure to noise method

The evaluation of exposure to noise was made in accordance with Polish occupational noise protection standards (Minister of Labor and Social Policy Regulation, 2014) and two hearing damage risk criteria developed for the army: Pfander criterion (Pfander, 1994) and Dancer criterion (Dancer, Franke, 1995). When the parameters of noise exceed a limit specified by three above mentioned criteria, it is tantamount to exposure to noise and is a potentially high hearing risk factor.

In accordance with the Minister of Labor and Social Policy Regulation (2014), the following three parameters are taken into account in the evaluation of exposure to noise: the C-weighted peak sound pressure level (L_{Cpeak}), the A-weighted maximum sound pressure level ($L_{\mathrm{A\,max}}$), and the daily noise exposure level ($L_{\mathrm{EX,\,8h}}$). The daily noise exposure level $L_{\mathrm{EX,\,8h}}$ is calculated from the A-weighted equivalent sound pressure level (L_{Aeq}) and the exposure duration. The daily noise exposure level $L_{\mathrm{EX,\,8h}}$ should not exceed 85 dB, the C-weighted peak sound pressure level (L_{Cpeak}) – 135 dB, and the A-weighted maximum sound pressure level ($L_{\mathrm{A\,max}}$) – 115 dB.

As it was mentioned in the Introduction, Dancer hearing damage risk criterion (Dancer, Franke, 1995) developed for military applications is similar to Polish occupational noise protection standards. In the evaluation of exposure to noise made in accordance with Dancer criterion two parameters are taken into account. The daily noise exposure level $L_{\mathrm{EX,\,8h}}$ should not exceed the same value that is specified in the case of Polish occupational noise protection standards, e.g. 85 dB. At the same time, unprotected exposure to impulses above 140 dB peak sound pressure level is not allowed, and the use of hearing protectors is then required (Dancer *et al.*, 1999).

The evaluation of exposure to noise methods presented above only cover an analysis of parameters related to the signal level, whereas the Pfander hearing damage risk criterion (Pfander, 1994) uses amplitude parameter (the peak sound pressure level, L_{peak}) and a time parameter (the impulse duration expressed as the C-duration). The C-duration is a sum of all time intervals in which the impulse noise waveform exceeds −10 dB relative to the maximum absolute value. The evaluation of exposure to impulse noise carried out in accordance with the Pfander criterion requires checking (with the use of graphical method) whether an impulse of a specific sound pressure level and C-duration is below or above a threshold specified by this criterion (line plotted in the graph as a function of the peak sound pressure level and C-duration). When the data point on the graph representing the impulse is below the criterion line then it can be considered as not potentially dangerous for hearing. Otherwise it means that the impulse poses a hearing damage risk.

The A-weighted equivalent sound pressure level was measured for the duration of the firing exercises for each type of weapon. The number of firings for measuring L_{Cpeak}, $L_{\mathrm{A\,max}}$, L_{peak}, and C-duration depended on the conditions present during the military field exercises and was between one and seven.

2.3. Measurement equipment

The measurements of the parameters of noise present at the operator positions were taken using a Brüel & Kjær PULSE measurement system and a Svantek SVAN 948 sound level meter. The Brüel & Kjær PULSE measurement system consisted of a microphone with a measuring range of up to 184 dB (Brüel & Kjær 4941), a Brüel & Kjær 2669 microphone preamplifier, and a Brüel & Kjær PULSE 3560 C measurement unit operated by Brüel & Kjær LabShop software installed on a portable computer. This measurement unit was used to acquire the measurement data. The acoustic impulse waveforms were recorded using a Brüel & Kjær 7701 Pulse Data Recorder software. The SVAN 948 sound level meter was equipped with a Svantek SV22 measurement microphone and a Svantek SV 12L microphone preamplifier or a Knowles BL1785 miniature microphone used for measurements under crew headgear. For measurements using the Svantek sound level meter, evaluation was carried out in compliance with Polish occupational noise protection standards, based on L_{Cpeak}, $L_{\mathrm{A\,max}}$, and L_{Aeq} parameter value measurements. The measurements taken using a measurement system based on a Brüel & Kjær PULSE system allowed the same evaluation as for sound level meter and in accordance with the Pfander and Dancer hearing damage risk criteria.

3. Test results

3.1. Evaluation of noise exposure according to the Polish occupational noise protection standards

Tables 2–6 present the measurement results for the C-weighted peak sound pressure level (L_{Cpeak}), the A-weighted maximum sound pressure level ($L_{\mathrm{A\,max}}$), the equivalent sound pressure level A (L_{Aeq}), and the calculated values of the daily noise exposure level ($L_{\mathrm{EX,\,8h}}$) during military field exercises at the operator and control positions depicted in Table 1. The results presented in Table 2 relate to measurements carried out in area 1, i.e. tank shooting range. The results of the tests obtained during exercises with the participation of infantry in area 2 are shown in Tables 3 (operator positions) and 4 (control positions). Tables 5 and 6 contain the results obtained during the tests in areas 3

Table 2. Noise parameter values measured in area 1 (tank shooting range).

Position	Measurement No.	L_{Cpeak} [dB]	$L_{\mathrm{A\,max}}$ [dB]	L_{Aeq} [dB]	$L_{\mathrm{EX,8h}}$ [dB]
Tank shooting-range controller – observation tower	1	120.4	89.1		
	2	123.2	91.2		
	3	122.9	92.3		
	4	120.7	86.9		
	1–4			78.6	75.6
Shooting controller – observation tower	1	117.9	84.5		
	2	117.1	84.0		
	3	119.0	84.2		
	4	116.8	82.4		
	1–4			77.0	74.0
Axis observers – observation tower	1	140.7	109.3		
	2	142.5	114.0		
	3	124.1	88.8		
	4	103.8	78.1		
	1–4			97.5	94.4
Tank crew (under headgear)	1	≥ 143.4	118.3		
	2	≥ 141.7	115.3		
	3	≥ 142.1	112.8		
	4	≥ 143.2	114.4		
	1–4			99.5	91.5

The symbol "≥" indicates that the upper measuring range limit of the sound level meter microphone has been reached.

