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The Impact of Fireworks Noise on the Acoustic Climate in Urban Areas

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New Year's Eve is an example of a situation in which urban residents are exposed to an almost continuous and increased noise level from the impulsive sounds sources – fireworks. This custom has become a source of many controversies related to the protection of human and animal health or environmental pollution. However, current legal regulations only slightly affect the subject of noise of fireworks and its harmfulness. Currently, it does not seem possible to completely prohibit the use of fireworks in urban areas, but this does not mean that it is not possible to decrease the degree of their annoyance.

The paper consists the issues of identification, analysis and assessment of impulsive noise of fireworks and acoustic climate during New Year's Eve. Material presented refers to measurements of time series, frequency spectrum and values of noise parameters of selected fireworks. It was presented, among others, that the measured values exceed the criteria for occupational noise ($L_{C\text{peak}}$), due to the direct hazard of hearing loss, from 1.8 dB at a distance of 25 m and 6.2 dB at a distance of 15 m. Also this work discusses results of impulsive noise measurements of fireworks recorded during New Year's Eve in years 2016–2017. Material refers to measurements at three measurement points spread over the city of Kraków. Obtained results were compared with typical noise levels for night time in urban area, indicating also the main sources of annoyance and hazard from this type of noise.

Keywords: impulsive noise; fireworks; environmental noise.

1. Introduction

Fireworks shows during the New Year's Eve are one of the inherent and at the same time spectacular elements of greeting the coming new year. The term 'fireworks' describes various types of pyrotechnic products used for entertainment and signaling purposes, which emit colourful lighting as well as acoustic effects (impulsive noise). Fireworks belong to the group of explosives, so-called low explosive, i.e. chemical compounds in which the rate of decomposition passes through the material at a speed below the speed of sound (Russell, 2009).

Recently, the growing trend is the abandonment of the pyrotechnic show at the expense of the major city events organizer. For example, the city of Kraków has not organized a firework show on New Year's Eve since 2012. Such a decision was caused by many factors such as caring for animals, fear of weather conditions or even the cost of pyrotechnic materials along with the infrastructure. Nevertheless, Kraków is not a city that celebrates this special night in silence. The fireworks purchased by the residents are fired well before midnight, and the last explosions can be heard even the next day. As in probably every other city in Poland, or even in Europe, it is vain to find a place where the noise generated by fireworks does not reach.

Analyzing the literature, it is hard to find articles dealing only or mainly with the noise aspects of fireworks. Among the available items, one can find papers on the measurement of physical noise parameters (Maglieri, Henderson, 1973; Babu, Azhagurajan, 2010), statistical description of fireworks noise (Deželak, Čudina, 2004) or exposure to noise of fireworks during festivals (Passos *et al.*, 2015).

In the medical literature, one can find a lot of papers on injuries caused by fireworks, but these are mainly information about burns or broken limbs (Tandon *et al.*, 2012). Nevertheless, there are papers that investigate the subject of noise, regarding the acoustic trauma due to noise exposure of fireworks (Plontke *et al.*, 2002; Fleischer *et al.*, 2003), or regarding hearing loss due to the noise of fireworks (Ward, Glorig, 1961; Smoorenburg, 1993; Clark, Bohne, 1999) including children (Gupta, Vishwakarma, 1989; Brookhouser *et al.*, 1992, Smith *et al.*, 1996; Segal *et al.*, 2003), as well as hearing damage caused by the leisure noise (Maassen *et al.*, 2001). There are also publications about human risk due to noise while staying in various places within life activity, lack of appropriate criteria for noise hazard assessment and requirements for concerning investigations in some cases (Korbiel *et al.*, 2017).

In the mass media, the harmfulness of fireworks is referred to rather as a loss of life or permanent disability, less often in the aspect of hearing damage or acoustic trauma. In preventive and educational programs (Polish Police, National Council on Fireworks Safety) the emphasis is put on, e.g. purchasing from a legal and verified source, maintaining a safe distance, or firing fireworks with all precautions, but not mentioning the use of hearing protectors, possible consequences of direct exposure to impulsive noise or other effects, such as feeling unwell, concentration or sleep disorders (Kryter, 2013).

