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Method of Acoustic Assessment of Machinery Based on Global Acoustic Quality Index

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For the use of acoustic assessment of machinery, a global index of acoustic quality has been developed. Acoustic quality index is considered as a product of the following partial indices: sound power index, index of distance between the workstation and the machine, radiation directivity index, impulse and impact noise index and noise spectrum index. Each partial index always assumes positive value. If the value of global index does not exceed 1, the noise of the assessed machine will not exceed the admissible value of A-weighted sound pressure level at the workstation.

Experimental tests were carried out in order to determine the values of global indices for a group of engine-generators, with the use of inversion method allowing for the determination of sound power level. The correctness of the determined values of indices was confirmed by the results of A-weighted sound pressure level measurements, at the hypothetically assumed workstations in simulated *in situ* conditions.

Keywords: machinery, noise, acoustic assessment, workstation.

1. Introduction

Reduction of noise emission from machines is one of the priority tasks and at the same time, one of the most efficient methods for reducing the risk resulting from exposure to noise. According to the requirements of the machinery directive 2006/42/EC (2006), a machine should be designed and manufactured in a way that will allow the hazards resulting from the emission of noise to be reduced to the lowest possible level. According to the machinery directive, only the emission sound pressure level must be taken into consideration, together with the sound power level, in carrying out the acoustic assessment of machine during the conformity assessment process. The European Standard ISO 11688-1 (2009), harmonized with this directive, refers among other things to the practice for the design of low-noise machinery. However, according to the practice, the exploitation parameters, which influence the value of sound pressure at workstations, are not taken into account on the design stage. Therefore it is proposed to develop a method for prediction of noise emission from the machinery in exploitation conditions, using the index method of acoustic assessment.

2. Global index of acoustic quality

For the purpose of acoustic assessment, a global index of acoustic quality Q_{GWA} was developed. The index is a function of 5 partial indices and can be described by the formula presented below:

$$Q_{\mathrm{GWA}} = Q_N \cdot Q_R \cdot Q_\Theta \cdot Q_{\mathrm{imp}} \cdot Q_F, \tag{1}$$

where Q_N – sound power index, Q_R – index of distance between the workstation and the machine, Q_Θ – radiation directivity index, Q_{imp} – impulse and impact noise index, Q_F – noise spectrum index.

The sound power index Q_N is defined by:

$$Q_N = 1 + \frac{L_{NA} - L_0}{50} \qquad \text{for} \qquad L_{NA} \geq L_0, \tag{2}$$

$$Q_N = \frac{1}{1 - \dfrac{L_{NA} - L_0}{50}} \qquad \text{for} \qquad L_{NA} < L_0, \tag{3}$$

where L_0 – standard admissible value of A-weighted sound power level of a machine (if there is no admissible value of sound power level, it is recommended to adopt $L_0 = 90$ dB), in dB, L_{NA} – A-weighted sound power level, in dB.

Index of distance between the workstation and the machine Q_R is described by the following formula:

$$Q_R = \frac{3.7}{3.2 + \log\left(\Omega r^2\right)}, \tag{4}$$

where r – distance between the workstation and the machine, in m, Ω – solid angle of radiation, in rad.

Radiation directivity index Q_Θ is defined as:

$$Q_\Theta = 1 + \frac{L_{pA} - L_{pAa}}{50}, \qquad \text{for} \qquad L_{pA} \geq L_{pAa}, \tag{5}$$

$$Q_\Theta = \frac{1}{1 - \dfrac{L_{pA} - L_{pAa}}{50}}, \qquad \text{for} \qquad L_{pA} < L_{pAa} \tag{6}$$

where L_{pAa} – averaged A-weighted sound pressure level value around the machine, in the distance equivalent to the distance between the workstation and the machine, in dB, L_{pA} – A-weighted sound pressure level value at the workstation in test environment, in dB.

Next index, i.e. the impulse and impact noise index Q_{imp}, should be defined according to Table 1.

Table 1. Impulse and impact noise index values.

C-weighted peak sound pressure level value $L_{C\text{peak}}$, in dB	Number of impulses during 8 hours of work	Impulse and impact noise index Q_{imp}
$135 < L_{C\text{peak}}$	$n = 0$	1.1
$125 < L_{C\text{peak}} \leq 135$	$n \leq 100$	1.08
$115 \leq L_{C\text{peak}} \leq 125$	$n \leq 1000$	1.06
$105 \leq L_{C\text{peak}} \leq 115$	$n \leq 10000$	1.04
$100 \leq L_{C\text{peak}} \leq 110$	$n \leq 100000$	1.02
$L_{C\text{peak}} \leq 100$	Without limitations	1.0

The last of partial indices, the noise spectrum index Q_F, adopts the values according to Table 2.

