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GLOBAL INDEX OF THE ACOUSTIC CLIMATE

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The paper deals with the essential problem of noise protection in the work environment. It develops the criteria of the assessment of the acoustic climate quality in industrial rooms, often already at the stage of their designing. The requirements of the acoustic safety of workplaces force to improve constantly the processing of the results of model and experimental investigations and to search for synthetic ways of presentation of the acoustic quality of industrial rooms in order to be able to estimate the risk of occupational diseases for the employees exposed to noise. Until quite lately, the index method of assessment of the acoustic climate of industrial rooms was based – on three partial indices: the technological one, the sound power and the acoustic properties of the room. The paper presented here expands the method by introducing additional indices: the index of impulse and impact noise, the index of fittings density of the room, the index of the noise spectrum distribution and the index of low-frequency noise. Such broad formulation of acoustic phenomena in industrial rooms by the single-numbered Global Index is an innovatory enterprise. The indices were experimentally estimated in the Forge.

1. Introduction

Problems of assessment and maintaining of proper acoustic conditions in industrial rooms has a large practical significance for the protection of work environment in industry. Selection of adequate measures for solving such problems depends on the results of the model analysis of a sound field inside rooms in which their shape, the realized technological processes, positions of work stations and conditions of combining placements and coordination of different noise sources are taken into account. This situation prompted us to describe the acoustic climate as a synthesis of a certain set of agents called "partial climates".

An acoustic climate of the work environment is determined by a system of acoustic phenomena occurring in this environment and described most often by means of suitable indices being functions of frequency, time and space [3, 11]. A-weighted equivalent sound level, L_{Aeq}, characterized by a high correlation with the people's feeling of noise annoyance, defines the quality of the acoustic climate in the work environment.

The equivalent sound level L_{eq} enables an assessment of noises of different nature as well as provides the possibility to find adequate functions connecting the L_{eq} values with parameters describing the work environment.

The sound pressure level in any point of the room, L_{pi}, which takes into consideration the influence of a direct sound and that of a diffused sound-field, can be found – in agreement with the Sabin's and Eyring's [1] sound field model – from the formula:

$$L_{pi} = 120 + 10 \log \left(\sum_{j=1}^{n} N_j \frac{Q_j}{4\pi r_{ij}^2} + \frac{4(1-\alpha)}{A} \right), \tag{1}$$

where N_j – sound power of the j-th source (machine or equipment), [W]; r_{ij} – distance of the i-th observation point from the j-th machine or equipment, [m]; Q_j – directivity factor of the j-th source; A – total absorption in the room, [m^2], α – average room absorption coefficient.

The analysis of data occurring in Eq. (1) leads to the index method of assessment of an acoustic climate in industrial rooms. An adequate measure of the acoustic climate is the Global Index of the Acoustic Climate, W_{GKA}. The assessment of the acoustic climate of an industrial room expressed by a single number is an attempt of the synthesis of all acoustic phenomena manifested inside the room into a single-numbered index. The partial indices introduced in this paper are illustrated by calculations performed for a Forge and the final assessment of the acoustic climate in that workshop is given in the last chapter.

2. Index of the acoustic climate quality in industrial rooms

The acoustic climate of every industrial room should be adequate to the room category describing its destination, which determines the permissible noise level, L_{PL}, dB. The hereby assumed (for the purpose of the assessment) values of the permissible noise level correspond to the values enabling the performance of basic tasks by the employees (Table 1).

The Global Index of the Acoustic Climate, W_{GKA}, is the result of the assessment of the climate quality W_{KA} and the assessment of hazards at the work stations W_{STP} if such hazards occur in the room under test. On the basis of the author's own research and analyses of the bibliographical data concerning the prediction of the sound field in industrial rooms, the author proposes the assessment of the acoustic climate of an industrial room to be done on the bases of three partial indices. They estimate: the noisiness of the technological process – W_T, the potential of the sound power of the machines and equipment installed in the room – W_N, and the acoustic and geometrical properties of the room itself – W_A.

Table 1. Categories of industrial rooms.

Industrial room category	Destination of the industrial room	Permissible noise level, L_{PL}, dB
I	Required concentration and verbal communication, e.g. design offices, data processing offices	55
II	Required verbal communication, e.g. precision-work shops	65
III	Laboratories with noise sources, rooms with machines and calculating equipment, etc.	75
IV	Remaining industrial rooms, e.g. heavy industry halls	85

The numerical value of the acoustic climate quality, W_{KA}, correlated with the noise-exposure risk for persons working in the particular room, shows to which extend the acoustic climate can be considered to be friendly to human beings.