2. Firework noise regulations

A large number of countries have their own regulations on pyrotechnics. In Poland, such a document is the law on explosives for civil use (Journal of Laws No. 2002, 117, item 1007). However, this is a document covering many aspects related to explosives, and consequently, from the acoustical point of view, the only law referring to noise control is Article 62c concerning the classification of pyrotechnic articles placed on the market and the limitations of this classification. Unfortunately, the legislator did not provide any guidelines on the measurement or permissible noise levels generated by fireworks. There are only unspecified terms such as: irrelevant or harmless noise level.

More information on, e.g. permissible noise levels generated by fireworks can be found in the Directive of the European Parliament and of the Council of 12 June 2013 on the harmonisation of the laws of the Member States relating to the making available on the market of pyrotechnic articles (Directive 2013/29/EU). Annex I on essential safety requirements sets out, inter alia, the minimum safe distance from the pyrotechnic material and the maximum noise level where the value of which is set at "*120 dB (A, imp) or an equivalent noise level measured by another appropriate method, at the safety distance*". There are doubts here about the lack of information on metrological conditions or even the fact that it is not unequivocally stated that the maximum sound level (A, imp) should be treated as the $L_{AI\,\max}$ parameter, the A-weighted maximum sound pressure level measured with the time constant I or maybe $L_{A\text{peak}}$ – the highest recorded value of A-weighted sound pressure level. It is also unclear what to be consider as "another appropriate method". This parameter is also questionable in the view of the standard for sound level meters (IEC 61672-1:2013, Annex C – Specifications for time-weighting I (impulse)), which contains the requirements for the time weighting F and S only, abandoning time weighting I because of the poor correlation with actual measurements of impulsive sounds. Complementary to the Directive 2013/29/EU are the series of standards EN 15947 with part 4 on test methods for pyrotechnic materials (PN-EN 15947-4:2016-02). According to the recommendations, one has to measure the maximum impulse A-weighted sound pressure level by the sound level meter sound placed at a height of 1 m and at distances defined for a given category of fireworks.

In Poland, Regulation of the Minister of Labour and Social Policy (Journal of Laws 2017, item 1348), includes the occupational exposure limit value, ELV (in Poland: NDN) for assessing occupational noise.

Table 1. Safety and noise related regulations of fireworks (source: Directive 2013/29/EU).

Cat.	Definition	Minimum age	Safe distance [m]	Max SPL [dBA, imp]
F1	Fireworks which present a very low hazard and negligible noise level and which are intended for use in confined areas, including fireworks which are intended for use inside domestic buildings.	12	1	120
F2	Fireworks which present a low hazard and low noise level and which are intended for outdoor use in confined areas.	16	8	120
F3	Fireworks which present a medium hazard, which are intended for outdoor use in large open areas and whose noise level is not harmful to human health.	18	15	120
F4	Fireworks which present a high hazard, which are intended for use only by persons with specialist knowledge (commonly known as fireworks for professional use) and whose noise level is not harmful to human health.	18	undefined	undefined

According to this Regulations a noise in the work environment is characterized by the following indicators:

- A-weighted noise exposure level normalized to an 8 h working day or the noise exposure level related to the working week (permissible value 85 dB, action value 80 dB);
- A-weighted maximum sound pressure level (permissible value 115 dB);
- C-weighted peak sound pressure level (permissible value 135 dB, action value 135 dB).

The last two indicators relate to hearing protection against the hazard of direct damage and they could also be applied in case of noise from fireworks.

Both the law on explosives for civil use and Directive 2013/29/EU do not provide any methodology to perform noise measurements, or even information about what standard or regulations should be used when measuring and assessing fireworks noise. Nevertheless, depending on the measurement situation, it is always worth considering the methodologies proposed in the environmental noise measurement standard (ISO 1996-1, 2016; ISO 1996-2, 2017) or at occupational noise (ISO 1999, 2013).

3. Impact of firework noise on acoustic climate of urban area

During the New Year's night, high-level impulsive noise is generated by the explosions of various types of fireworks. Due to the huge number of impulsive events (reaching several dozen thousand or more), it is almost impossible to separate individual sources from each other, hence the noise from fireworks can be considered as continuous at certain time intervals.

As previously noted, in inner-city areas it is very difficult for residents to isolate themself from the noise of fireworks. What is more, most of them, especially around the midnight, go outside to watch firework shows. Therefore, a large part of the society is exposed during this night to high-level impulsive noise, while very rarely (if at all) people are wearing hearing protectors. On the other hand, a significant number of the residents launch the fireworks themselves that night, exposing themselves to the direct exposure of very high peak sound pressure levels.