Table 3. Noise parameter values measured in area 2 at operator positions (exercises with the participation of infantry).

Position	Measurement No.	L_{Cpeak} [dB]	$L_{\mathrm{A\,max}}$ [dB]	L_{Aeq} [dB]	$L_{\mathrm{EX,8h}}$ [dB]
BWP-1 crew (under headgear) 73 mm gun on BWP-1	1	≥ 143.9	114.3		
	2	≥ 144.2	113.9		
	3	≥ 144.8	113.5		
	4	≥ 144.4	112.9		
	5	≥ 144.1	113.2		
	6	≥ 144.6	114.2		
	7	≥ 144.4	113.3		
	1–7			95.5	86.5
BWP-1 crew (under headgear) PPK MALUTKA	1	133.6	117.3		
	2	134.4	117.4		
	3	132.9	117.4		
	1–3			101.4	94.1
PPK SPIKE operators	1	160.7	128.7	94.5	85.5

The symbol "≥" indicates that the upper measuring range limit of the sound level meter microphone has been reached; PPK – anti-tank guided missile; BWP – infantry fighting vehicle.

and 4, that is, during artillery exercises and firing from the howitzer, respectively.

As it was mentioned in Subsec. 2.2, calculating the daily noise exposure level $L_{\mathrm{EX,8h}}$ requires information about the exposure duration. In the case of field exercises in area 1 for the T-72 tank, exposure level was determined under an assumption that the exposure duration at all positions located outside the tank was

Table 4. Noise parameter values measured in area 2 at control positions other than operator positions (exercises with the participation of infantry).

Measurement location	Noise source	L_{Cpeak} [dB]	$L_{\text{A max}}$ [dB]	L_{Aeq} [dB]	$L_{\text{EX, 8h}}$ [dB]
Paramedic	BWP-1 gun and RGP	139.2	99.5	84.0	
	PPK MALUTKA	111.1	87.0	67.5	
	BWP-1 gun and RGP + PPK MALUTKA				78.0
Observers – observation tower	BWP-1 gun and RGP	138.4	97.9	83.4	
	PPK MALUTKA	110.8	85.2	67.1	
	BWP-1 gun and RGP + PPK MALUTKA				77.4
Artillery observers	BWP-1 gun and RGP	141.2	104.4	88.5	
	PPK MALUTKA	113.4	93.8	73.2	
	BWP-1 gun and RGP + PPK MALUTKA				82.5

PPK – anti-tank guided missile, BWP – infantry fighting vehicle, RGP – shoulder-launched anti-tank rocket-propelled grenade launcher.

Table 5. Noise parameter values measured in area 3 (artillery exercises during ZU-23-2K gun firing).

Position	Measurement No.	L_{Cpeak} [dB]	$L_{\text{A max}}$ [dB]	L_{Aeq} [dB]	$L_{\text{EX, 8h}}$ [dB]
Gun crew	1	156.3	128.8		
	2	158.3	128.3		
	3	153.0	121.3		
	1–3			110.7	104.7
Gun crew fire control	1	160.1	129.8		
	2	162.8	130.7		
	3	154.9	123.3		
	1–3			113.0	107.0
Truck driver	1	151.1	119.7		
	2	148.0	117.5		
	3	149.3	113.6		
	1–3			100.9	94.9
Observers – observation tower	1	125.1	91.4	80.7	74.7

Table 6. Noise parameter values measured in area 4 (howitzer firing exercises).

Measurement location	Measurement No.	L_{Cpeak} [dB]	$L_{\text{A max}}$ [dB]	L_{Aeq} [dB]	$L_{\text{EX, 8h}}$ [dB]
Howitzer crew (under headgear)	1	≥ 141.2	110.5		
	2	≥ 143.8	112.5		
	1–2			86.5	80.5
Howitzer crew fire control	1	140.5	105.4	84.5	78.5

The symbol "≥" indicates that the upper measuring range limit of the sound level meter microphone has been reached.

4 hours. The exposure duration for tank crew was determined in a different way because crews changed during the exercises. Hence, the $L_{\text{EX, 8h}}$ under tank crew headgear (at the entrance to the ear canal) was calculated under an assumption that one soldier took part in 3 incursions during which a total of 15 shots were fired. For the BWP-1 crew (field exercises in area 2), the $L_{\text{EX, 8h}}$ was determined with an assumed exposure duration of 1 hour (73 mm gun firing) or 1.5 hours (PPK MALUTKA firing). However, for the control positions situated in locations marked with "4", "5", and "6" in Fig. 2 located at some distance from the BWP-1 and PPK SPIKE operator positions, the $L_{\text{EX, 8h}}$ was determined with an assumed exposure duration of 3.5 hours in total. It was assumed that the exposure duration for the PPK SPIKE operating crew was 1 hour. In

the case of field exercises in area 3 the $L_{\mathrm{EX,8h}}$ related to the ZU-23-2K gun crew was determined with an assumed exposure duration of 2 hours. The same exposure duration (2 hours) was assumed for the GOZDZIK self-propelled howitzer field exercises (area 4).

The results presented in Tables 2–6 show high levels of L_{Cpeak}, $L_{\mathrm{A\,max}}$, and L_{Aeq} occurring during the military field exercises at both the operator positions and control positions located at some distance from the operator positions. For crews of the fighting vehicles (T-72 tank, BWP-1 and GOZDZIK howitzer), despite wearing tank crew headgear, the value of L_{Cpeak} exceeded 143 dB. However, the fact that the L_{Cpeak} values measured under headgear using a miniature microphone, presented in Tables 2, 3, and 6 are underestimated because the upper measuring range limit of the sound level meter microphone has been reached should not be overlooked. For the fighting vehicle crews, high values were also recorded for $L_{\mathrm{A\,max}}$ and L_{Aeq} parameters, which, respectively, remained within the 110.5–118.3 dB and 86.5–101.4 dB ranges. Even higher values of the noise parameters were recorded at PPK SPIKE and ZU-23-2K guns operator positions, for which L_{Cpeak} and $L_{\mathrm{A\,max}}$ values reached or exceeded 160 and 130 dB, respectively. Despite being at a certain distance from the operator positions and at control positions, L_{Cpeak} and $L_{\mathrm{A\,max}}$ values exceeding 140 and 95 dB were recorded (axis observers for tank firing and paramedic and observers during BWP-1 gun and RGP firing). However, lower values of the noise parameters ($L_{\mathrm{Cpeak}} < 125$ dB, $L_{\mathrm{A\,max}} < 93$ and $L_{\mathrm{Aeq}} < 76$ dB) were recorded at the tank shooting-range controller and the shooting controller (T-72 tank) positions as well as the observers on the tower (ZU-23-2K).