Table 2. Noise spectrum index values.

$\Delta_{C\_A} = L_{pC} - L_{pA}$, in dB	Noise spectrum index Q_F
≤ 0	1.00
0.1–2.0	1.02
2.1–4.0	1.4
4.1–9.0	1.6
9.1–15.0	1.8
>15.0	1.10

Each partial index always adopts a positive value, dimensionless, and the value of 1 is a neutral value. If the value of each index is higher than 1, it means that a given parameter has an adverse influence on acoustic climate in working environment, whereas the value lower than 1 means that a given parameter can improve acoustic conditions.

If the value of the global index of acoustic quality Q_{GWA} is lower than 1, the machine can be considered acoustically safe, otherwise when the value of Q_{GWA} is higher than 1, the noise emitted by the machine will exceed the admissible value of the sound pressure level at the workstation.

3. Inversion method

Inversion may be one of the methods used in acoustic modelling for the acoustic assessment of machines, on the basis of the analysis of acoustic field parameters (Engel *et al.*, 2002; Pleban *et al.*, 2005; Pleban, 2007). By modelling the process of radiation of vibro-acoustic energy from source to receiver and knowing the real values of sound pressures at measurement points, one can invert the model of the propagation path and thus determine the parameters of the sound source.

The scheme of the determination of the parameters of substitute sources by using the inversion method is presented in Fig. 1 (Pleban *et al.*, 2005).

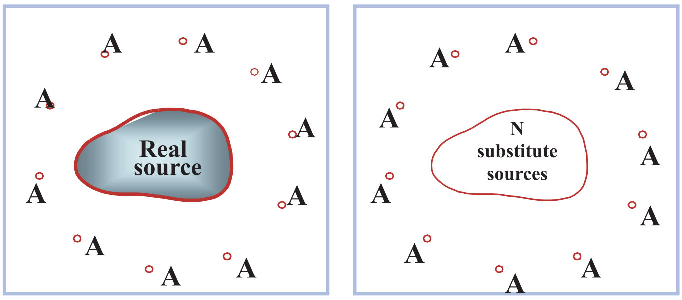

Fig. 1. Scheme of determination of the parameters of substitute sources.

The sound pressure at observation points A can be determined from the following dependence:

$$\boldsymbol{\pi} = \mathbf{G}\boldsymbol{\alpha} + \mathbf{e}, \tag{7}$$

where $\boldsymbol{\pi}$ – m-dimensional vector of the measured complex amplitudes of sound pressure at the observation points, $\boldsymbol{\alpha}$ – n-dimensional vector of complex parameter values of the model source, $\mathbf{G}$ – matrix $m \times n$ defining the complex value of sound pressure at the observation points, determined on the basis of parameters of substitute sources, $\mathbf{e}$ – m-dimensional vector of error.

To calculate the parameters of substitute sources by using the inversion method (Engel *et al.*, 2005), one must know the real distribution of acoustic pressure around the machine. This requires the determination, on the surface of a hemisphere, of both the distribution of the amplitude of acoustic pressures, as well as the distribution of phase shift angles between acoustic signals.

As a result of sound modelling, we obtain the number n of the substitute sources, their sound power or sound pressure amplitude and the position of every source.

The above-mentioned parameters of substitute sound sources can be used to determine the distribution of sound pressure levels around the machine. The distribution of sound pressure levels can be calculated using the following relationship (Pleban *et al.*, 2005; Pleban, 2007):

$$L_p\left(\theta,\varphi\right)=10\log\left(\sum_{i=1}^{n}A_iR_i\left(\theta,\varphi\right)\frac{\exp(-ikr_i)}{r_i}\right)\quad[\mathrm{dB}],\tag{8}$$

where A_i – moment of the i-th substitute source [Pa·m],

$R_i(\Theta,\varphi)=\exp[ik(x_i\cos\varphi\sin\Theta+y_i\sin\varphi\sin\Theta+z_i\cos\Theta)]$ – directional radiation characteristics of the i-th source, x_i, y_i, z_i – co-ordinates of the location of the i-th source [m].