In order to examine the scale of fireworks noise and its potential impact on residents exposed to impulsive noise, a series of noise measurements in an urban area environment was performed. Measurement equipment was located at a height of 1.5 m in relation to the floor at three points located on balconies or in window openings of flats located in three districts of Kraków:

- Point 1: Prądnik Biały district, measurement point on the balcony on the 9th floor of the block in the vicinity of publicly accessible areas, such as the football pitch or school;
- Point 2: Prądnik Czerwony district, measurement point on the balcony on the 8th floor of the block in a closed housing estate;
- Point 3: Grzegórzki district, measurement point located in the window opening on the 4th floor of the block on an open, low-rise housing estate.

Fig. 1. Measurement points in the city of Kraków (source: maps.google.com).

Table 2 presents measurement results of noise indicators: $L_{A\text{eq},1\text{h}}$, $L_{A\max}$, $L_{A\text{peak}}$, $L_{C\text{peak}}$ as well as statistical levels L_{A10}, L_{A50}, L_{A90} and L_{A95}. The $L_{A\text{eq},1\text{h}}$ parameter represents the A-weighted equivalent sound pressure level set for the most unfavourable hour during the New Year's Eve, for which the interval between 11:30 PM and 0:30 AM was assumed. The results were compared with the typical (i.e. without the presence of impulsive noise sources) overnight noise for the same time interval. Additionally, for measurements on New Year's Eve, a rating equivalent sound pressure level $L_{R\text{eq},1\text{h}}$ was determined by adding an adjustment for impulsive character of the noise, K_I = 11.7 dB according to PN-ISO 1996-2:1999/A1:2002. The determination of rating levels is mandatory in the assessment of environmental noise, in which the noise components that may cause increased annoyance, such as tonality or impulsiveness,are present (ISO 1996-1, 2016).

Table 2. Noise indicators for New Year's Eve (NYE) compared to typical nighttime derived for data obtained between 11:30 PM and 0:30 AM.

	Point 1		Point 2		Point 3	
	NYE	Typical	NYE	Typical	NYE	Typical
$L_{A\text{eq},1\text{h}}$ [dB]	79.3	52.8	74.5	47.2	77.1	45.6
$L_{R\text{eq},1\text{h}}$ [dB]	91.0	–	86.2	–	88.8	–
$L_{AF\max}$ [dB]	110.1	66.7	102.9	61.3	110.8	63.4
$L_{A\text{peak}}$ [dB]	136.5	76.7	126.1	78.6	136.4	77.5
$\text{L}_{C\text{peak}}$ [dB]	136.5	85.2	126.5	86.4	137.4	83.9
L_{A10} [dB]	79.8	56.0	78.3	49.5	74.4	48.2
L_{A50} [dB]	70.3	51.8	65.7	46.3	65.6	41.3
L_{A90} [dB]	63.9	49.4	59.9	43.9	58.9	38.6
L_{A95} [dB]	61.5	48.4	58.6	41.9	56.0	36.2

$L_{A\text{eq},1\text{h}}$ – A-weighted equivalent sound pressure level for 1-hour interval, dB; $L_{R\text{eq},1\text{h}}$ – rating equivalent sound pressure level for 1-hour interval, dB; $L_{AF\max}$ – A-weighted maximum sound pressure level, dB; $L_{A\text{peak}}$, $L_{C\text{peak}}$ – peak sound pressure level with A or C weighting, dB; $L_{An\%}$ – A-weighted sound pressure level exceeded for n% of the measurement time, dB.

During the observation, both for points 1 and 3, exposure level value for $L_{C\text{peak}}$ has been exceeded (with equally high $L_{A\text{peak}}$ values) (Journal of Laws 2017, item 1348). Only in the case of point 2, such exceedances did not occur, probably because the measurement point was located inside a closed housing estate, hence limited number of fireworks launched in the close vicinity of the sound meter was registered (despite the fact that the dominant noise was the one from the fireworks). Nevertheless, the values exceeding 125 dB may still be harmful to the auditory system. This is also reflected in the results of $L_{A\max}$, which values in points 1 and 3 exceed 110 dB. In each of the three measurement points, obtained equivalent sound pressure level $L_{A\text{eq},1\text{h}}$, reaches very high values, similar to the statistical level L_{A10}. The difference between L_{A10} and $L_{A\text{eq},1\text{h}}$ is 0.5 dB, 3.8 dB and −2.7 dB respectively. Rating equivalent sound pressure level $L_{R\text{eq},1\text{h}}$ at each measurement point reaches high values, the highest level was calculated in point 1 and equals 91.0 dB.