The presented test results show that the limit values of the C-weighted peak sound pressure level (L_{Cpeak}), the A-weighted maximum sound pressure level ($L_{\mathrm{A\,max}}$), and the daily noise exposure level ($L_{\mathrm{EX,8h}}$) were exceeded for the following positions: T-72 crew, PPK SPIKE operators, ZU-23-2K gun crew, ZU-23-2K gun crew fire control, and the truck driver. For the BWP-1 crew, the $L_{\mathrm{EX,8h}}$ limit value is exceeded during both gun fire and PPK MALUTKA firing. In addition, for the crew, the L_{Cpeak} allowable value is exceeded during gun fire, whereas $L_{\mathrm{A\,max}}$ limit value is exceeded during PPK MALUTKA firing. Also for the GOZDZIK howitzer crew, the exposure to noise results in the L_{Cpeak} limit value is exceeded.

The soldiers located at a certain distance from the operator positions may also be exposed to high C-weighted peak sound pressure levels exceeding the limit value. This pertains to the axis observers during T-72 tank firing, the observers and the paramedics within the range of the noise generated during BWP-1 gun and RGP firing, as well as the howitzer GOZDZIK crew fire control. The people inside the observation tower (tank shooting range), i.e., the shooting range controller and the shooting controller, were not exposed to noise exceeding the limit values because, unlike the other personnel members, they were inside the building and their exposure to the noise was limited.

3.2. Evaluation of noise exposure according to the Pfander criterion

In evaluating the exposure to impulse noise in accordance with the Pfander hearing damage risk criterion, the values of L_{peak} and C-duration for individual impulses were used to present the measurement results on a graph (Fig. 5) with the criterion line plotted. Examples of waveforms used to obtain its parameters are shown in Figs. 6–8. As it was mentioned in Subsec. 2.2, if a data point (Fig. 5) is located above the criterion line, it means that the noise characterised by the parameters constituting the coordinates of this point poses a hearing damage risk. An analysis of the measurement results with reference to the Pfander hearing damage risk criterion demonstrated that the noise parameter values at the axis observer position during T-72 tank firing, the PPK SPIKE operation and the gun crew fire control position, and inside the truck during ZU-23-2K gun firing already exceeded those allowed by the Pfander criterion upon exposure to just one firing. Exposure to two shots results in the Pfander criterion for the ZU-23-2K gun crew being exceeded as well. Multiplying the number of firings means an increase of the impulse effective duration, hence a shift to the right on the figure showing the criterion. Keeping in mind that the exposure to only one or two shots

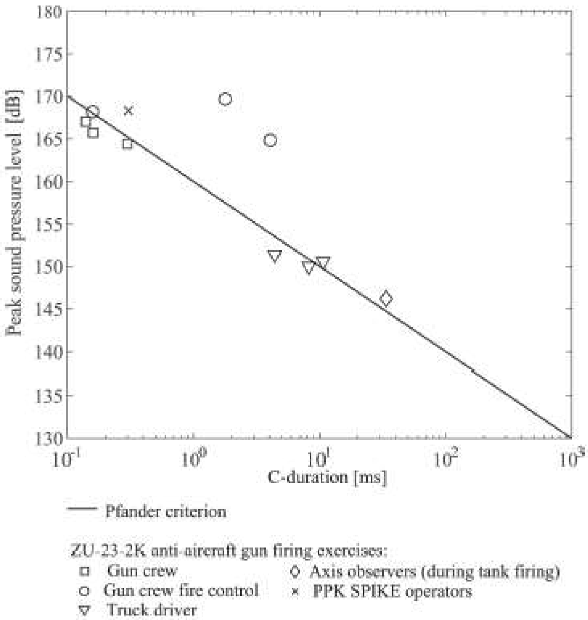

Fig. 5. Parameters of the impulses measured during the exercises. The parameters of impulses were determined assuming exposure to just one firing.

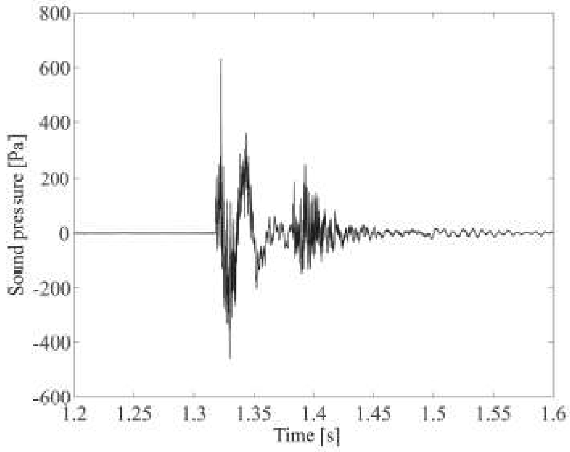

Fig. 6. Waveform of the sound pressure recorded inside the truck during ZU-23-2K gun firing.

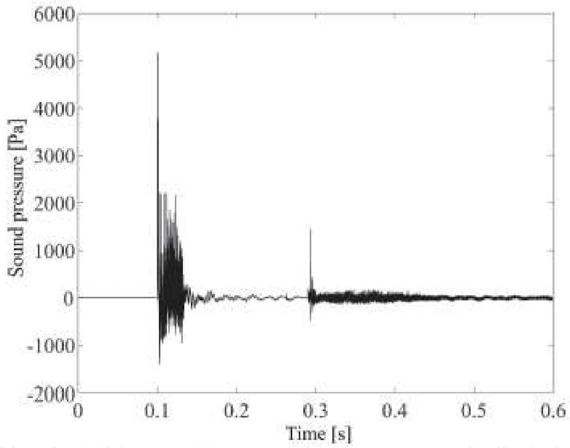

Fig. 7. Waveform of the sound pressure recorded during PPK SPIKE (anti-tank guided missile) firing.