4. Experimental tests on engine-generators

4.1. Instrumentation and tested engine-generators

Inversion methods allow for the acoustic assessment of machinery based on the analysis of acoustic field parameters. The inversion method described above was used to determine the sound power index – by modelling the process of vibroacoustic energy radiation through the source to the recipient, and knowing the actual value of sound pressure in measurement points, the propagation can be reversed in order to determine the parameters of the sound source. The equipment of National Instruments NI PXI-1042Q with two NI PXI-4472B modules enabling 16-channel data registering was used for the purpose of measurements. Sound pressure was measured with the use of twelve GRAS 40PQ microphones.

The measurements were carried out with the use of LabVIEW 8.20 software, in which virtual equipment allowing for the simultaneous registration of signal from 12 microphones was created. Then simultaneous registration of the amplitude and phase of measurement signal were created in the files. A software measurement module is presented in Fig. 2.

SVAN 945 sound level meter was used to determine the other indices as the instrument of accuracy that enables the registration of all sound parameters required for the acoustic assessment.

The tests programme included the measurement of acoustic field around four engine-generators (Fig. 3) of different power:

- CMI C-G800 800 W – two-stroke engine,
- CMI C-G2000 2.0 kW – four-stroke engine,
- NT250Up 2.6 kW – four-stroke engine,
- CMI C-G3500 3.5 kW – four-stroke engine.

All generators were powered by gasoline engines, cooled by air, producing electric current of standardised voltage of 230 V and frequency of 50 Hz.

During the work of each engine-generator, the eclectic current was received, supplying the heater with regulated heating power of 400 W, 700 W and 1500 W. The engine-generators were operating on the following settings presented in Table 3.

Based on the results of each measurement session from individual engine generators, partial indices of acoustic assessment of machinery were determined as well as the global index value presented below.

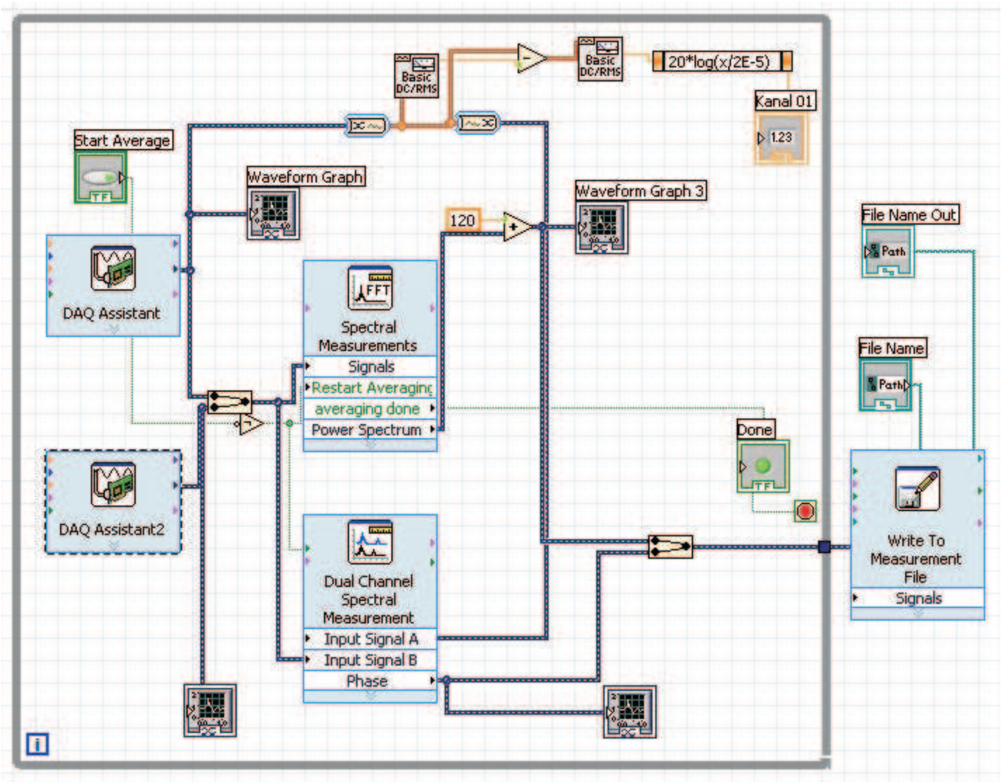

Fig. 2. Programme code in G-language (LabVIEW 8.20 environment).

Fig. 3. Gasoline engine-generators prepared for acoustic measurements.