The Index of the Acoustic Climate Quality, W_{KA}, introduced by the author is expressed by the formula:

$$W_{KA} = \sqrt{\frac{W_T^2 + W_N^2 + W_A^2}{3}}, \tag{2}$$

where W_T, W_N, W_A – partial indices of the assessment of the acoustic climate quality.

2.1. Technological index

The technological index is determined on the bases of identification of the actual noisiness of the technological process. The sound levels measured at measuring points positioned above the floor of the room allow producing an acoustic map. The map shows the distribution of the sound energy in the space of the room and its isophones provide information where the permissible noise values are exceeded and where the hazardous zones, in which hearing impairment may affect the employees, are located. The values of the surface areas enclosed by equal sound level contours, L_{Aeq} (Fig. 1), determine the technological index W_T:

$$W_T = \frac{\sum\limits_{h=0}^{n} \eta_h S_h}{S_H}, \tag{3}$$

where η_h – weighted index of noisiness of surface S_h for the h-th isophone, S_h – surface area of the room encircled by equal sound level contours $(L_{PL} + h)$ (L_{PL} is the permissible noise level value for the room under test, $h = 0, 1, \ldots n$), S_H – total surface area of the room, [m^2].

The isophone $(L_{PL} + n)$ represents the contour of the highest sound level in the room under tests. The weighted index of noisiness, η_h, has been determined for each

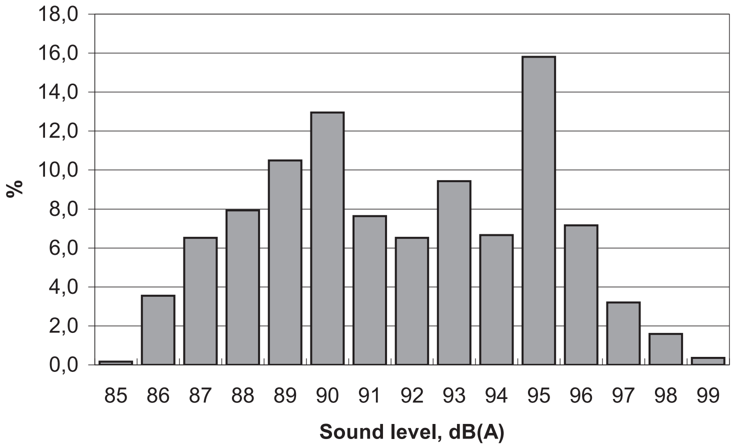

Fig. 1. Percentage division of the surface area encircled by 85 – 99 dB isophones – in the Forge.

surface area, S_h, separately. The values of that index fall within the range $0 < \eta_h \leq 1$:

$$\eta_h = \frac{1}{10^{0.1(L_{Aeq_h} - L_{\mathrm{PL}})}}, \tag{4}$$

where L_{Aeq_h} – A-weighted equivalent sound level of the h-th isophone, [dB].

The values of the weighted index of noisiness η_h for the surface area S_h, enclosed by the equal sound level contour (for $L_{PL} = 85$ dB), are presented in Fig. 2.

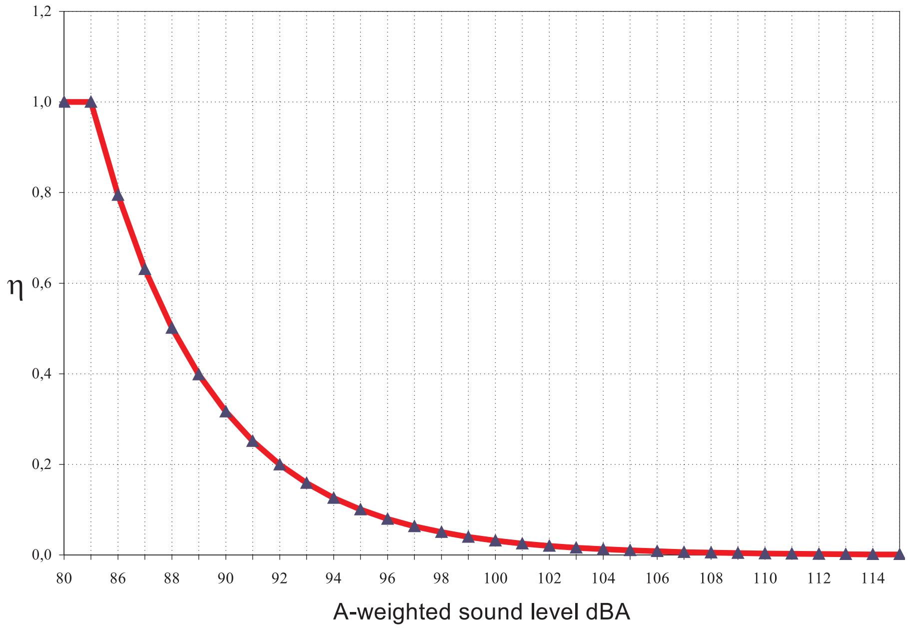

Fig. 2. Weighted index of noisiness of the h-th surface area, η_h.