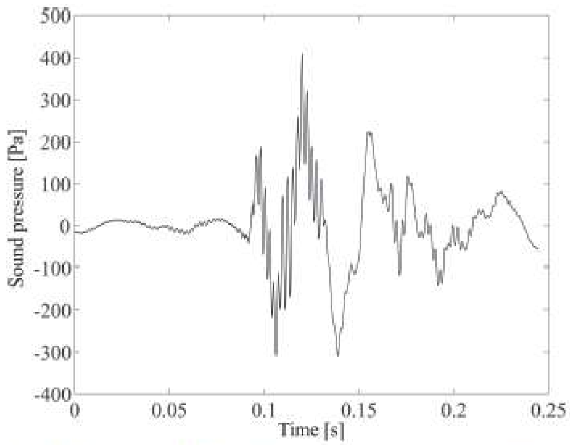

Fig. 8. Waveform of the sound pressure recorded at the axis observer position during T-72 tank firing.

during military field exercises is improbable, the total duration of exposure to impulses generated during the exercises will result in exceeding the criterion line to a much greater extent than that presented in Fig. 5.

When comparing the results of the evaluation of exposure to noise carried out in accordance with Polish occupational noise protection standards and in accordance with the Pfander hearing damage risk criterion, their compatibility should be stated. In five positions for which the occupational and the Pfander criterion could be compared, they indicated that the exposure limit values were exceeded. In the case of the Pfander criterion, the assessment for the comparison was carried out assuming the exposure for at least two shots.

3.3. *Evaluation of noise exposure according to the Dancer criterion*

As it was mentioned in Subsec. 2.2, the evaluation of exposure to noise made in accordance with Dancer criterion requires to take into account two $L_{\mathrm{EX,\,8h}}$ and L_{peak} parameters. Due to the availability of measurement data, the same cases that were included in Subsec. 3.2 were analysed in the evaluation carried out in accordance with Dancer criterion. The values of L_{peak} are the same as presented in Fig. 5 (Subsec. 3.2), while the values of $L_{\mathrm{EX,\,8h}}$ were included in Tables 2, 3, and 5 in Subsec. 3.1. In all analysed cases, the values of $L_{\mathrm{EX,\,8h}}$ parameter exceeded 85 dB. Thus, impulse noise present in all analysed positions (axis observers – observation tower in area 1; PPK SPIKE operators in area 2; gun crew, gun crew fire control, and truck driver in area 3) should be considered potentially dangerous to hearing. It should be noted that when the limit value of 85 dB is exceeded, the evaluation of exposure to noise made in accordance with Dancer criterion must coincide with the evaluation carried out in accordance with the Polish occupational noise protection standards. In the opposite situation (no limit value exceeded) in the case of the Polish criterion, the values of the L_{Cpeak} and $L_{\mathrm{A\,max}}$ parameters will be decisive.

With the use of the Dancer Criterion the assessment according to the value of the L_{peak} parameter is also related to. It has a significant meaning when the limit value (85 dB) of the $L_{\mathrm{EX,\,8h}}$ parameter is not exceeded. Then the L_{peak} value exceeding 140 dB means that hearing protectors should be used. The L_{peak} value exceeded 140 dB in 12 out of 14 cases considered in the analysis. Nevertheless, the earlier analysis of the $L_{\mathrm{EX,\,8h}}$ value showed the risk of hearing damage.

4. Conclusions

The performed tests of impulse noise reaching the operator and control positions during analysed military field exercises, showed numerous situations when the limit values at the tested positions were exceeded, with respect to both the Polish occupational noise protection standards and developed for the army Pfander and Dancer hearing damage risk criteria. Moreover, the tests demonstrated that the crews of the T-72 tank, BWP-1 infantry fighting vehicle, and 2S1 GOZDZIK howitzer, despite wearing hearing protection (crew headgear) when firing from the weapons of these vehicles, were exposed to noise exceeding the exposure limit values. This stems from the fact that the crew headgear does not attenuate the noise generated by the weapons and engines of the vehicles sufficiently. The determined occurrence of very high noise levels makes it necessary for the soldiers to wear hearing protector devices. For positions where verbal communication is required, hearing protectors equipped with electronic systems to improve speech sound transmission may be used.

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Assessment of Impulse Noise Hazard and the Use of Hearing Protection Devices in Workplaces where Forging Hammers are Used

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The impulse noise is agent harmful to health not only in the case of shots from firearms and the explosions of explosive materials. This kind of noise is also present in many workplaces in the industry. The paper presents the results of noise parameters measurements in workplaces where four different die forging hammers were used. The measured values of the *C*-weighted peak sound pressure level, the *A*-weighted maximum sound pressure level and *A*-weighted noise exposure level normalized to an 8 h working day (daily noise exposure level) exceeded the exposure limit values. For example, the highest measured value of the *C*-weighted peak sound pressure level was 148.9 dB. In this study possibility of the protection of hearing with the use of earplugs or earmuffs was assessed. The measurement method for the measurements of noise parameters under hearing protection devices using an acoustical test fixture instead of testing with the participation of subjects was used. The results of these measurements allows for assessment which of two tested earplugs and two tested earmuffs sufficiently protect hearing of workers in workplaces where forging hammers are used.

Keywords: impulse noise, noise attenuation, hearing protection device, die forging hammer.

1. Introduction

Impulse noise poses a risk for hearing both in the case of gunshots and explosions and in the case of many workplaces related to metalworking. Among the machines used at such workplaces, the highest values of *C*-weighted peak sound pressure level ($L_{C\text{peak}}$) of impulse noise are generated by die forging hammers in forges – they can reach 147 dB (Młyński *et al.*, 2012). Peak sound pressure level (L_{peak}) of impulse noise generated in the forging process can produce values in the 120–140 dB range with occasional occurrences of values in the 150–160 dB range (Taylor *et al.*, 1984).

