On adaption of psychoacoustical loudness measure for differentiate impulsive noise events

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Summary

Due to the subjective perception of the noise, determining the degree of annoyance of an acoustic signal containing bothersome features can be highly complex process. One such example is the impulsive noise. Typical measurable noise parameters such as exposure or equivalent sound level, A or C-weighted, their combinations or frequency spectrum are most often used for energy assessment, but their usability in cases where the degree of true annoyance caused by impulsive noise is limited. In this case, it is a need for use other measures that would be better correlated with the subjective features of the auditory impression, and therefore more useful in its objective evaluation. For this purpose common psychoacoustic measure – loudness was proposed as promising indicator. The definition of loudness was presented and then adapted to the objective set out in this paper. Values of thereof was calculated, and the analysis of the results obtained on the basis of test material - impulsive noise generated during a collision of train cars in industrial environment. Based on the results, the degree of usefulness in differentiating the annoyance of impulsive sounds was determined.

PACS no. 43.50.Rq, 43.50.Pn

1. Introduction

The impulsive noise, due to its nature, causes a feeling of increased annoyance, higher than other non-impulsive sounds with the same sound pressure level. The stronger the impulse, the higher the sound level is emitted to the environment. Occasional and often unpredictable occurrences arouse anxiety, which can result that in the long term those sounds could be perceived as more annoying than those that regularly reach the human ears, i.e. those to which one can get used to. Furthermore, impulsive noise can be particularly troublesome during the night, causing sleep disturbance problems, e.g. interrupting the process of falling asleep or unexpected waking up [1].

The international standard regarding assessment of environmental noise, ISO 1996-1:2016 [2] provides the information indicating that impulsive noise is definitely more annoying than e.g. traffic noise, which leads to the process that the equivalent and exposure levels should be adjusted with the appropriate value of the impulsive adjustment, which is sometimes called a “penalty”. The value of the adjustment, depending on the source of the impulsive sound, may be equal to 5 or 12 dB in the case of regular impulsive sound sources and highly impulsive sound sources, while the adjustment for high-energy impulsive sound sources may exceed 12 dB.

The measurement of sound pressure level together with its spectrum allows to determine a number of parameters dedicated to describe the impulsive character of noise. The most important and most common indicators are: peak and maximum sound levels, as well as the sound exposure level, which is a measure of the acoustic energy of a given impulsive sound [1]. Combinations of these parameters, with other indicators as, for example, the rise time or duration of the impulse, allow to create useful measures, such as the rapidity of impulse rise or impulsiveness of the given impulsive event [2]. Also, the analysis of the spectrum distribution allows to obtain relevant information about the nature of a given acoustic event. Among the useful parameters, one can distinguish the spectral centroid with its shifting associated with the presence of the impulse [3], as well as kurtosis [4].

The usefulness of parameters based on the physical characteristics of impulsive sound sources in the process of differentiation the degree of annoyance is quite high, however, the objective evaluation, based on the above parameters, may be insufficient to fully comply with the actual perception of impulsive noise. Therefore, it is necessary to search for other, new indicators that can better correlate with the subjective features of the auditory sensation.

A natural indicator, which is strongly correlated with the subjective human reaction to auditory stimulus is loudness. The paper presents the concept of using this parameter and its modifications with the intentions to develop the feature vector of impulsive noise, on the basis of noise generated during collisions of train cars in industrial environment. This work is a theoretical preparation in the form of research psychoacoustic listening tests, which aim will be to determine the correlation between the parameters of the physical characteristics and loudness of impulsive noise.

2. Loudness

The term "loudness" describes a feature of the auditory sensation that allows the classify of sounds from the quietest to the loudest. Due to the fact that loudness is rather subjective feature, it is not possible to determine its value directly [5]. One of the most popular ways of determining loudness is to convert sound pressure level to loudness level, and then, on its basis, one can determine loudness of the given acoustic event.

Among other things, due to the individual perception of sound by humans, both loudness level and loudness itself should be determined statistically, to equalize differences in individual perception. The loudness and loudness level is assessed mainly based on the observation of a sample of people being part of the overall population [6].