Table 3. Power received for individual work settings of heater.

Type of engine-generator	Power received from the engine-generator, in W			
CMI C-G800 800 W	0	350	–	–
CMI C-G2000 2.0 kW	0	350	700	1400
NT250UP 2.6 kW	0	350	700	1400
CMI C-G3500 3.5 kW	0	350	700	1400

4.2. Sound power indices

As mentioned before, sound power level of the engine-generators was determined with the use of inversion method. It was assumed that each generator was modelled with the use of one, omnidirectional substitute source. The measurements (modelling) were carried out for the frequency range from 10 Hz to 12500 Hz.

Figures 4 and 5 present the sound power levels of two of the tested engine-generators. The results allowed for the determination of sound power indices of generators. The results of indices calculations for all settings of generators are presented in Table 4.

Table 4. Sound power indices of engine-generators.

Type of engine-generator	Power received from the engine-generator, in W	A-weighted sound power level, in dB	Sound power index Q_N
CMI C-G800 800 W	0	86.2	0.93
	350	89.0	0.98
CMI C-G2000 2.0 kW	0	89.8	1.00
	350	89.9	1.00
	700	91.2	1.02
	1400	94.3	1.09
NT250Up 2.6 kW	0	93.9	1.08
	350	94.9	1.10
	700	94.7	1.09
	1400	95.9	1.12
CMI C-G3500 3.5 kW	0	93.9	1.08
	350	94.9	1.10
	700	94.7	1.09
	1400	95.9	1.12

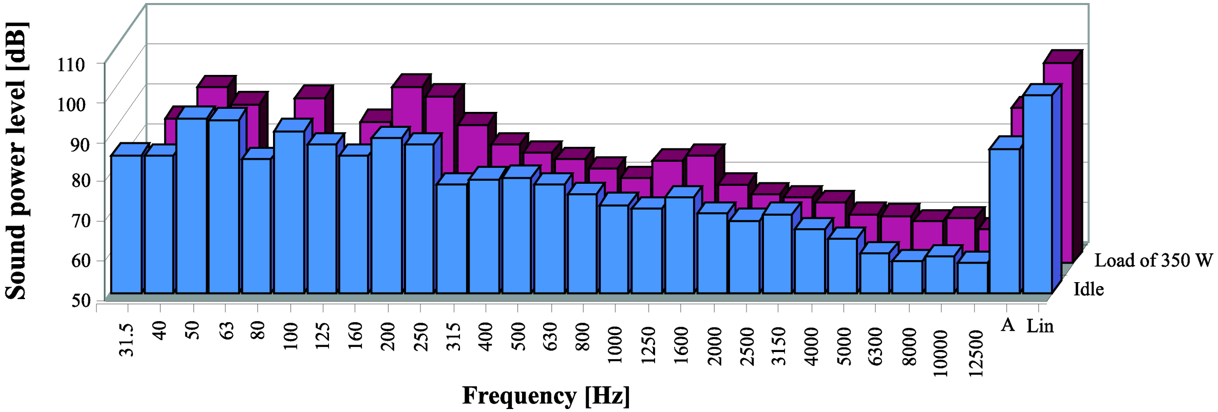

Fig. 4. Sound power level of CMI C-G800 800 W engine-generator.

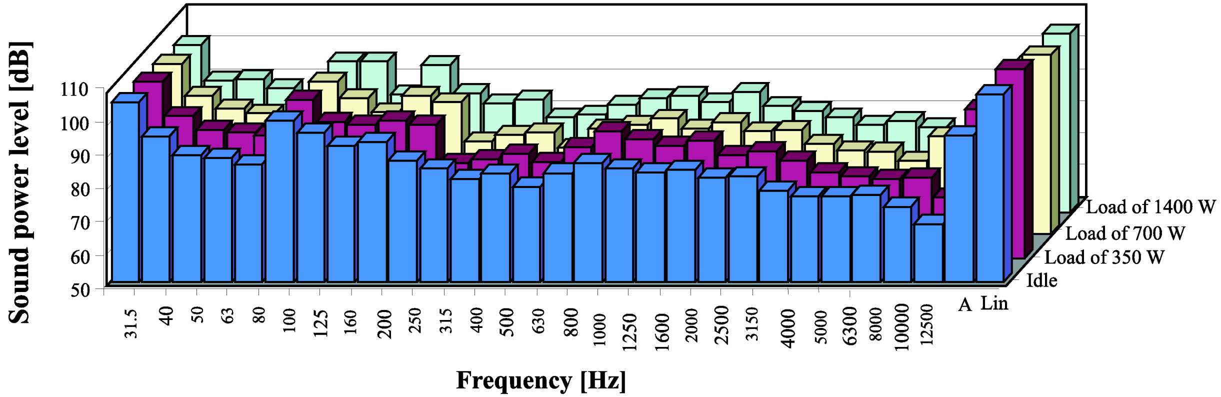

Fig. 5. Sound power level of NT250Up 2.6 kW engine-generator.