Issues related to the characterization of noise produced by hammers, the assessment of the risk posed by noise generated during forging, and hearing protection against this kind of noise have been dealt with over the years (Młyński *et al.*, 2012; Taylor *et al.*, 1984; Sulkowski, Lipowczan, 1982; Starck *et al.*, 2002; Smeatham, Wheeler, 1998). These works show that impulse noise generated by hammers presents a risk of hearing loss. Hence, providing hearing protection for people working in forges is essential. The obligation to pay special attention to impulse noise is also imposed on the employer under the provisions of Directive 2003/10/EC (2003). Moreover, longtime exposure to noise, regardless of noise source, may cause i.a hearing loss (Pawlaczyk-Łuszczyńska *et al.*, 2013; Dobrucki *et al.*, 2013).

At high values of *C*-weighted peak sound pressure level (exceeding exposure limit value) produced in a forge, organizational methods of noise reduction are ineffective. The need of operating a hammer manually during the metalworking process makes the use of technical means, such as enclosures, inapplicable. In most cases, the nature of the risk posed by the impulse noise produced by hammers makes it impossible to introduce sound reduction methods other than the application of hearing protection devices. Therefore, the correct selection of hearing protection devices is essential for providing sufficient sound pressure level reduction of the noise reaching the ear.

The objective of this work is to determine the characteristics of noise produced by four different die forging hammers and to assess the associated risk of hearing damage, in accordance with the criterion applied to workplaces (Minister of Economy and Labour, 2005). In addition, the method of determining noise parameter values under hearing protection devices is presented in order to evaluate the degree of noise reduction provided by these devices. The assessment of the suitability of two types of earplugs and two types of earmuffs for hearing protection at the studied workplaces in the forge was carried out on the basis of measurements taken using an acoustic test fixture – a head and torso simulator. The presented method of assessing hearing protection devices makes it possible to avoid exposing subjects to impulse noise characterized by high values of peak sound pressure level.

2. Method

2.1. Measurements and assessment of noise exposure at a workplace

The scope of impulse noise measurements at workplaces in the forge covered the determination of the following noise parameters: the C-weighted peak sound pressure level ($L_{C\text{peak}}$), A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\text{h}}$) (daily noise exposure level) and the A-weighted maximum sound pressure level ($L_{A\max}$). These parameters are required in compliance with the noise exposure assessment criterion applied to workplaces in Poland (Minister of Economy and Labour, 2005). Measurements were performed in accordance with the ISO 9612 standard (2009).

Exposure limit values specified in Polish regulations (Minister of Labour and Social Policy, 2002) were used for the noise exposure assessment. Exposure limit values for specific noise parameters are equal to: $L_{C\text{peak}}$ – 135 dB, $L_{EX,8\text{h}}$ – 85 dB, $L_{A\max}$ – 115 dB.

2.2. Determining sound pressure levels under hearing protection devices

Using hearing protection devices requires making a careful selection in order to ensure a sufficient reduction of sound pressure level of the noise reaching the employee. There are calculation methods for selecting hearing protection devices that allow for the assessment of the A-weighted equivalent sound pressure level (L_{Aeq}) under a hearing protection device (ISO 4869-2, 1994) or enable the estimation of the peak sound pressure level (L_{peak}) under a device – see information Appendix B to the EN 458 standard (2004). However, these methods cannot be used for the determination of any noise parameters. If the exposure limit values of the $L_{C\text{peak}}$ or $L_{A\max}$ parameters are exceeded at a workplace, there is a need of verifying whether the values of these parameters under a hearing protection device are reduced below the level defined in the hearing damage risk criterion. The aforementioned calculation methods do not allow for the determination of the $L_{C\text{peak}}$ and $L_{A\max}$ parameters under hearing protection devices. In addition, their accuracy is limited (Lenzuni *et al.*, 2012; Młyński, Kozłowski, 2013).

In view of the fact that when hearing protection devices are used there is no possibility of calculating noise parameters such as $L_{C\text{peak}}$ and $L_{A\max}$ in a simple way, the assessment of exposure to impulse noise reaching the ears of an employee can be performed by carrying out measurements of the sound pressure level of impulse noise reaching underneath the hearing protection devices. The assessment of the impact of using hearing protection devices by means of measurements must not be performed with human subjects, as the impulse noise sound pressure level produced at workplaces in a forge exceeds exposure limit values. In such a situation, a hearing protection device that provides a potentially insufficient sound reduction for the noise at the workplace would pose a hearing damage risk for the subject participating in the research.

Due to impossibility of carrying out measurements with the participation of subjects, the consequences of using hearing protection devices can only be studied using head and torso simulators (Lenzuni *et al.*, 2012). Nevertheless, such an approach involves certain limitations regarding the precision of the simulation (Berger *et al.*, 2012). Specific corrections can then be applied in order to approximate the results obtained using head and torso simulators – acoustic test fixtures – to the results obtained when hearing protection devices are used by human subjects. Such corrections may include taking into account the occlusion effect, physiological masking and bone conduction (Giguère, Kunov, 1989) and have been applied in the studies of the effectiveness of impulse noise reduction by firearms (Lenzuni *et al.*, 2012), for example. A correction taking into account the influence of bone conduction is also recommended by the ANSI/ASA S12.42-2010 standard (2010).

In the present study, the measurements of noise parameters under hearing protection devices were performed using an acoustic test fixture described in chapter 4. In order to minimize the influence of the limited accuracy of the simulation of human features by the acoustic test fixture used in the study, individual correction frequency response was applied to each of the hearing protection devices under investigation, taking into account overall factors related to the use of hearing protection devices by humans. In order to correct noise time waveforms registered using the acoustic test fixture at workplaces in the forge, sound attenuation values were applied in reference to the noise attenuation values measured using the acoustic test fixture in the laboratory.

The sound attenuation values applied are taken from the data published in the user's manual of the hearing protection device. Sound attenuation is determined based on the threshold of hearing measurements (ISO 4869-1, 1990) and is specified in seven or eight one-third-octave frequency bands of the test signal. The attenuation of the hearing protection devices studied in the present work was measured for the same test signal using the acoustic test fixture.

