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PROPOSAL OF THE RULE FOR RATING LEVELS OF INDUSTRIAL IMPULSIVE NOISE REGARDING THE RISK OF HEARING DAMAGE

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Abstract. *Since the release of the core standards for determining occupational noise exposure, ISO 1999:2013 and ISO 9612:2009, adjustments for noise types that were previously thought to have additional damaging effects of noise uneven in the time and frequency domain have been left out when rating noise levels in the workplace. Recent literature as well as models of the effect of noise on hearing indicate a particularly damaging effect of impulsive noise. At the same time, the regulation requires consideration of the type of noise, including any exposure to impulsive noise. This paper proposes a rule for rating that would reduce the risk of hearing damage arising from disregarding the impulsive nature of noise.*

Key words: *industrial noise, impulsive noise, rating levels*

1. INTRODUCTION

In order for an effect to be well-founded, it is necessary to have proven empirical evidence, and a corresponding theoretical explanation — specifically, when considering the effect of a physical agent on a human, the connection of the physical phenomenon that causes it with the biological response — the effect on the organism.

1.1. Empirical evidence of the additional effect of occupational impulse noise on hearing

A number of studies on the effect of industrial impulsive noise on hearing carried out from the seventies to the 2020s show that exposure to impulsive noise among workers cause significant hearing loss compared to exposure to steady noise [1,2,3]. Studies carried out in several countries (US, Canada, Russia, Norway, Finland, Sweden) have shown that

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most of the hearing loss was in the higher frequencies (3–8 kHz). The hearing loss at 4 kHz was approximately 5–10 dB for those under 30 and 35–40 dB for those between 50 and 60 years of age.

1.2. Two theories of mechanism of impact on hearing

Brüel (1976) explained how impulse noise can cause more damage than the amount of energy calculated would indicate, compared to continuous noise [4]. The averaging time of the brain is about 35 ms, and therefore these impulses are more intensive than they appear to be based on loudness, that is short impulses sound less loud than longer ones of the same intensity. The increased risk to hearing arises because, first of all, these impulses are transmitted with full force to the inner ear (the averaging times of the outer and middle ears being 50 and 35 ms, respectively). Short impulses with relatively high energy content around 4 kHz are almost always amplified by resonance in the outer and middle ear so that these impulses reach the inner ear with an amplitude of 10–12 dB higher than other types of noise. Given this amplification, certain loud sounds may damage the nerve ends of the inner ear producing permanent hearing loss, even though a sound level meter with a fast time constant would indicate that their level is lower than the danger level.

Clifford and Rogers (2009) provided a new explanation of the mechanism by which impulse noise may be more damaging than continuous sound [5]. As sound energy to the cell increases, the mechanism of cochlear damage shifts from biochemical injury to mechanical injury. Outer hair cells appear to be more sensitive than inner hair cells to impulse noise because of their energy requirements, which lead to increased production of reactive oxygen and nitrogen species and self-destruction by apoptosis.

From Brüel's theory, as an indicator of impulsivity a quantity with the same name as the phenomenon arises, impulsive noise. Impulsive noise is measured with sound level meter using exponential RMS integration for impulse exponential time constant, $\tau = 35$ ms, that is AI-weighted equivalent continuous sound pressure level, L_{pAIeq} comparing to linear RMS integration for fast time constant, $\tau = 125$ ms that is used for measuring A-weighted equivalent continuous sound pressure level, L_{pAeq}, that is time-weighting I specified in the well-known sound level meter's International Standard IEC 61672-1 (at least in previous updates as will be noted later).

As for Clifford and Rogers' theory statistical measurements such as kurtosis hold promise for the quantitative prediction of hearing loss. A basic form for noise metrics is designed by combining the equivalent sound pressure level and a temporal correction term defined as a function of kurtosis of the noise. Kurtosis is defined as the fourth standardized moment about the mean of the data, Eq. (1):

$$\frac{E\left(x-m\right)^4}{s^4}, \tag{1}$$

where s is the standard deviation of x, $E(x - m)$ represents the expected value of quantity, m is the mean of x. Kurtosis describes the peakedness of a distribution, which is independent of the overall level and was suggested as a metric of impulsiveness by Erdreich [6].