For example, in the standard ISO 226:2003 [7], there is a description of the methodology allowing to determine loudness level of pure tones, depending on the level of sound pressure level of and their frequency. In the case of loudness of broadband sounds, mainly stationary, one can use the methods described in the series of standards ANSI S3.4-2007 [8] and the latest revision of the standard ISO 532-1 2017 [9], i.e. Zwicker loudness [9]. Furthermore, according to i.e. research published by Kuwano et al. [10], but also according to ISO 1996-1 [2], loudness evaluation based only on measurement of $L_{Aeq,T}$ in the case of impulsive sounds can be inaccurate.

In the studies [10-11], sound exposure level, *SEL* and maximum sound level L_{max}, most often A-weighted, were considered as reliable input parameters, however it should be noted that in the case of high-energy impulsive sound sources assessment, more adequate is to use of C-weighting, due to the low-frequency components present in the measured signal [12]. In this assessment, the elements of the temporal envelope of a given impulse are also important. From those elements one can distinguish the duration of the impulse, which can be divided into the rise time and decay time, as well as the amplitude peak value (peak level).

In the case of broadband noise, for which it is possible to perform frequency analysis using filters with constant relative bandwidth (eg. 1/1 or 1/3 octave), an approximate formula for the total loudness N of the measured sound event can be used:

$$N = N_{max} + F\left(\sum_{i=1}^{k} N_i - N_{max}\right) \qquad (1)$$

where:

N_{max} – greatest of the loudness value among the analyzed bands [sone],

N_i – loudness for i-th frequency band [sone],

F – band coefficient,

k – number of frequency bands.

For 1/1 octave bands: F=0.3, k =8 (63–8k Hz).
For 1/3 octave bands: F=0.15, k = 24 (50-10k Hz).

The N_i components are determined in the following way: on the basis of the registered sound pressure level in a given frequency band, loudness level in phones is determined, and then the result obtained is converted into loudness in sones.

3. Research material

The research material consists of sets of acoustic parameters obtained on the basis of the measurements of sound pressure levels 1/3 octave bands spectrum from collisions of empty train cars, the examples of highly impulsive sound sources, as described in the standard ISO 1996-1 [2]. Noise measurements were made at a distance of 10 meters from the source, and further away from the collisions, from 150 to 250 m. The measurement data recording step was set at 50 ms. The 1/3 octave band spectrum were calculated for bands from 50 Hz to 10 kHz.

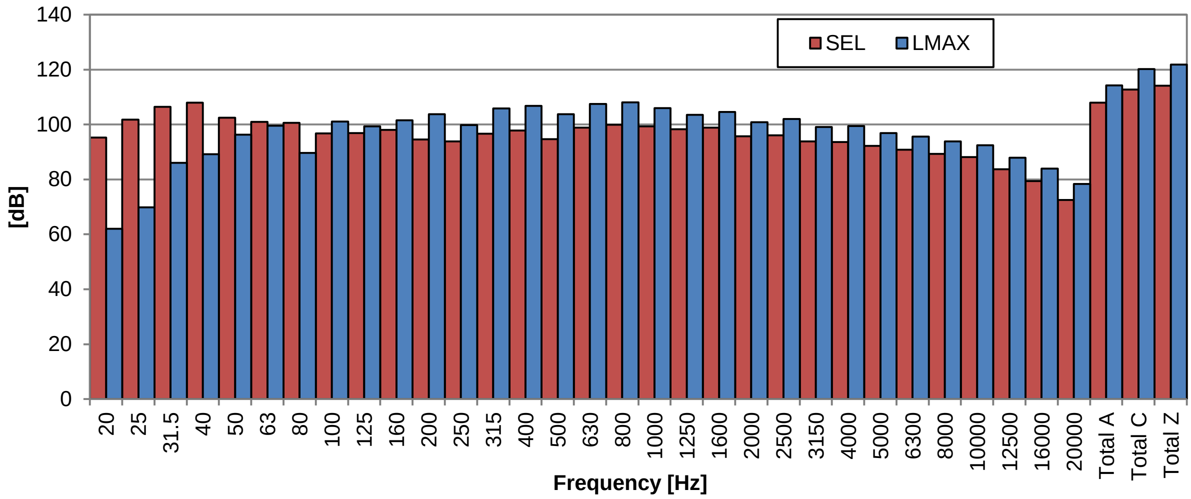

Figure 1. SEL spectrum and maximum level spectrum of collision of wagons registered close to the noise source.