During the construction phase of correction functions it was assumed that the assumed protection value provided by the studied earplugs and earmuffs would apply to 98% of the population of people using hearing protection devices. This assumption requires taking into consideration the data for sound attenuation of hearing protection devices (included in Table 1) in the form of the difference between mean attenuation and the doubled standard deviation for this attenuation (Voix, Zeidan, 2010; Lenzuni, 2009).

2.3. Assessment of the effectiveness of using hearing protection devices

The measurements of exposure limit values of noise parameters at a workplace (Minister of Labour and Social Policy, 2002) used in the hearing damage risk criterion in accordance with the methodology of carrying out noise measurements at a workplace (ISO 9612, 2009) are performed in the absence of the worker or using a microphone located 10 cm away from the worker's head. In the present study, the measurements of noise parameters reaching underneath hearing protection devices were taken by means of the acoustic test fixture's microphone. It is therefore necessary to make reference between the values measured under the hearing protection device with the acoustic test fixture's microphone and the actual values that would be present at the location of the person exposed to noise.

The sound pressure levels $L_{C\text{peak}}$, $L_{EX,8\,\text{h}}$, $L_{A\,\text{max}}$ measured under the hearing protection device were compared to the levels occurring at the distance of 10 cm from the acoustic test fixture located at the investigated workplace using $\Delta L_{C\text{peak}}$, $\Delta L_{EX,8\,\text{h}}$, $\Delta L_{A\,\text{max}}$ determined in compliance with the relationships (1)–(3):

$$\Delta L_{C\text{peak}} = L_{C\text{peak},\,ATF\_no\_HPD} - L_{C\text{peak},\,10\,\text{cm}}, \quad (1)$$

$$\Delta L_{EX,8\,\text{h}} = L_{EX,8\,\text{h},\,ATF\_no\_HPD} - L_{EX,8\,\text{h},\,10\,\text{cm}}, \quad (2)$$

$$\Delta L_{A\,\text{max}} = L_{A\,\text{max},\,ATF\_no\_HPD} - L_{A\,\text{max},\,10\,\text{cm}}, \quad (3)$$

where: – the index "$_{ATF\_no\_HPD}$" denominates the sound pressure level at the acoustic test fixture's microphone location without a hearing protection device put on the fixture, – the index "$_{10\,\text{cm}}$" denominates the sound pressure level measured using the microphone located 10 cm away from the acoustic test fixture.

The assessment of the values of noise affecting the worker using hearing protection devices, in accordance with the aforementioned assumptions, is performed based on sound pressure levels measured using the acoustic test fixture's microphone under the hearing protection device, corrected in compliance with the sound attenuation data for a given hearing protection device and reduced by the determined $\Delta L_{C\text{peak}}$, $\Delta L_{EX,8\,\text{h}}$ and $\Delta L_{A\,\text{max}}$ values.

The criterion for assessing whether sufficient hearing protection is provided by specific earplugs and earmuffs was taken from the result of the comparison between the determined noise parameters values under hearing protection devices and of a certain limit value. Hearing protection devices are selected correctly when there is no risk of hearing damage (Directive 2003/10/EC, 2003; Minister of Economy and Labour, 2005). Therefore, verification was performed to check whether the determined values of the $L_{C\text{peak}}$ and $L_{A\,\text{max}}$ parameters did not exceed exposure limit values (Minister of Labour and Social Policy, 2002). Then, the hearing protection devices that resulted in reducing the A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\,\text{h}}$) to the value that did not exceed the lower exposure action value were considered sufficient for providing hearing protection at the investigated workplaces. The lower exposure action value is lower by 5 dB from the exposure limit value and equals 80 dB (Directive 2003/10/EC, 2003; Minister of Economy and Labour, 2005). Taking the value of $L_{EX,8\,\text{h}}$ equal 80 dB as a criterion is justified by the fact that below this value there is practically no risk of causing hearing loss (Pawlaczyk-Łuszczyńska, 2010; ISO 1999, 1990).

3. Test object

3.1. Workplaces

Measurements were taken at operator workplaces of four die forging hammers (position: forger): LASCO-400, LASCO-315, MPM 3150 and MPM 1600. Research was also carried out at trimming press or forge rolling machine operator workplaces (position: trimming machine operator) that neighbour the hammer operator workplaces, located approximately 4 m away.

3.2. Hearing protection devices

Two models of popular foam earplugs and two types of popular earmuffs were selected for the study. Of the selected earmuffs, one type was intentionally chosen with small sound attenuation and the other one –with large attenuation. The hearing protection devices chosen for the study are listed in Table 1. The table also specifies the following values of their characteristic parameters, as published in the user information (ISO 4869-2, 1994): sound attenuation, H (high-frequency attenuation value), M (medium-frequency attenuation value), L (low-frequency attenuation value) and SNR (single number rating).

Table 1. Sound attenuation of the investigated earplugs and earmuffs in one-third-octave frequency bands: m_f – mean value, s_f – standard deviation; the values of the SNR, H, M, L parameters characterizing the acoustic properties of the investigated earplugs and earmuffs. Values are given in dB.

Hearing protection device		One-third-octave-band centre frequency [Hz]								SNR	H	M	L
		63	125	250	500	1000	2000	4000	8000				
Earplugs													
Howard Leight MAX (HL MAX)	m_f	34.6	37.1	37.4	38.8	38.2	37.9	47.3	44.8	37	36	35	34
	s_f	3.0	4.5	4.3	3.7	3.5	4.0	3.5	7.2				
3M 1100	m_f	30.0	33.1	36.3	38.4	38.7	39.7	48.3	44.4	37	37	34	31
	s_f	3.9	5.0	7.4	6.2	5.6	4.3	4.5	4.4				
Earmuffs													
Peltor Optime I	m_f		11.6	18.7	27.5	32.9	33.6	36.1	35.8	27	32	25	15
	s_f		4.3	3.6	2.5	2.7	3.4	3.0	3.8				
Peltor Optime III	m_f		17.4	24.7	34.7	41.4	39.3	47.5	42.6	35	40	32	23
	s_f		2.1	2.6	2.0	2.1	1.5	4.5	2.6				

4. Measurement setup

A diagram of the measurement system used in the study is shown in Fig. 1. In order to record the time waveform of the noise sound pressure, a Brüel & Kjær 4135 microphone was used, which has a measurement range of up to 164 dB. The microphone was located 10 cm from the worker's head at the "ear" level.