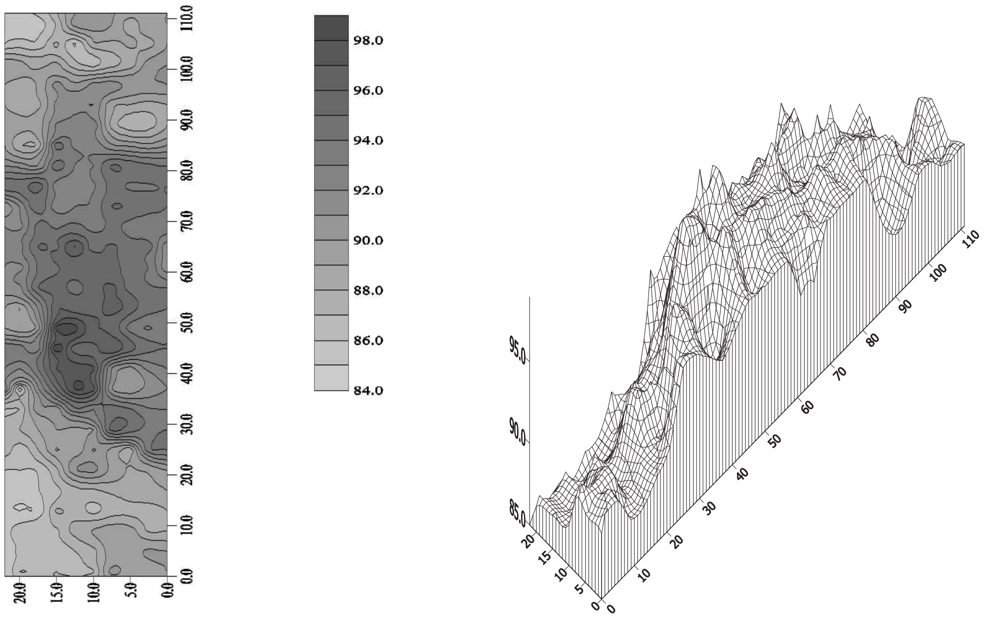

Fig. 3. Distribution of the sound A level in the Forge: a) two dimensional, b) three dimensional.

The acoustic map of the Forge provides the possibility of assessing the layout of workplaces and noise hazards occurring there. It also allows planning additional workplaces or a rearrangement of the existing ones in order to reduce the health of persons exposed to noise. Predicting that index for newly designed industrial rooms is also possible. An assessment of the sound level at the points of the measuring grid can be done by means of a simulation of the sound propagation inside the room. The selection of the prediction method is limited by the possibility of employing an adequate acoustic model.

2.2. Index of the sound power

All machines and equipment installed in the industrial room are considered to be actual sources of sound energy. The density of that energy at any point of the room is a function of the sound power of the machines and equipment. The partial acoustic climate depends on the noise level generated by the i-th source.

The index of the installed sound power is given by the following equation:

$$\begin{aligned} W_N &= 1 & \sum_{i=1}^{n} N_i &\le N_{a0}, \\ W_N &= \frac{N_{a0}}{\sum\limits_{i=1}^{n} N_i} & \sum_{i=1}^{n} N_i &> N_{a0}, \end{aligned} \tag{5}$$

where N_i – sound power of the i-th machine or equipment installed and operating in the industrial room, [W]; V_H – volume of the room, [m^3]; n – total number of machines and equipment operating in the room; N_{a0} – sound power of the substitute sound source emitting noise of the L_{PL} level in the area equivalent to the floor surface area S_H:

$$L_{N_{a0}} = L_{PL} + 10 \log S_H. \tag{6}$$

The reference power, called by the author the specific sound power of the room with the floor surface area, S_H for$L_{PL} = 85$ dB, is as follows:

$$N_{a0} = 10^{0.1(85+10 \log S_H)-12}. \tag{7}$$

The specific sound power of the industrial room, N_{a0}, is a characteristic value of the room under test. The sound power of individual machines and devices can be estimated either on the bases of attests or directly at the site of machine operation. In the assessment of the index of the installed sound power, the provision of substituting the actual sound source by several substitute elementary sources was assumed. The application of such a model for computing the sound power of the actual sound source as well as for the prediction of the sound propagation inside the industrial room is also possible.