As expected, the values of all parameters measured for a typical noise at night are lower than those measured on New Year's night by several dozen decibels, and those differences are often in range of 50–60 dB.

4. Analysis of impulsive sound sources

The purpose of this part of the paper was to determine the noise that reaches the resident's ear every time the fireworks are fired, assuming that residents do not use hearing protectors and stay in the minimum safe distance from the explosion, specified by the manufacturer. The need for such measurements is essential due to the fact that firework manufacturers do not provide any information about the noise level generated by their products.

The research material consisted of two types of single-shot firecrackers and a 25-shot fireworks battery. Parameters of all materials used are presented in Table 3. Measurements were made during the daytime in the open space using sound level meters: SVAN 945A, SVAN 958, and SVAN 959 placed on a tripod (Fig. 2). As mentioned in Sec. 2, according to the PN-EN 15947-4:2016-02 standard, the measurements should be carried out at a height of 1 m, while the aim of this work was not to examine the compatibility of pyrotechnic materials with the requirements set by the standard, but the impact of its noise on humans. Thus, a measuring height of 1.5 m was assumed as the height at which human ears are placed. Each time the meter was set at the minimum safe distance for the operator, depending on the category of fireworks, i.e. 8 m for firecracker A (category F2), 15 m for firecracker B and for fireworks battery (category F3), as well as 25 m

Table 3. Material for measurement.

	Cracker A	Cracker B	Battery of fireworks
Category	F2	F3	F3
No of shoots	1	1	25
Total duration of shoot [s]	~ 2	~ 3.5	~ 35–40
Length, diameter [mm]	50/3.8	62/15.5	230/30
Weight of explosive [g]	~ 0.1	~ 2.1	> 100 (total)

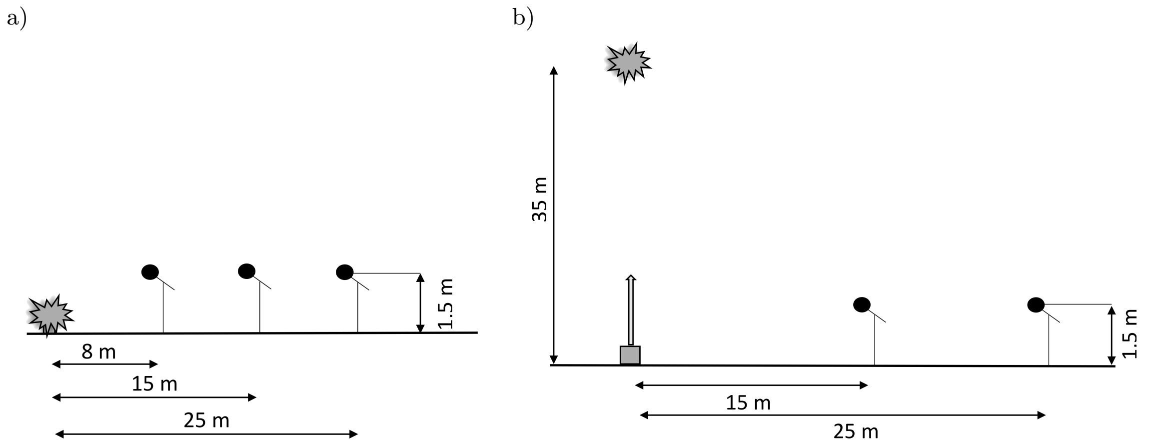

Fig. 2. Measurement points for sound level meters used for registering the noise of firecrackers (a) and 25-shots fireworks battery (b).

(minimum safe distance for the spectators – not mentioned in the PN-EN 15947-4:2016-02 and Directive 2013/29/EU).

Fifteen explosions were recorded for each type of firecracker tested and one full run of 25-shots fireworks battery. Determined parameters of noise were saved using time weighting F, as well as the frequency spectrum. The registration step was set to 50 ms and the frequency band was limited to the range 20–20 000 Hz, limited due to the sample length (50 ms) and bandwidth in the low frequency range. In practice, the 1/3 octave spectrum was recorded correctly in bands above 100 Hz. Examples of registered time series (waveforms) are presented in Figs. 3 and 4.