1.3. Study of the relation between the indicators of impulsiveness

In addition to the listed indicators of impulsivity supported by these two theories, many others appear in the literature, standards and national regulations: the highest peak in the series of successive peaks — peak level, A duration — a duration of the first overpressure, B duration — the duration from the highest peak level to a point of time when the envelope of pressure fluctuation stays within 20 dB of the peak pressure level, crest factor — the difference between peak and RMS level of the noise, C-weighted peak sound pressure level, number of impulses that overpass the given peak pressure during the working day [7,3]. In a recent study [8], the relationship of a number of these indicators (impulsive adjustment K_I, C-weighted peak sound pressure level $L_{p,Cpeak}$, and crest factor) to kurtosis as a promising candidate for predicting the damaging effect of impulsivity was examined. Here impulsive adjustment for the impulsive noise is determined as the difference between the AI-weighted equivalent continuous sound pressure level L_{pAIeq} and A-weighted equivalent continuous sound pressure level L_{pAeq}, Eq. (2):

$$K_{I} = L_{pAIeq} - L_{pAeq} \quad (2)$$

Since kurtosis was identified as a promising factor in an indicator based on a new model that is still being tested on animals (chinchillas) [9] and on certain groups of shipbuilding workers in China [10] in new approaches to the problem of the impact of impulsive noise on humans, the original idea was to find from the existing ones the indicators that correlate with kurtosis the best. It was shown on a sample of 140 various noise exposures measured in situ in the industry where impulsive noise occurs that Brüel's adjustment for impulsivity K_I strongly correlates with kurtosis at the significance level of 0.01, while other examined indicators of impulsivity do not correlate significantly. The correlation at the stated significance level means that there is a 99 % probability that measurands K_I and kurtosis are correlated, and therefore may be stated that they do measure the same quality, in contrast to others that are not significantly correlated to kurtosis and therefore it is very probable that they do not measure same quality.

As it appears, two theories give two measurements that equally well (or at least very similarly) predict the effect of impulsivity. A similar duality in prediction is also found in the evaluation of vibrations containing occasional shocks on humans. It turns out that the effect of that kind of vibration can be viewed in two different ways: by evaluating *MTVV* calculated by exponential RMS integration, similar to Brüel's impulsiveness for impulsive noise, and the fourth degree of vibration dose (*VDV*) [11], i.e. the sixth degree of vibration dose (ISO 2631-5 method [12]) which as statistical measures of vibration distribution in the time domain would correspond to kurtosis. Since noise and vibrations are physically the same (oscillations of the physical environment), they manifest themselves as one or the other depending on the environment (gas, liquid, solid body), and the biological individual on which they act is the same — a human being, one would expect a similar duality of theoretical explanation to be demonstrated for the case of impact of impulsive noise on humans.

1.4. Inconsistencies in existing regulations and available evaluation methods

The national Regulation [13] based on Directive 2003/10/EC of the European Parliament and of the Council [14] in Article 10 mandates the evaluation of noise, including the evaluation of different noises in the time (especially impulsive) and frequency domain (eg tonal noise). The mandatory method for the determination of occupational noise exposure is the ISO 9612 method [15]. From this standard, since its 2009 update, the method of determination of rating level for the type of noise, which was previously provided in Annex C [16], has been removed. In the current ISO 9612 update is stated that this International Standard deals with A-weighted levels but is applicable also to C-weighted levels. As seen before, C-weighted peak sound pressure level is not a good predictor of the effect of impulsive noise on hearing, at least in the industry where impulsive noise appears (exposures to blasts are excluded). Exposures determined by the ISO 9612 method are to be compared to the limits set on the basis of the estimation of noise-induced hearing impairment that is given in ISO 1999 [17]. The current update states that the prediction method presented is based primarily on data collected with essentially broadband, steady, non-tonal noise. In the previous update, [18] further stated that users may wish to consider tonal noise and/or impulsive/impact noise as being about as harmful as a steady non-tonal noise that is approximately 5 dB higher in level due to the fact that the application of the database to tonal or impulsive/impact noise represents the best available extrapolation.