In the case of an emitting impulse or impact noises, the sound power index W_N is corrected by the impulse noise index, W_{imp}, described below.

Acoustic characteristics of selected machines and devices operating in the Forge are presented in Fig. 4. The determined sound power index is $W_N = 0.35$.

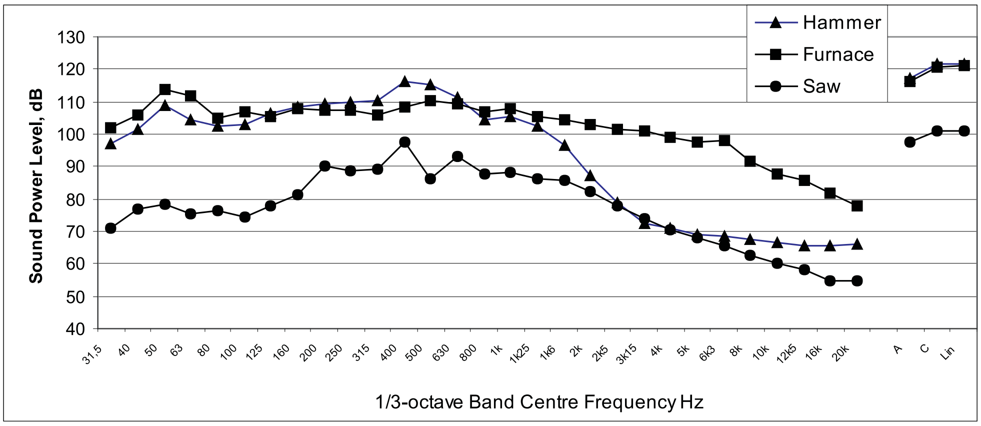

Fig. 4. Acoustic characteristics of the main noise sources in the Forge.

2.3. Index of the acoustic properties of the room

A sound field at any point inside the industrial room is the sum of several reflected waves, which amplitudes and phases depend in a complex way on the shape, size and acoustic properties of the surfaces surrounding the room. Solutions of acoustic problems of industrial rooms should be looked for among methods, in which exact values characterizing the spatial distribution of a sound field (as a frequency function) are substituted by average values, however, with all the consequences of such simplifications.

The acoustic properties of a room manifest themselves mainly in the zone of the diffusion field. The distribution of the sound level in this field is significantly influenced by the shape, size and configuration of the sound absorbing materials on the walls and by the density of the equipment and fittings in the room (Fig. 5).

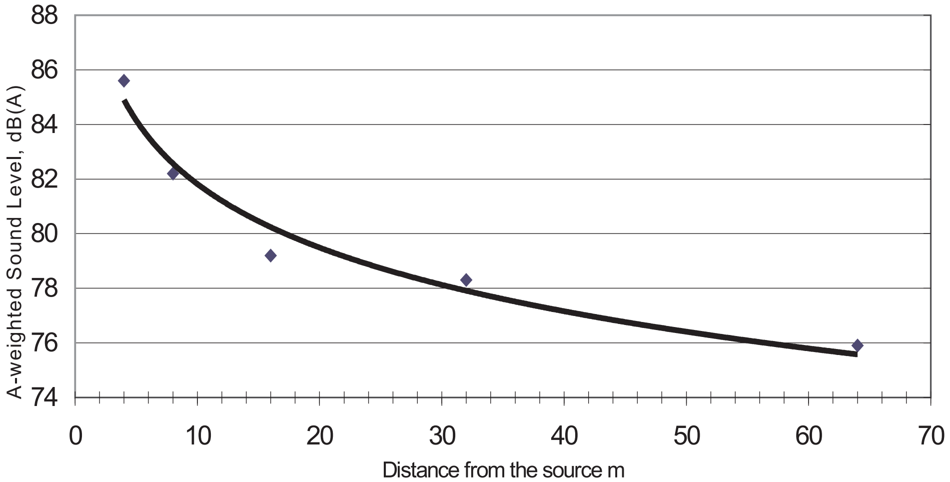

Fig. 5. The A-weighted sound level as a function of the distance from the source in the Forge.

One of the acoustic features of the room is the average coefficient of the sound absorption estimated by reverberation time measurements. The reverberation time is a parameter, which can be either measured in the already existing room or planned at the stage of preparing the documentation for a brand new room. The diffused field is related to the reflected waves. A measure of the quantity of the reflected waves is the coefficient of sound absorption by the surrounding surfaces, the various objects and persons present in the room. This coefficient is the ratio of the absorbed sound, E_{abs} to the total sound energy of the incident wave, E_{total}.