A comparison of the obtained parameters of noise results and impulsive noise descriptors is presented in

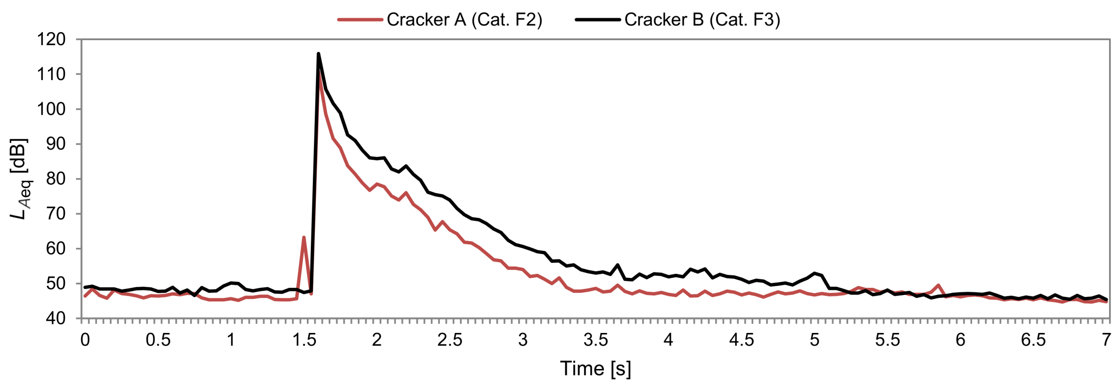

Fig. 3. Time series of L_{Aeq} for explosions of Cracker A and Cracker B.

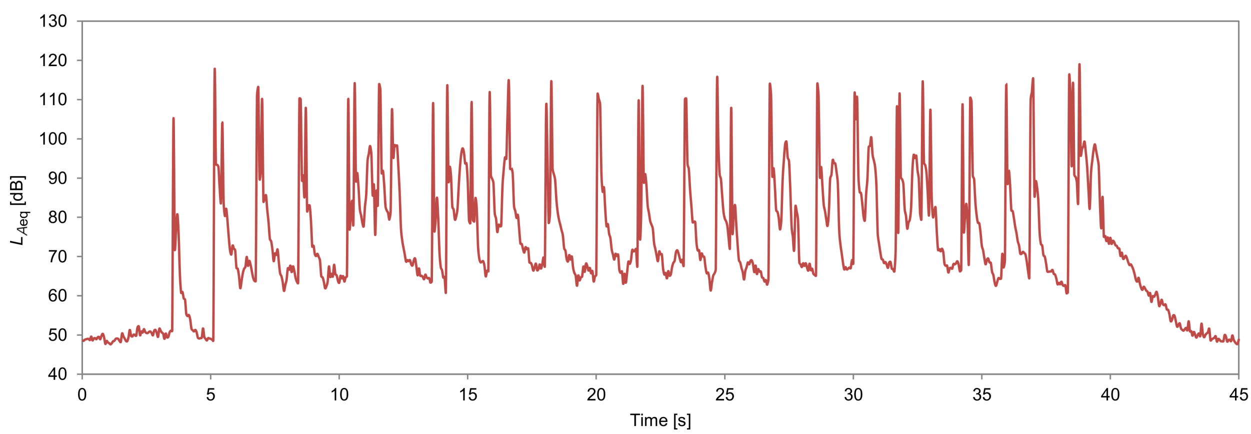

Fig. 4. Time series of L_{Aeq} for explosion of battery of fireworks.

Table 4. For firecracker A and firecracker B two results were presented: the "worst case" value, i.e. the measurement in which the highest parameter values were achieved, as well as the median value from the sample; whereas in the case of fireworks batteries a combined measurement was made, on the basis of which the maximum values for each parameter were determined.

The distributions of the SEL spectrum at minimum safe distances for the operator and the spectators, together with the background noise spectrum are presented in Figs. 5–7.

All of the three types of fireworks generate very high sound pressure levels. The estimated values of A-weighted maximum sound power level, calculated from data measured at operator position, for each of fireworks exceeds 135 dB. Median peak sound pressure level $L_{C\text{peak}}$ and $L_{A\text{peak}}$, measured at the minimum safe distances for the operator, are respectively 137.9 dB (both C-weighted and A-weighted) for firecracker A, 139.8 dB (C-weighted) and 139.5 dB (A-weighted) for firecracker B, while in the case of the battery of fireworks, measured the highest values of these parameters were equal to 141.2 dB (C-weighted) and 141.3 dB (A-weighted). At the minimum distance for the spectators, obtained (respectively C-weighted and A-weighted) 119.4 dB and 120.0 dB (firecracker A), 128.3 dB and 128.7 dB (firecracker B), 136.8 dB and 136.1 dB (battery of fireworks).