4. Proposal of parameters

4.1. Exposure level-based loudness (N_{EX}) and maximum level-based loudness (N_{MAX})

The first two loudness parameters are exposure level-based loudness (N_{EX}) and maximum level-based loudness (N_{MAX}). In both cases, loudness was determined based on the 1/3 octave spectrum in the 50 - 10k Hz bands. In the case of the N_{EX} loudness, the spectrum of sound exposure level, *SEL*, determined for the total duration of the pulse was used, while in the case of N_{MAX} loudness, the spectrum obtained at the moment of the collision of train cars was selected.

Differences in the shape of the spectrum and sound level values in individual 1/3 octave bands are presented in Figure 1. It can be observed that much higher values of lower frequency bands of the *SEL* spectrum do not translate into its overall (total) value. In the analyzed frequency range (50 Hz - 10 kHz), both spectra are clearly flattened, which clearly indicates the impulsive character of the noise source.

In the further part of the paper will be presented the results of the estimated loudness based on the obtained spectra of the A-weighted maximum sound level L_{Amax} and the determined spectra of the sound exposure level *SEL*.

4.2. Instantaneous loudness-based impulsiveness (IL)

In classical approach, i.e. measurements of physical parameters (ISO 1996-1:2017 [2],CHABA report [12]), impulsiveness parameter, also known as the "crest level" is defined as the difference between the peak level and the RMS level:

$$I = L_{xPeak} - L_{xRMS}, \tag{2}$$

where:

x – frequency weighting, commonly A or C,

L_{RMS} – root mean square value of sound pressure level during impulsive event, [dB].

Over the years, the impulsiveness parameter has been modified, currently it is most often determined by using measurements with A weighting and the equivalent sound level $L_{Aeq,t}$ as RMS level.

$$I = L_{APeak} - L_{Aeq,t} \tag{3}$$

As it was presented in previous authors' research [3,13] impulsiveness parameter I can be useful in the process of identification of impulsive noise. However, it provides similar values irrespective of the fact whether I is determined from the data received at the source or in the distance from it.

Therefore, it was decided to modify the concept of impulsiveness to instantaneous loudness-based impulsiveness (*IL*). In the general case, the modified *IL* parameter will take the following form:

$$IL = N_{impulse} - N_{background} \tag{4}$$

In further considerations, the *IL* parameter will be determined in two ways, and therefore two concepts will be adopted regarding the selection of $N_{impulse}$ and $N_{background}$ values:

The first one is based on the recommendations of DIN 45631/A1 [14]. In this case, for $N_{impulse}$ it is recommended to use the N_5, that is, a loudness that is exceeded in five percent of the time. Likewise, loudness N_{95} represents $N_{background}$.

$$IL_{din} = N_5 - N_{95} \tag{5}$$

In the second method, the authors propose to adopt the maximum level-based loudness (N_{MAX}) as $N_{impulse}$, and exposure-based loudness (N_{EX}) for $N_{background}$.

$$IL_{max} = N_{MAX} - N_{EX} \tag{6}$$

4.3. Total loudness-based impulsiveness (TL)

The instantaneous loudness-based impulsiveness parameters presented in section 4.2 refer to the so-called the instantaneous loudness, and therefore determined for the characteristic or arbitrarily chosen moment of duration of the impulsive sound. However, due to the non-stationary nature of impulsive noise, the evaluation of the instantaneous maximum volume may be insufficient. In this case, one can use the determination of the total loudness, and therefore the parameter called total loudness-based impulsiveness (TL). It can therefore be interpreted as the average value of the instantaneous loudness difference and the determined acoustic background, approximated by the constant value of N_{95}.

$$TL = \frac{1}{K}\sum_{j=1}^{K}\left(N_j - N_{95}\right) \tag{7}$$

where:

N_i – loudness for j-th period of time [sone],

K – duration of impulse, $K = j \cdot T$ [s]

T – registration step, [s].

4.4. Loudness-based impulsiveness feature vector

On the basis of parameters described in paragraphs 4.1-4.3, a loudness-based impulsiveness feature vector can be created, which consists of eight elements.

$$X = \langle N_{MAX}, N_{EX}, N_5, N_{50}, N_{95}, IL_{din}, IL_{max}, TL \rangle \tag{8}$$

5. Analysis of usefulness of loudness-based parameters

In the previous research of the authors [3,13] it was presented that in the case of impulsive noise generated during collisions of train cars, values of classical impulsiveness parameter I are similar regardless of e.g. sound exposure level, and its value vary from 25 to 30 dB when measured at the source, and from 15 up to 25 dB in further distances.