Thus, the index of the acoustic properties of the room, W_A, is given by a formula:

$$W_A = 1 - e^{\frac{-0.161 V_H}{S_C T}}, \tag{8}$$

where V_H – volume of the room, [m^3]; S_C – total area of surfaces surrounding the room (walls, ceiling, floor), [m^2]; T – reverberation time measured in the room, [s].

The fittings density of an industrial room can influence the absorbing capacity of that room, Q_F. This influence depends on the number and location of machines and devices as noise sources. It as well as gives also the possibility of an additional formation of the sound field in the room. The average fittings density, Q_F is defined according to [6]:

$$Q_F = \frac{S_f}{4V_H}, \tag{9}$$

where S_f – the total surface area of all elements of fittings exposed to the sound field, [m^2]; V_H – room volume, [m^3].

The average fitting density of the room, Q_F, can be estimated on the bases of three parameters: H – average height of the fittings in the room, m; N_f – number of fittings elements in the room, S_{ff} – floor surface area taken by machines with reference to the total surface area, m^2.

The total surface of all elements of fittings present in the room and exhibited in the sound field, S_f, equals:

$$S_f = N_f(0.41 \cdot l^2 + 2.82 \cdot H \cdot l), \tag{10}$$

where

$$l = \sqrt{\frac{S_{ff} \cdot L \cdot W}{0.41 \cdot N_f}}, \tag{11}$$

where L – length of the room, [m]; W – width of the room, [m].

For the majority of industrial rooms, the indexes of acoustic properties have small values. This is generally caused by an insufficient acoustic adaptation of such rooms. The average coefficient of the sound absorption, determined for the industrial room and all machines present there, is given by the following expression:

$$\alpha_t = \frac{S_c \alpha_e + S_f \alpha_f}{S}, \tag{12}$$

where α_e – average coefficient of sound absorption determined for the empty room (without machines and equipment); α_f – average coefficient of absorption of sound when machines and equipment are installed in the room; $S = S_c + S_f$, [m^2]; S_c – total area of surfaces surrounding the room, [m^2].

Thus, the total value of the index of the acoustic properties of the room, W_A, is the sum of the indices of the acoustic properties of the empty room, W_e, and of those of the room fitted with machines and equipment, W_f :

$$W_A = W_e + W_f. \tag{13}$$

The computer simulation (Fig. 6.) indicates that an adequately large value of the density, Q_F, can have a significant influence on the creation of the acoustic field inside the room and on the value of index W_A [4, 11]. In the case of the Forge, where the average value of Q_F is small and the machines' frames are made of materials of low noise absorption coefficients (metals), this influence is negligible.

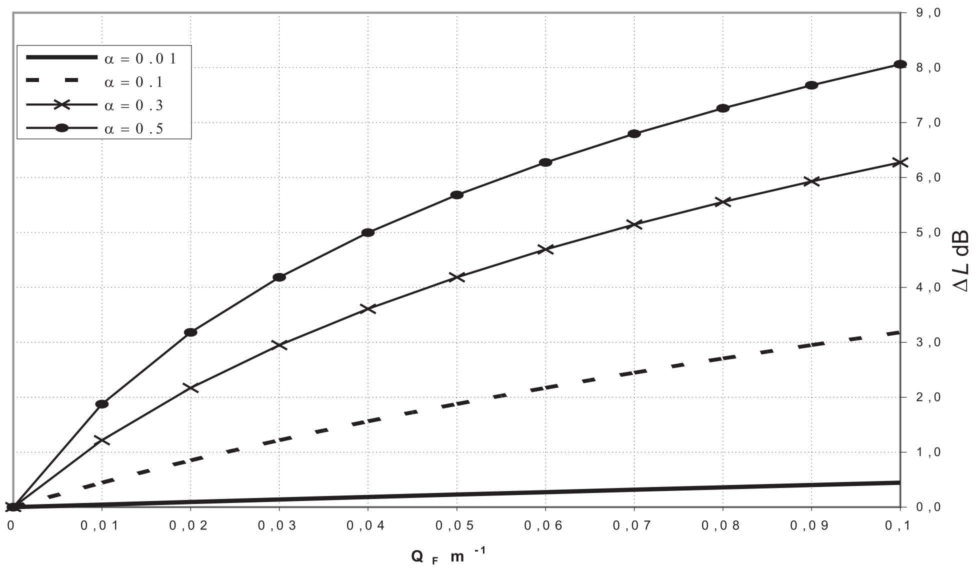

Fig. 6. Influence of the fittings density of the room, Q_F, on the reduction of the sound level, ΔL, in the Forge for the average values of the coefficient of sound absorption of machines and equipment, $\alpha = 0.01$, 0.1, 0.3, 0.5.