Similarly, in the case of maximum levels, very high values of $L_{CF\,\max}$ and $L_{AF\,\max}$ parameters were registered at the operator position. The median of these parameters was respectively: 109.7 dB and 109.1 dB (fire-

Table 4. Values of noise parameters and impulsive noise descriptors for Cracker A, Cracker B and for battery of fireworks.

	Cracker A (worst case/median)		Cracker B (worst case/median)		Battery of fireworks (max. from 25 pcs.)	
Distance from the source	8 m	25 m	15 m	25 m	15 m	25 m
$L_{C\text{peak}}$ [dB]	139.8 137.9	122.3 119.4	140.0 139.8	131.1 128.3	141.2	136.8
$L_{A\text{peak}}$ [dB]	139.5 137.9	122.8 120.0	139.6 139.5	131.4 128.7	141.3	136.1
$L_{CF\,\max}$ [dB]	112.6 109.7	91.1 89.3	118.5 116.5	103.0 99.7	119.1	115.5
$L_{AF\,\max}$ [dB]	112.7 109.1	90.6 88.3	115.1 113.6	99.8 96.5	118.8	111.2
$L_{AS\,\max}$ [dB]	104.2 103.6	80.1 77.8	106.2 104.1	89.4 85.9	108.4	100.7
$L_{AI\,\max}$ [dB]	116.3 112.7	94.2 91.9	118.7 117.2	103.4 100.1	122.4	114.8
L_{CE} [dB]	103.9 100.8	82.5 80.7	110.1 108.0	94.7 91.8	119.8	117.6
L_{AE} [dB]	103.8 100.5	82.0 79.6	106.8 105.1	91.2 88.8	116.5	113.3
$DL_E = L_{CE} - L_{AE}$ [dB]	0.1 0.3	0.0 0.9	1.7 2.9	1.4 2.9	3.3	4.3
$I_A = L_{A\text{peak}} - L_{A\text{eq,T}}$ [dB]	52.8 50.2	44.1 41.6	53.0 48.6	45.8 41.9	40.8	38.8
$\Delta L_A = L_{A\max} - L_{At}$ [dB]	65.7 62.1	45.9 43.6	68.1 66.6	55.1 51.8	67.8	64.2
$V_{LA} = \Delta L_A / t_{\text{rise}}$ [dB/s]	1314 1241	918 872	1362 1331	1102 1036	1356	1284
$L_{WA} = L_{A\max} + 10\log\frac{4\pi r^2}{Q}$ [dB]*	138.9 135.3	–	146.6 145.1	–	158.4	–

$L_{CF\,\max}$, $L_{AF\,\max}$ – C/A-weighted maximum sound pressure level with time weighting F, dB; $L_{AI\,\max}$, $L_{AS\,\max}$ – A-weighted maximum sound pressure level with time weighting I/S, dB; L_{CE}, L_{AE} – C/A-weighted sound exposure level, dB; D_{LE} – difference in C and A-weighted sound exposure levels; I_A – impulsiveness (crest level), where $L_{A\text{eq,T}}$ represents A-weighted equivalent sound pressure level for impulsive event duration (Kukulski, 2017); ΔL_A – increase in sound pressure level, where L_{At} – A-weighted sound pressure level before impulsive event (Wszołek, 2015); V_{LA} – rapidity of impulse rise, where t_{rise} represents time in which signal rises from 10% to 90% of its maximum absolute value of the sound pressure (ISO 10843:1997); L_{WA} – A-weighted sound power level.

* For Cracker A and Cracker B, directivity factor $Q = 2$, for battery of fireworks, $Q = 1$.