For example, the value of I = 21 ± 0.5 dB was determined for the SEL value from 56.8 - 78.8 dB. Much more varied results were obtained when determining loudness-based parameters IL_{din} (5) and IL_{max} (6). A graphical comparison of I, IL_{din}, IL_{max} parameters is presented in Figure 2. Moreover, both IL_{din} and IL_{max} values increase significantly with increasing SEL values.

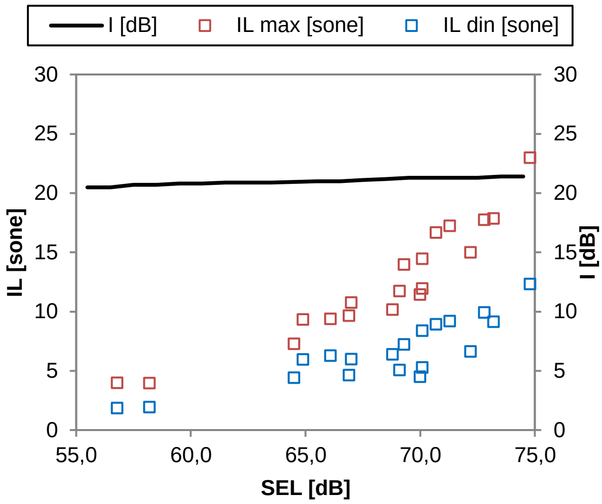

Figure 2. Graphical comparison between impulsiveness and loudness-based impulsiveness obtained for train cars collisions with SEL value range 56.8 – 78.8 dB.

Analysis of the distribution of all obtained results showed that all loudness-based parameters that may be useful in differentiation, i.e. N_{MAX}, N_{EX}, N_5, IL_{din}, IL_{max} and TL increase exponentially with the increase in the sound exposure level SEL. Figure 3 presents two exemplary matched regression curves to the obtained IL_{din} and IL_{max} data.

The obtained matches are very accurate and in each case the coefficient of determination are close to 1. Equations regression curves (9-14) and R^2 values arranged in the order from best to worst match. The classification is as follows:

$$N_{EX} = 0.0778e^{0.0728(SEL)},\ R^2 = 0.999 \tag{9}$$

$$N_{MAX} = 0.0716e^{0.08(SEL)},\ R^2 = 0.9971 \tag{10}$$

$$N_5 = 0.0907e^{0.0728(SEL)},\ R^2 = 0.9914 \tag{11}$$

$$IL_{din} = 0.0508e^{0.0783(SEL)},\ R^2 = 0.9879 \tag{12}$$

$$TL = 0.0289e^{0.0683(SEL)},\ R^2 = 0.9845 \tag{13}$$

$$IL_{max} = 0.0104e^{0.0918(SEL)},\ R^2 = 0.9834 \tag{14}$$

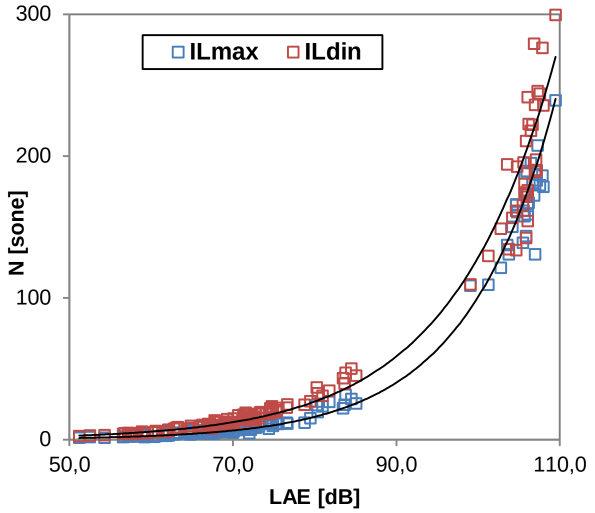

Figure 3. Instantaneous Loudness-based impulsiveness IL_{max}, IL_{din} as a function of sound exposure level.