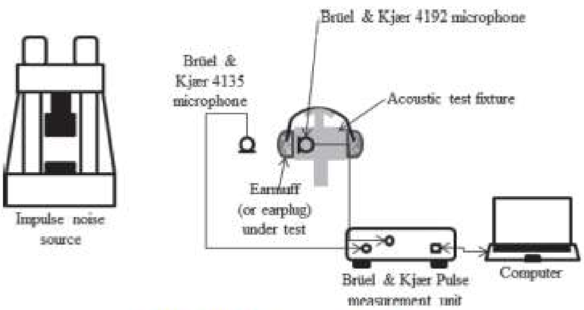

Fig. 1. Diagram of the measurement system.

Measurements under the cups of earmuffs and under earplugs were taken using an acoustic test fixture compliant with the ISO 4869-3 standard (2007). The test fixture is additionally equipped with two coupled chambers with a Brüel & Kjær 4192 measurement microphone. One of the aforementioned chambers – conical tube – simulates the dimensions and geometry of the external ear canal. Its dimensions correspond with the average dimensions of the human external ear canal. The chamber was lined with a layer of an elastic material resembling human skin. The second chamber of the acoustic test fixture serves to imitate the acoustic properties of the middle ear.

5. Results

5.1. Sound pressure level at workplaces

The values of the C-weighted peak sound pressure level ($L_{C\text{peak}}$), the A-weighted maximum sound pressure level ($L_{A\max}$) and the A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\text{h}}$) determined at forgers' and trimming machine operators' workplaces for the four die forging hammers considered in the study are shown in Figs. 2-4. Exposure limit values of the noise parameter considered in each case are also marked in the figures. In order to determine the A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\text{h}}$) it was assumed that the exposure time related to the operation of hammers and at adjacent workplaces equaled to 360 minutes during a workday.

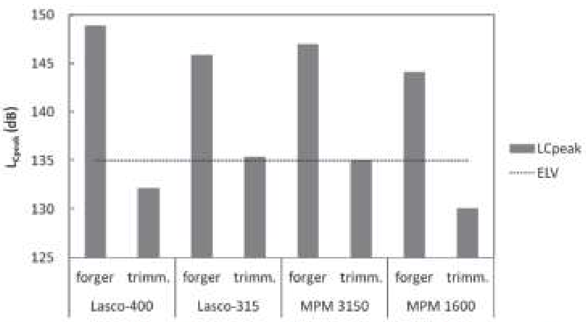

Fig. 2. C-weighted peak sound pressure level ($L_{C\text{peak}}$) determined at workplaces in the forge. ELV – exposure limit value, trimm. – trimming machine operator.

The noise measurements demonstrated that the exposure limit values of the C-weighted peak sound pressure level ($L_{C\text{peak}}$), A-weighted maximum sound pres-

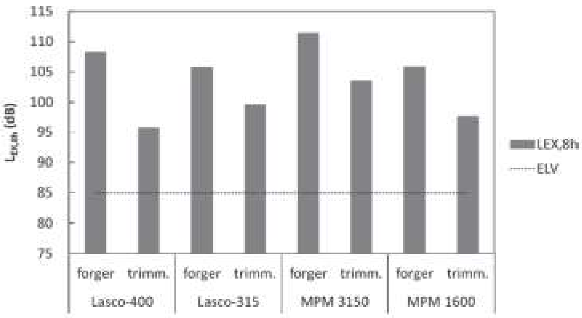

Fig. 3. *A*-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\,h}$) determined at workplaces in the forge. ELV – exposure limit value, trimm. – trimming machine operator.

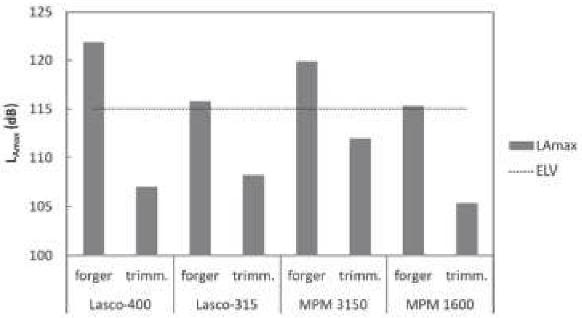

Fig. 4. *A*-weighted maximum sound pressure level ($L_{A\,\max}$) determined at workplaces in the forge. ELV – exposure limit value, trimm. – trimming machine operator.

sure level ($L_{A\max}$) and the *A*-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\,h}$) were exceeded at workplaces of operators (forgers) of all the studied hammers. For workplaces adjacent to the hammer operator workplaces, the exposure limit values of the *A*-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\,h}$) were exceeded for all the studied hammers and the *C*-weighted peak sound pressure level ($L_{C\text{peak}}$) value was exceeded in the case of the Lasco-315 hammer.

5.2. Sound pressure level under hearing protection devices

The results of the determination of parameters of noise to which the workers (forgers and trimming machine operators) are exposed when using hearing protection devices at workplaces in the forge are presented in Figs. 5–7. The assessment criterion values of the noise parameter considered in each case are also marked in the figures. Values shown in Figs. 5–7 are sound pressure levels measured using the acoustic test fixture's microphone under a hearing protection device and corrected in accordance with the methodology described in chapters 2.2 and 2.3. In order to determine the *A*-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\,h}$), similar as in the case of noise measurements at workplaces, it was assumed that the exposure time related to the operation of hammers and at adjacent workplaces equaled to 360 minutes during a workday.