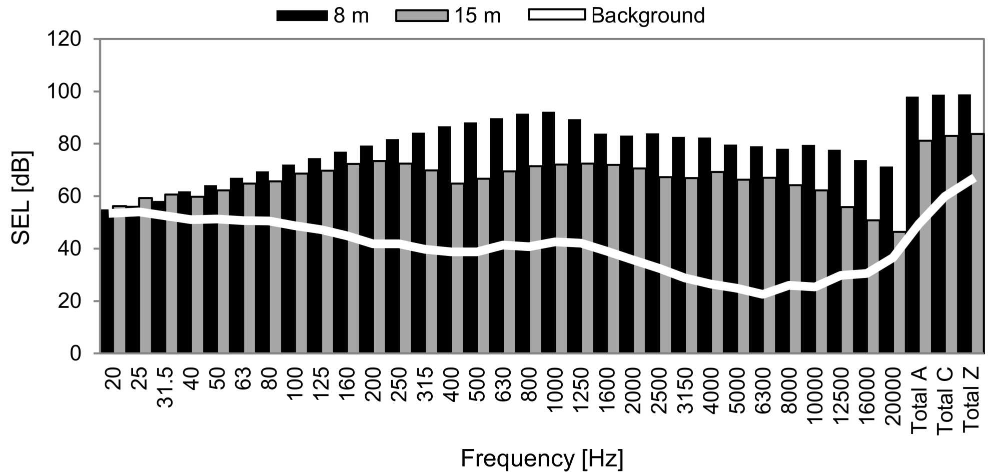

Fig. 5. Sound exposure level spectrum of Cracker A compared to background noise.

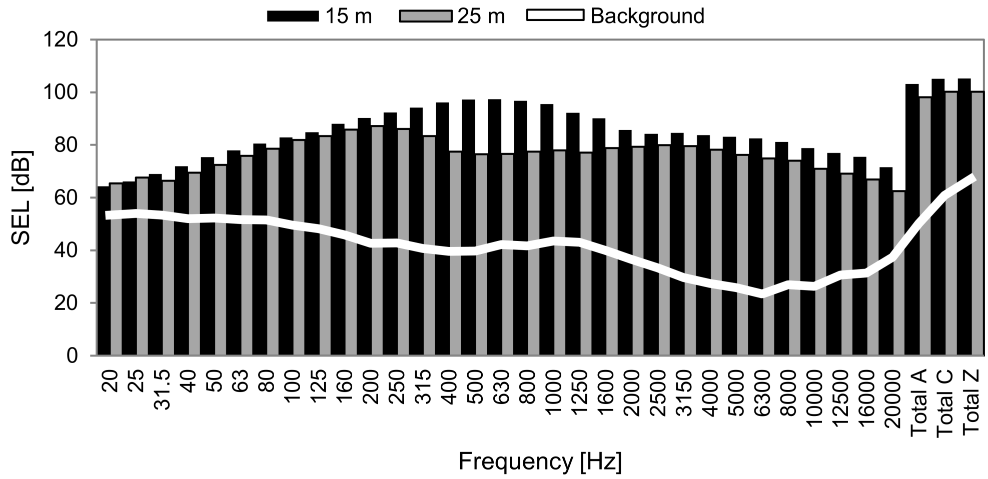

Fig. 6. Sound exposure level spectrum of Cracker B compared to background noise.

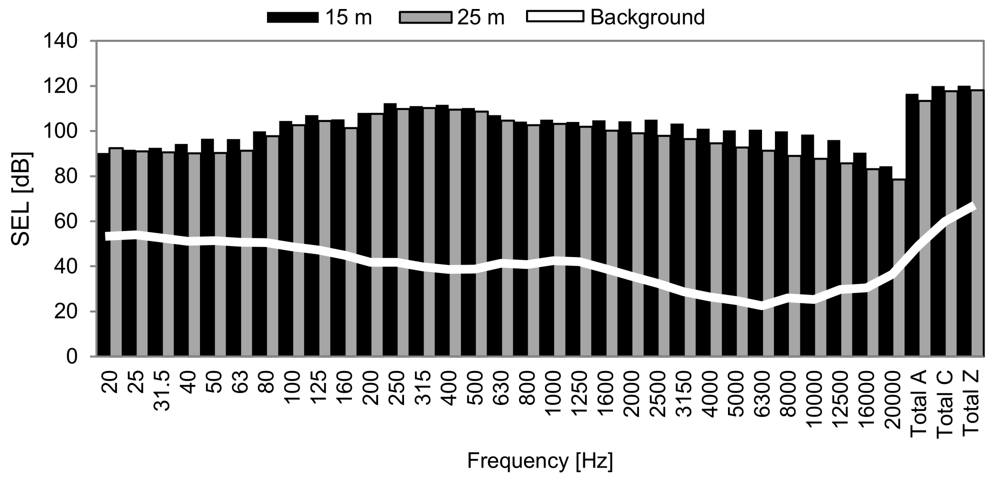

Fig. 7. Sound exposure level spectrum of fireworks battery compared to background noise.