3. Additional indices of the acoustic climate of an industrial room

The partial indices of the acoustic climate estimated above do not exhaust the possibility of analysing other factors responsible for the creating of the acoustic climate in the room. Harmfulness, annoyance and arduousness of noises depend on their physical features and on their changes in time. The noise spectrum as well as the frequency of occurrence, the length of time intervals with excessive noise, the character of noise (continuous, discontinuous, pulsating) provide essential information.

3.1. The noise spectrum distribution index

The estimation of the acoustic spectrum can be made on the basis of the relevant N curve (NR curves) [1]. The shape of the curves of noise assessment reveals that greater importance is attributed to higher frequencies than to lower ones, which is substantiated by a greater arduousness of high frequency noises. However, this method would be extremely troublesome in the case of a general multipoint estimation carried on in the industrial room. Therefore the introduction of the method described in [9] and [15] with the possibility of its adaptation to the noise assessment in industrial rooms seems to be justified. The assumption that the method determines the differences between the measured sound levels – with the application of the compensating A and C networks – is followed by the ascription of those differences to the spectrum classification (in the range of classes I to VI) as presented in Table 2.

Table 2. Classification of the noise spectra [8, 12].

No	Noise class	Coefficient of spectrum distribution $\Delta_{C\_A} = L_C - L_A$, dB
1	I	≤ 0
2	II	0.1 – 2.0
3	III	2.1 – 4.0
4	IV	4.1 – 9.0
5	V	9.1–15.0
6	VI	> 15.0

The noise spectra classified as class I are characteristic of high-frequency noise, the noise level differences $L_C - L_A$ of the classes II, III and IV are characteristic of spectra of medium frequencies with a shift of the maximal values in the direction of rather low frequencies, while class V includes spectra of significantly lower frequencies. The standard noise spectra in octave frequency bands for the five classes are presented in Fig. 7 (on the basis of reference [17]). The author introduced for the reasons of identification class VI, which Δ_{C-A} values, according to [8], testify to distinct problems with low frequency noises and the probability of the occurrence of infra-sound noises.

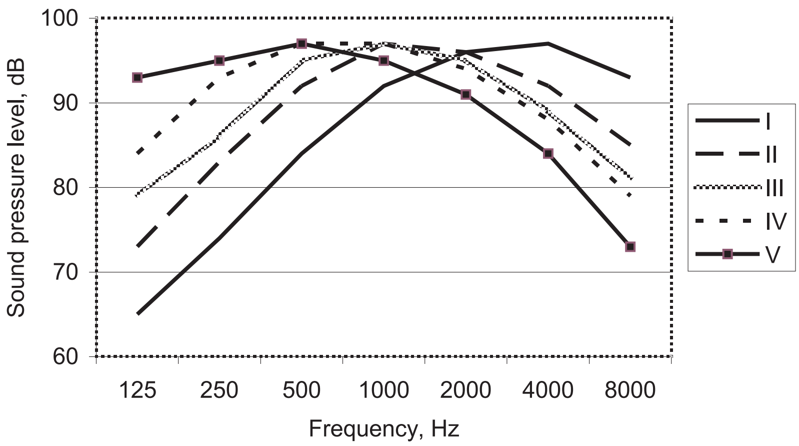

Fig. 7. Standard noise spectra of classes I to V.

The information concerning the coefficient of the noise spectrum distribution in industrial rooms allows the preliminary determination of the required noise control measures and can also indicate the necessity of infrasound noise measurements at the workplaces according to the recommendations of the standards.

The coefficient of the noise spectrum distribution in the Forge is $\Delta_{C\_A} = 4.7$ dB, which corresponds to class IV (medium to low frequency noise).

3.2. Index of the impulse and impact type of noise

Many industrial machines generate impulse and impact noises, especially in heavy industry, e.g. impacts of metals on metals (presses, hammers, etc). An employee is exposed to noise, which level depends on the acoustic performance of the room related mainly to the reflected acoustic waves. An important practical aspect is the room response to an impulse excitement, what is related in turn to the processes of the sound build-up and decay.