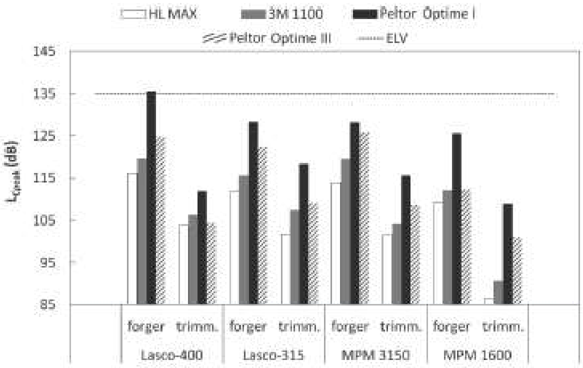

Fig. 5. *C*-weighted peak sound pressure level ($L_{C\text{peak}}$) determined under hearing protection devices used at workplaces in the forge. ELV – exposure limit value, trimm. – trimming machine operator.

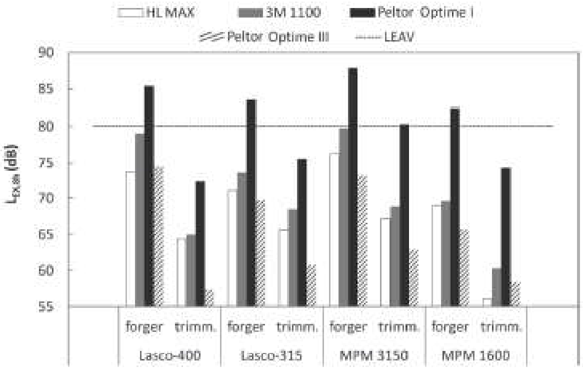

Fig. 6. *A*-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\,h}$) determined under hearing protection devices used at workplaces in the forge. LEAV – lower exposure action value, trimm. – trimming machine operator.

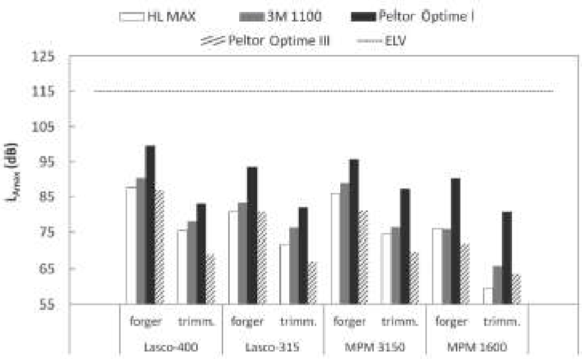

Fig. 7. *A*-weighted maximum sound pressure level ($L_{A\,\max}$) determined under hearing protection devices used at workplaces in the forge. ELV – exposure limit value, trimm. – trimming machine operator.

Earplugs provided the biggest reduction in the value of the C-weighted peak sound pressure level ($L_{C\text{peak}}$), but it shall be noted that this was demonstrated when they were put very deeply (inserted almost completely) into the testing device's chamber that simulated the external ear canal. In practice, achieving a similar level of protection requires good skills for placing the earplugs in the ear in an equally careful way.

In the case of the A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\text{h}}$), the lowest values of this parameter were demonstrated when Peltor Optime III earmuffs were used. Protection proved to be insufficient in the case of Peltor Optime I earmuffs with small sound attenuation.

The lowest values of the A-weighted maximum sound pressure level ($L_{A\max}$), similar as in the case of the $L_{EX,8\text{h}}$ parameter, were determined when Peltor Optime III earmuffs were used, whereas using Peltor Optime I earmuffs resulted in the highest sound pressure levels. However, for the $L_{A\max}$ parameter, the reduction to a value below the exposure limit is achieved by each of the hearing protection devices considered in the study.

The results shown in Figs. 5–7 demonstrated that at all the investigated workplaces in the forge, hearing can be protected by using any of the two studied models of earplugs (Howard Leight MAX, 3M 1100) and the Peltor Optime III earmuffs.

In the case of the Peltor Optime I earmuffs with lower sound attenuation values than for Peltor Optime III, the values assumed as the criterion for the peak sound pressure level $L_{C\text{peak}}$ were exceeded at the workplace of the forger operating the Lasco-400 hammer. Exceeding the criterion value of the A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\text{h}}$), related to the use of Peltor Optime I earmuffs occurred at workplaces of forgers operating all four die forging hammers, as well as the trimming machine operator of the MPM 3150 hammer. Lower attenuation earmuffs (Peltor Optime I) can only be used at workplaces of trimming machine operators close to the Lasco-400, Lasco-315 and MPM 1600 hammers.

6. Summary and conclusions

Using an acoustic test fixture allows for taking measurements of noise parameters under hearing protection devices without exposing human subjects to noise produced at workplaces. Using the measurement method to evaluate the results of using hearing protection devices provided means of assessing noise parameters under hearing protection devices (as it reaches a person's ear), i.e. of the A-weighted noise exposure level normalized to an 8 h working day ($L_{EX,8\text{h}}$), of the C-weighted peak sound pressure level ($L_{C\text{peak}}$) and of the A-weighted maximum sound pressure level ($L_{A\max}$). In the case of the last two parameters, the determination and assessment of these values is not possible using calculation methods for the selection of hearing protection devices.

The study presents a method of analyzing measurement data obtained using an acoustic test fixture that gives results representing noise parameter values that would be determined in the case of using hearing protection devices by humans.

For impulse noise produced by industrial sources, the assessment of hearing damage risk must take into account the parameter related both to the equivalent sound pressure level ($L_{EX,8\text{h}}$), and to the values referring to instantaneous sound pressure levels ($L_{C\text{peak}}$ and $L_{A\max}$). The assessment of the noise generated by die forging hammers in the forge demonstrated that exposure limit values are exceeded in the case of all three parameters mentioned above. Therefore, the verification of whether hearing protection devices would provide sufficient reduction of the value of each of these parameters was necessary. It turned out that not every hearing protection device is suitable against impulse noise in the forge, both in terms of the value of the $L_{EX,8\text{h}}$ parameter and of the $L_{C\text{peak}}$ parameter.

Due to the eventual migration of workers between individual workplaces in the forge, it is recommended to use the hearing protection devices that meet the requirement of providing sufficient protection at all workplaces.

The earplugs and earmuffs selected for using at specific workplaces shall effectively reduce the noise sound pressure level if they are used in an appropriate way, i.e. correctly placed, frequently inspected in terms of their technical condition and used continuously during the stay in an environment exposed to noise.

Acknowledgment

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