4.3. Indices of distance between the workstation and the machine

For all the tested engine-generators it was assumed that the workstation is located 1 m from the machine. Therefore the index of distance between the workstation and the tested machine, calculated according to the formula (4), was equal to $Q_R = 0.925$.

4.4. Radiation directivity indices

Radiation directivity index was determined according to formula (6). Indices values for individual settings of the tested engine-generators are presented in Table 5.

Table 5. Radiation directivity indices of engine-generators.

Type of engine-generator	Power received from the engine-generator, in W	Radiation directivity index Q_Θ
CMI C-G800 800 W	0	0.93
	350	0.93
CMI C-G2000 2.0 kW	0	0.97
	350	0.98
	700	0.97
	1400	0.94
NT250Up 2.6 kW	0	0.96
	350	0.95
	700	0.98
	1400	0.93
CMI C-G3500 3.5 kW	0	0.98
	350	0.97
	700	0.96
	1400	0.97

4.5. Noise spectrum indices

The values of noise spectrum distribution index for the tested engine-generators are presented in Table 6. The values were determined basing on the measurements at 1 m distance from the engine-generators.

Table 6. Noise spectrum indices of engine-generators.

Type of engine-generator	Power received from the engine-generator, in W	$\Delta_{C\_A} = L_{pC} - L_{pA}$, in dB	Noise spectrum index Q_F
CMI C-G800 800 W	0	7.9	1.06
	350	7.1	1.06
CMI C-G2000 2.0 kW	0	3.8	1.04
	350	3.7	1.04
	700	4.6	1.06
	1400	5.8	1.06
NT250Up 2.6 kW	0	1.6	1.02
	350	1.7	1.02
	700	1.7	1.02
	1400	3.1	1.04
CMI C-G3500 3.5 kW	0	3.7	1.04
	350	3.5	1.04
	700	4.3	1.06
	1400	3.1	1.04

Noise spectrum indices Q_F assume the values from 1.02 to 1.06. Spectrum characteristics for the chosen settings of two of the tested engine-generators are presented in Figs. 6 and 7.

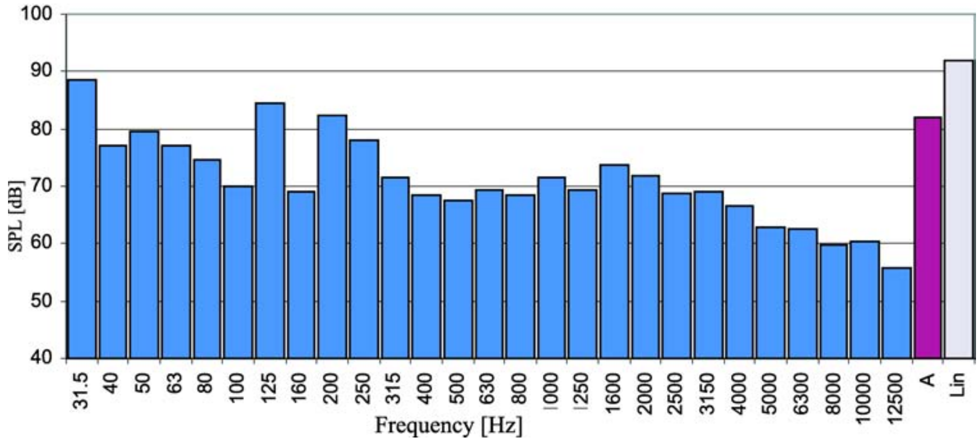

Fig. 6. Averaged sound pressure level (SPL) around the engine-generator CMI C-G2000 2.0 kW, in the distance of 1 m (load of 700 W).