Based on the analysis it seems possible to estimate the values of a set of parameters that differentiate the loudness-based impulsiveness of a collision of cars. This estimation can be based only on the value of sound exposure level *SEL*.

Table I. Comparison of values of impulsiveness *I* [dB] and loudness-based impulsiveness parameters [sone] for five examples of impulsive noise with similar SEL value.

SEL	**106.9**	**107.0**	**107.0**	**107.1**	**107.2**
I	25.1	25.2	24.3	26.5	26.5
N_{MAX}	369.4	364.8	304.7	382.4	362.5
N_{EX}	197.6	184.8	174.4	195.6	180.2
N_5	286.1	194.0	242.1	203.2	194.5
IL_{din}	278.8	188.6	235.8	197.1	189.7
IL_{max}	171.8	180.0	130.3	186.8	182.3
TL	59.9	34.4	55.7	40.8	43.3

Table I presents the comparison of the values of classical impulsiveness and determined parameters from the feature vector, calculated from five collisions of train cars measured at the source and characterized by almost the same SEL value, i.e. 107 dB.

It can be observed that the parameter I, measured in decibels, for each collision provides a similar value, while the loudness-based parameters are provide quite a high degree of differentiation at almost the same sound exposure level.

In addition, the average values of loudness-based impulsiveness parameters will be presented for the noise of collisions of train cars measured at four measurement points. The analysis involved eight cases:

a) At the source, 10 m from the collision, day,
b) At the source, 10 m from the collision, night,
c) 150 m from the collision, day,
d) 150 m from the collision, night,
e) 230 m from the collision, day
f) 230 m from the collision, night,
g) 250 m from the collision, day
h) 250 m from the collision, night.

The obtained values of determined parameters of the impulsive noise feature vector are presented in Table II. In the analyzed cases it is clear that the loudness of collisions of train cars is definitely higher while calculated from the measurements taken at night. There is also a visible dependence of the decrease of the parameter values along with the distance from the source, but it does not refer to the parameters N_{50} and N_{95}, reflecting the loudness of the acoustic background.

The parameters based on the determination of loudness have a large potential, because, as shown, they provide much more varied information than the parameters determined in a classical (SPL measurement) approach. However, these calculations presented promising results only for one source of impulsive noise, so it is certainly not possible to speak about the universality of these parameters in the process of differentiation of any of impulsive sounds. Furthermore, the next step must be to correlate the results obtained on the basis of measurements with the subjective human reaction to the noise coming from the collisions of train cars.

Nevertheless, the aim of the work, set at the beginning of the paper, i.e. the preparation of a set of parameters (feature vector) of impulsive noise has been achieved.

Table II. Average values of loudness-based impulsiveness feature vector elements obtained for each category.

Case N°	N_{MAX}	N_{EX}	N_5	N_{50}	N_{95}	IL_{din}	IL_{max}	TL
a)	323.9	164.3	187.5	14.9	5.4	182.1	159.6	35.9
b)	347.2	178.4	209.4	18.9	5.8	203.6	168.8	42.5
c)	20.3	12.7	15.4	3.4	1.9	13.5	7.6	3.2
d)	43.6	26.2	32.5	6.5	2.9	29.6	17.4	7.2
e)	8.5	6.0	6.9	3.0	1.9	5.0	2.5	1.6
f)	23.0	14.7	17.4	3.9	2.1	15.3	8.3	3.7
g)	12.7	8.3	9.5	2.8	1.7	7.8	4.4	2.2
h)	15.7	11.0	12.2	3.9	2.0	10.2	4.7	3.2

6. Conclusions

Results presented in the paper confirmed that the usage of parameters based on the calculated loudness allows for a clear differentiation of impulsive noise from the collision of train cars. What is important, all of the proposed parameters are characterized by an very high degree of matching.

Based solely on the value of R^2, it seems that the process of differentiation of impulsive noise annoyance can be possible only on the bases of the values of parameters N_{EX} or N_{MAX}. However, the actual reduction of the feature vector elements or the selection of a single indicator will require empirical verification in the form of, for example, listening tests on a viable, large research group.

The work will be continued by the authors, who are hoping that the results of these studies, among others, the correlation between values and subjective reaction, will be published in the near future.

Acknowledgement

This project has been funded by the academic grant N° 15.11.130.625.

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