The campaign to remove the correction for noise types dates back to the 1980s and continues to the present day. By the update of IEC 61672-1:2013 [19] the technical specifications of time-weighting I have been removed. Finally, it was removed from ISO 7779 by the update ISO 7779:2018 [20].

Some explanations that, if any, are given for this would be that there are no confirmed effects of impulsivity that would further affect the human beyond the equivalent noise level (not true, there are and they are proven), the absence of an adequate theoretical model that would describe the eventual mechanism of additional effect of impulsivity (not true, there are at least two as shown before) and that there is simply no good argument for choosing the right one out of the multitude of impulsivity indicators. As for the last of these arguments recent research points to kurtosis, and there is also well-established Brüel's impulsivity as demonstrated in the correlation study mentioned before that equally well or very similarly predicts the effect.

2. Proposal of the Rule for Rating

For task-based measurement for the task where impulse noise occurs rating level is calculated according to Eq. (3):

$$L_{\mathrm{r}} = L_{\mathrm{pAeq}} + K, \tag{3}$$

where K is adjusted according to 2.1. or 2.2. depending on the choice.

Daily noise exposure level is calculated from the L_{pAeq}-s (where impulse noise doesn't occur) and from L_{r}-s (where impulse noise occurs) for each task and the duration of each of the tasks according to Clause 9 of ISO 9612.

For job-based measurement from the jobs identified, for each homogeneous noise exposure group and each sample taken among the members of the group for the sample where impulse noise occurs rating level is calculated according to Eq. (3).

Daily noise exposure levels for workers in a homogenous exposure group are calculated from the L_{pAeq}-s (where impulse noise doesn't occur) and from L_{r}-s (where impulse noise occurs) for each sample according to Clause 10 of ISO 9612.

For full-day measurement for each full-day measurement where impulse noise occurs rating level is calculated according to Eq. (3).

Daily noise exposure level is calculated from the L_{pAeq}-s (where impulse noise doesn't occur) and from L_r-s (where impulse noise occurs) according to Clause 10 of ISO 9612.

2.1. Rule based on impulsive adjustment K_I only

$$
\begin{aligned}
K &= 0 \text{ dB} && \text{if} \quad L_{pAIeq} - L_{pAeq} < 2 \text{ dB} \\
K &= L_{pAIeq} - L_{pAeq} && \text{if} \quad 2 \text{ dB} \le L_{pAIeq} - L_{pAeq} < 5 \text{ dB} \\
K &= 5 \text{ dB} && \text{if} \quad L_{pAIeq} - L_{pAeq} \ge 5 \text{ dB}
\end{aligned} \tag{4}
$$

In Eq. (1) rule based on impulsive adjustment K_I only is given. As may be seen it's practically the same rule given by the former update of ISO 9612 [16]. The advantages of choosing this rule would be well-established metrics of objective test method theoretically and empirically confirmed. Flaws may be seen when comparing K_I to kurtosis for different industrial impulsive noises [8]. Fig. 1 shows the correlation of K_I and kurtosis classified into distinctive zones according to impulsivity significance. Here K_I and kurtosis are to be considered significant when greater than 3 dB.

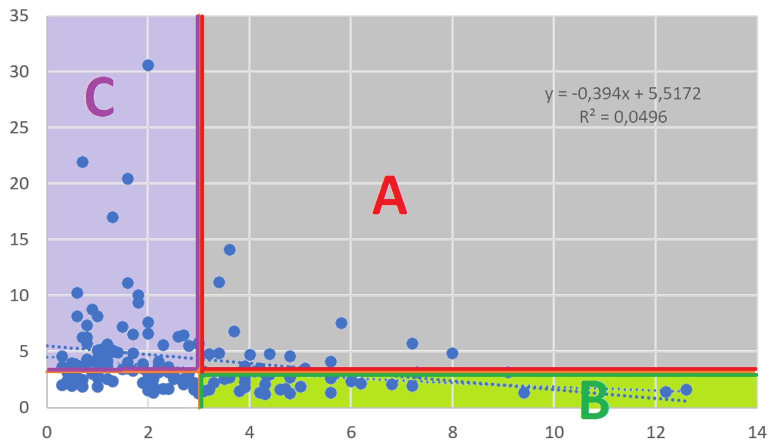

Fig. 1 Correlation plot for K_I and kurtosis classified into zones according to impulsivity significance [8]

Here in zone A are noises that have both impulsivity adjustments greater than 3 dB, in zone B noises whose K_I level is greater than 3 dB and kurtosis not, and in zone C noises whose kurtosis is greater than 3 dB but K_I not. Considering kurtosis as a promising basis for new metrics for noise impulsivity as recent research shows [5,9,10] by choosing this rating noises with high kurtosis and low K_I would be missed (e.g. some noises in in metal working industry, quasi-impulsive noises [8]).