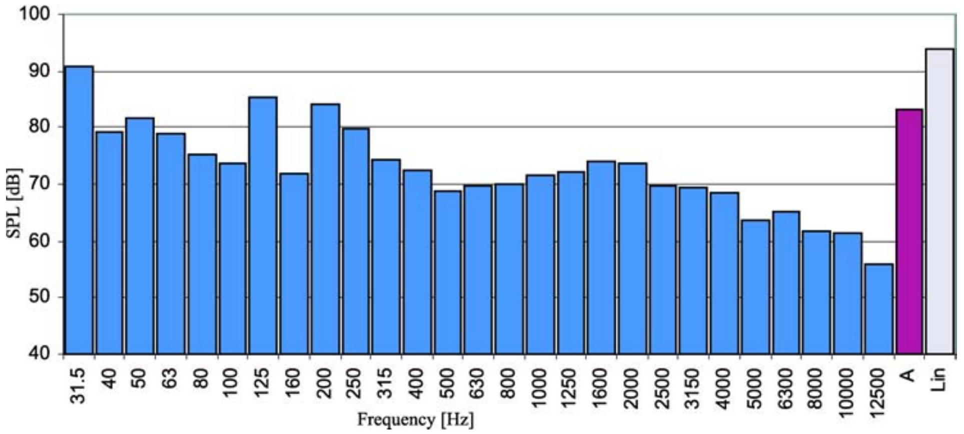

Fig. 7. Averaged sound pressure level (SPL) around the engine-generator CMI C-G3500 3.5 kW, in the distance of 1 m (load of 700 W).

4.6. Global indices of acoustic quality of tested generators

Global indices of acoustic quality Q_{GWA} for each engine-generator are presented in Table 7.

Table 7. Results of calculations of global indices of acoustic quality of the tested engine-generators.

Type of engine-generator	Power received from the engine-generator, in W	Global index of acoustic quality, Q_{GWA}	*A*-weighted sound pressure level at workstation, in dB
CMI C-G800 800 W	0	0.85	74.4
	350	0.89	77.5
CMI C-G2000 2.0 kW	0	1.02	85.4
	350	1.03	85.6
	700	1.03	85.6
	1400	1.05	86.4
NT250Up 2.6 kW	0	0.96	83.8
	350	0.96	84.2
	700	1.02	85.4
	1400	0.98	84.4
CMI C-G3500 3.5 kW	0	0.93	80.2
	350	0.94	80.8
	700	0.97	83.3
	1400	1	84.9

When the obtained Q_{GWA} index is higher than 1.0, it means that the noise emitted by the generator will exceed the admissible value of the A-weighted sound pressure level (85 dB(A)) at a workstation. The results of noise measurements at hypothetical workstations (located 1 m from the generators in simulated *in situ* conditions) presented in Table 7, confirm the correctness of the obtained Q_{GWA} indices values.

5. Conclusions

For the use of acoustic assessment of machinery, a global index of acoustic quality has been developed. Acoustic quality index is considered as a function of partial indices.

Partial indices can be divided, among other things, into the indices depending on a given machine only (e.g. sound power index) and the indices depending on the localisation of a machine in an industrial hall (e.g. index of distance between the workstation and the machine). Each partial index always adopts a positive value, dimensionless, and the value of 1 is a neutral value. If the value of each index is higher than 1, it means that a given parameter has an adverse influence on acoustic climate in working environment, whereas the value lower than 1 means that a given parameter can improve acoustic conditions.

If the value of the global index of acoustic quality is lower than 1, the machine can be considered to be acoustically safe, otherwise when the value of the global index is higher than 1, the noise emitted by the machine will exceed admissible values of the sound pressure level at workstation. The installation of such machine in an industrial hall can be hazardous also for other employees which are not directly involved in its operation.

The global indices of acoustic quality of the tested engine-generators assumed the values from 0.85 to 1.05. The correctness of the determined values of global indices of the tested engine-generators was confirmed by the results of A-weighted sound pressure level measurements at hypothetical workstations of the generators.

Verification tests of the global index will be continued and a software for prediction method of noise emission of the machinery and support of the correct distribution of machinery in industrial rooms based on the global index, will be developed. It will allow for among other things:

- determination of global index distribution in chosen sections of limited cubicoid areas, which is a typical shape of an industrial hall with the use of statistical prediction method of sound pressure level in the room,
- graphic visualisations enabling an independent assessment of partial indices influencing the value of global index, taking into account several machines simultaneously,

– optimization of machines and workstations location, aimed at minimization of harmful effects of noise with the use of genetic algorithm, applying the notion of global index value for the calculation of adaptation.

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