The presence of impulse components of noises is shown by the difference of the sound equivalent levels, L_{pAeq} , measured with the time-characteristics of the measuring instrument I, and S.

$$\Delta_{I-S} = L_{pAIeg} - L_{pAeg}. \tag{14}$$

If this difference equals 3 dB or more, the noise is considered to be an impulse one. The duration of an impact event is 0.1 to 2 s and depends mainly on the acoustic performance of the room [14]. Both, the impulse and impact noises are more hazardous for health and more arduous for people than continuous broad-band noises. Parameters of the impulse are: peak values of the sound pressure level, impulse duration, sound building-up time, spectrum, number of impulses and interval of their repetition. None separate criteria for the impulse noise assessment were developed, apart from the A-weighted equivalent sound level and the requirements of not exceeding the permissible value $L_{\text{Cpeak}} = 135$ dB. Neither the permissible peak values of the sound pressure nor the permissible number of impulses at those peak values are given.

An estimation of the impulse noise, which takes into account the number of impulses occurring during an 8-hour work-shift, is applied in some countries. The indices of impulse and impact noises are mainly assessed due to the C-weighted peak level, L_{Cpeak}. Their values are given in Table 3.

Table 3. Assessment of the impulse noise.

No	Sound level value L_{Cpeak}, dB	Number of impulses at 8-hour work-shift	Index of the impulse noise, W_{imp}
1	$135 < L_{\text{Cpeak}}$	$n = 0$	0.5
2	$125 < L_{\text{Cpeak}} \leq 135$	$n \leq 100$	0.6
3	$115 \leq L_{\text{Cpeak}} \leq 125$	$n \leq 1000$	0.7
4	$105 \leq L_{\text{Cpeak}} \leq 115$	$n \leq 10000$	0.8
5	$100 \leq L_{\text{Cpeak}} \leq 110$	$n \leq 100000$	0.9
6	$L_{\text{Cpeak}} \leq 100$	no limitation	1

The index of the impulse noise W_{imp} is taken into account when determining the acoustic power index, W_N. The author introduced the impulse noise index, W_{imp} into the formulation 8 in order to calculate the total sound power of machines and equipment operating in a room:

$$W_N = 1 \qquad \sum_{i=1}^{n} \frac{1}{W_{\mathrm{imp}\,i}} N_i \leq N_{a0},$$
$$W_N = \frac{N_{a0}}{\sum_{i=1}^{n} N_i} \qquad \sum_{i=1}^{n} \frac{1}{W_{\mathrm{imp}\,i}} N_i > N_{a0}, \tag{15}$$

where N_i – power of the i-th machine, [W].

The C-weighted peak levels (L_{Cpeak}(t)) versus time for the process of pulley forging at the hammer operator workplace in the Forge are presented in Fig. 8.

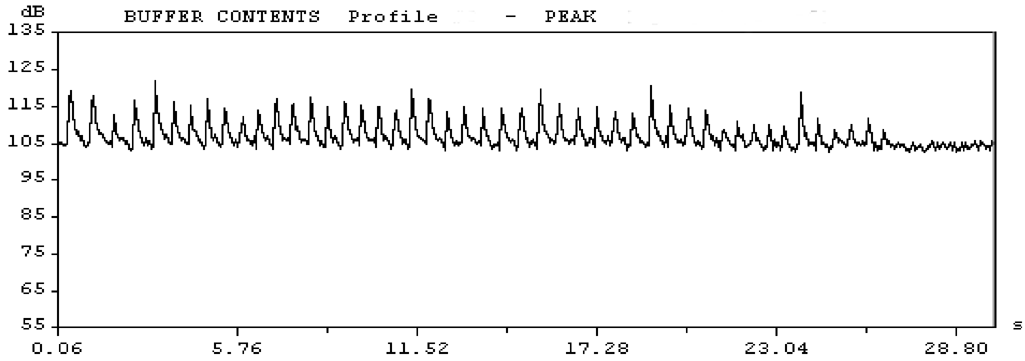

Fig. 8. Process of forging – hammer operator workplace – $L_{\mathrm{Cpeak}}(t)$.

4. Index of hazardous workplaces

The acoustic assessment of the workplace has been done on the bases of comparisons of values actually measured at workplaces with the permissible values of noise exposure, referred to the 8-hour work-shift, $L_{EX,8h}$, maximal A-weighted level, L_{Amax} and the C-weighted peak level, L_{Cpeak}. If any one of those noise levels is exceeded the workplace is classified as hazardous due to the hearing protection.

The index of the hazardous workplaces W_{STP} is calculated from the formula:

$$W_{STP} = 1 - \frac{n_Z}{n_C} \quad \text{if} \quad n_C \neq 0$$
$$W_{STP} = 1 \quad \text{if} \quad n_C = 0 \tag{16}$$

where n_Z – number of workplaces at which the permissible noise levels are exceeded (L_{Aeq}, L_{Amax} or L_{Cpeak}); n_C – total number of workplaces in the room under testing.