cracker A), 116.5 dB and 113.6 dB (firecracker B), and for battery of fireworks the maximum values reached the level of 119.1 dB and 118.8 dB. At the spectators point, those levels are definitely smaller, respectively over 20 dB lower in the case of A firecracker, over 15 dB for B firecracker, while in the case of battery of fireworks, these differences do not exceed 10 dB. Values of $L_{AI\,\max}$ were derived from waveforms by change in time weighting in post-processing phase.

Sound exposure levels are also very diverse, which is caused, among others, by the amount of explosive inside the firework. That amount affects the content of low-frequency components in the spectrum (Figs. 5 and 6). The exposure level for battery of fireworks was also derived for the total duration of the pyrotechnic show, which caused much higher values of these parameters. In addition, along with the distance, the difference in the exposure levels, DL_E, increases. This is quite obvious due to the strong attenuation at higher frequencies through the propagation of sound.

All from the three examples of fireworks are characterized by high values of descriptors I_A, ΔL_A, V_{LA}, which confirms the impulsive nature of these sound sources. The values of these parameters decrease with the distance from the source, however, regardless of the sound source and distance, these parameters clearly indicate a strong impulsiveness of recorded signals.

Also, when analyzing deformation of sound exposure level spectrum along with distance, one can observe the high frequencies attenuation effect in the air. The biggest differences were observed for firecracker A, for which the differences in particular bands are over 20 dB (bands 315–800 Hz and 10–16 kHz). For firecracker B such large differences occur only in the bands 400 and 500 Hz, while deformation of spectrum for battery of fireworks is negligible and visible only in high frequency bands. This can be explained by the relatively large height of the source and the "straight" sound propagation path.

It should be emphasized, when assessing with the guidelines for minimum safe distance, the permissible value of the maximum noise level equal to 120 dB, as defined in the Directive of the European Parliament and of the Council (Directive 2013/29/EU) is not exceeded for both firecrackers, and slightly exceeded for battery of fireworks. However, taking into account the permissible Exposure Level Values contained in the Regulation of the Minister of Labour and Social Policy (Journal of Laws 2017, item 1348), it can be observed that peak levels exceed the ELV for firecrackers and battery of fireworks. In the case of both firecrackers, a distance of 25 m for the spectators is relatively safe, while for battery of fireworks there is a slight exceeding in $L_{C\text{peak}}$, i.e. 1.8 dB. At the minimum distance in which the operator may be present, $L_{C\text{peak}}$ values regularly exceed ELV by approximately 2–5 dB in the case of firecrackers type A and B, and for battery of fireworks, 6.2 dB. On the other hand, there is no results of the A-weighted maximum sound pressure level $L_{AS\,\max}$ that exceed 115 dB according to regulations (Journal of Laws 2017, item 1348) for each of examined firework type.

5. Conclusions

The limited number of legal regulations regarding the noise generated by fireworks and the imprecise terminology of the harmfulness criteria are a significant gap in the field of research into environmental noise. Unfortunately, at the same time the issue of hearing protection is still neglected in preventive social actions. There is the need for an extension of the research recommendations of the safety of pyrotechnics to the issue of hearing protection, as well as creating a new methodology for precise determination of noise and its impact on human.

Such a need is confirmed by the measurement results presented in the paper, indicating harmful to the hearing system values of peak and maximum sound pressure levels, both in the operator and spectators locations. The measured values exceed the criteria for occupational noise, due to the direct hazard of hearing loss, from 1.8 dB at a distance of 25 m and 6.2 dB at a distance of 15 m. What is more, when considering that those maximum and peak sound pressure level for potential impact on young people and pregnant women, limits must be set 5 dB lower, and thus exceeding will be about 5 dB higher. This assumption raises the urgent need to provide unambiguous information on fireworks at a safe distance including also the information about risk of permanent hearing loss. With the above, there is a need to develop a methodology for determining these parameters and criteria for evaluation the harmfulness of the fireworks.

Analysis of noise at minimum safe distances indicates the necessity of using personal protective equipment (hearing protectors) obligatory by fireworks operators, but it should also be recommended to the spectators, even though the levels recorded in this point do not exceed the permissible noise levels.

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