2.2. Rule based on both impulsive adjustment K_I and kurtosis

$$K = 0\,\mathrm{dB} \quad \text{if} \quad L_{\mathrm{pAIeq}} - L_{\mathrm{pAeq}} < 2\mathrm{dB}, \text{ and } kurtosis < 2\mathrm{dB}$$

$$K = \frac{\left(L_{\mathrm{pAIeq}} - L_{\mathrm{pAeq}}\right) + kurtosis}{2} \quad \text{if} \quad 2\mathrm{dB} \le \frac{\left(L_{\mathrm{pAIeq}} - L_{\mathrm{pAeq}}\right) + kurtosis}{2} < 5\mathrm{dB} \qquad (5)$$

$$K = 5\,\mathrm{dB} \quad \text{if} \quad \frac{\left(L_{\mathrm{pAIeq}} - L_{\mathrm{pAeq}}\right) + kurtosis}{2} \ge 5\mathrm{dB}$$

In Eq. (5) rule based on both impulsive adjustment K_I and kurtosis is given. This rule is balanced, on the one hand, there is metrologically well-based K_I, on the other kurtosis has a role in balancing for situations mentioned in 2.1. as flaws of choice of that rule. Adding kurtosis is problematic in the sense that the exact metric of the model based on it has not yet been developed (or at least published), namely theoretically it is evident that a true indicator of the damaging effect of temporally uneven noise (and impulsive) is some function of kurtosis, but for now, in the available literature, the authors have not come up with an exact formulation. On the other hand, the measured similarities in value and in the very order of values of impulsivity K_I and kurtosis would justify such averaging because this would increase the effect of impulsivity for statistically more uneven noise i.e. higher values of kurtosis (which effect is the basis of the theoretical explanation of the new model) and reduce it for impulsive noise statistically less uneven in time i.e. lower values of kurtosis (which is again in line with the new theoretical model). Therefore, the choice of this rating rule will ensure that some cases of harmful impulsivity are not omitted from consideration.

2.3. On the limits of adjustment

This rating is adapted to the national regulation. Namely, according to the Regulation [13], there are two action values and the limit value (80, 83 and 85 dB). The adjustment 2 to 5 dB stands for if the measured noise level is between two limits, say 80 and 83 dB, the adjustment of 2 dB would shift the level above the next limit for some values of the measured exposure. An adjustment greater than 5 dB is not required, because exposure to noise above 83 dB requires personal protective equipment by the Regulation. For regulations in other countries, e.g. taken from the Directive [14] (80 and 85 dB), it would make sense to take other limits of adjustment for the range of impulsivity, e.g. 3 and 6 dB. Here, values above 5 dB would make sense if the noise level is close to 80 dB, in which case a correction of 5 dB could leave the corrected value below 85 dB (the level that requires personal protective equipment by the Directive) and leave the worker unprotected.

3. Conclusion

Numerous studies on the effect of industrial impulsive noise on hearing conducted worldwide demonstrate that exposure to impulsive noise among workers causes significant hearing loss compared to steady noise exposure, due to the need for a proper assessment of the occupational risk of hearing damage on the one hand and the requirements of regulations on the other. Therefore, a rule for rating levels of industrial impulsive noise was proposed based on selected indicators of impulsivity. Of the multitude of indicators of impulsivity present in the literature, primacy is given here to the impulsive adjustment which has been present in the literature since the 1970s and whose measurement represents an objective method of examination and kurtosis, the statistical measure, which is a promising candidate supported by recent theoretical research and experimental studies, and arguments for this choice are given.

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