Since the permissible values of noise exposure are exceeded at all workplaces in the Forge, the index of the hazardous workplaces $W_{STP} = 0$.

5. Index method of assessment of the acoustic climate in industrial rooms

The idea of the index method of the assessment of the acoustic climate is the single-numbered Global Index of the Acoustic Climate in an industrial room, W_{GKA}, which allows the explicit classification of those rooms. The global index is a function of partial indices having values in the range from 0 to 1. This is a result of aggregation of the assessment of the acoustic climate quality in industrial rooms (W_{KA} index) and the hazard assessment at the workplace (W_{STP} index):

$$W_{GKA} = \kappa_1 W_{KA} + \kappa_2 W_{STP}, \tag{17}$$

where κ_1, κ_2 – weight coefficients of the acoustic climate assessment: $\kappa_1 = 0.9$, $\kappa_2 = 0.1$.

Both the partial indices chosen for the estimation of the acoustic climate have a fundamental meaning for the description of the acoustic circumstances in industrial halls. The index of the acoustic climate quality W_{KA} contains information on the acoustic conditions in the hall, and the index of workplace hazard W_{STP} gives information on the influence of partial acoustic climates on workers at their workplaces. The selection of weighting indices is problematic. It is based on experimental data, the estimation of occupational risk and subjective opinions of workers (Questionnaire data). The more attention is paid to the acoustic climate on the whole industrial hall the higher the κ_1 weighting. The noise hazard at workplaces has a significant meaning with reference to health and safety at work legislation but in this way of the assessment of the acoustic climate the danger of a local incidence must not be significant. Therefore the value of κ_2 is relatively low.

Partial indices and the Global Index in the Forge were determined experimentally. Previous experiences of the author concerned rather small industrial rooms of volumes not larger than 1000 m^3. In the case presented in this paper the dimensions of the industrial room were: $111.0 \times 22.0 \times 14.5$ m. Its volume was over 35 000 m^3 and the fittings density rather small. The Forge – as belonging to heavy industry – has a permissible noise level L_{PL} = 85 dB.

Series of measurements of the sound level distribution above the floor surface and the sound power level of machines and devices operating in the room were performed. Machines and devices as well as gas-fired furnaces were the noise sources emitting stable broad-band noises, while forging hammers emitted impact noises.

The determined values of partial indices for the Forge are:

- technological index $W_T = 0.27$,
- sound power index $W_N = 0.35$,
- acoustic quality index $W_A = 0.15$.

The acoustic climate quality index for the Forge determined on the bases of the partial indices is $W_{KA} = 0.31$.

The Global Index of the acoustic climate W_{GKA} equals according to formula (17):

$$W_{GKA} = 0.9 \cdot W_{KA} + 0.1 \cdot 0 = 0.28$$

The low value of the global index requires the undertaking a lot of efforts in order to improve the acoustic climate in the Forge. Special attention should be paid to the increasing of the value of the sound power index and of that of the technological one. Those changes will significantly improve the acoustic climate in the room and thereby improving the work conditions at the place.

6. Conclusions

The assessment criteria of the acoustic climate of industrial rooms should be relatively simple, it means they should contain a small number of parameters comprising the final assessment (e.g. single-numbered Global index) and a large number of "input" parameters, which influence the final assessment. The Global Index is a complex phenomenon, which allows on the bases of regulations of elementary factors to estimate the index of all vibroacoustic processes occurring in an industrial room. The method proposed here is a tool for the "the first approximation" of the assessment of existing and newly designed industrial rooms. Such assessment can be a starting point for more precise investigations of the existing rooms. At the stage of the designing process, the uniform index (or a collection of indices) facilitates the quantitative estimation of different conceptions and the selection of the best solution.

The acoustic climate of an industrial room is a function of several parameters. In his previous papers, the author estimated the acoustic climate on the basis of the global index which was a function of three indices: the technological process, sound power of machines, acoustic and geometric properties of the room.

In the present paper, three new indices influencing the total climate are introduced: the index of impulse and impact noise, the average fittings density of the room, the distribution of the noise spectrum with taking into account the low frequency noises.

Those additional indices were estimated when assessing the acoustic climate of the Forge and the final result of the Global Index of the Acoustic Climate of that shop equals 0.28. This value testifies [3, 11] to the alarming acoustic situation in the tested room and the high risk for the noise-exposed persons. The low values of partial indices indicate the necessity of undertaking a wide range of works aimed at the improvement of the acoustic climate in the Forge.

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