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A Global Index of Acoustic Assessment of Machines—Results of Experimental and Simulation Tests

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A global index of machines was developed to assess noise emitted by machines and to predict noise levels at workstations. The global index is a function of several 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. Tests were carried out to determine values of the global index for engine-generator; the inversion method for determining sound power level was used. It required modelling each tested generator with one omnidirectional substitute source. The partial indices and the global index were simulated, too. The results of the tests confirmed the correctness of the simulations.

acoustic assessment machinery noise

1. INTRODUCTION

According to the requirements of Directive 2006/42/EC, machinery must be designed and constructed in such a way that risks resulting from the emission of noise are reduced to the lowest possible level, taking into account technical progress and the possibility of reducing noise, in particular at source [1, 2]. This requirement deals with risk associated with exposure of machinery operators to noise generated by machinery. Prolonged exposure to noise from machinery is the main cause of occupational noise-induced hearing impairment. In this connection Standard No. EN ISO 11688-1:2009 [3] harmonized with this Directive refers, among other things, to designing low-noise machinery. However, in practice, exploitation parameters, which influence the value of sound pressure at workstations, are not taken into account at the design stage.

Moreover, Directive 2006/42/EC requires manufacturres to deliver a noise emission declaration. The declaration includes three different noise emission quantities: *A*-weighted emission sound pressure level (SPL) at the workstation, peak *C*-weighted instantaneous sound pressure value (if it exceeds 130 dB) and *A*-weighted sound power level (if the *A*-weighted emission SPL at the workstation exceeds 80 dB(*A*)). This declaration has two main purposes: to assist users in selecting machinery with reduced noise emission and to provide information necessary for risk assessment to be carried out according to Directive 2003/10/EC [4].

Therefore, the manufacturer's noise emission declaration only provides information about the contribution of the machinery itself to noise at the workstation, while the level of workers' exposure cannot be simply determined from this noise declaration, since operators' exposure is also

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influenced by exploitation factors. Therefore, this paper proposes a new method for predicting noise emission from machinery in exploitation conditions, using the index method of acoustic assessment. This method is based on the global index of acoustic assessment of machines.

2. GLOBAL INDEX OF ACOUSTIC ASSESSMENT OF MACHINES

For the purposes of acoustic assessment of machinery and prediction of noise emission from machinery at the workstation and other positions in exploitation conditions, a global index Q_{GWA} was developed [5]. The index is a function of five partial indices and can be defined by Equation 1:

$$Q_{GWA} = Q_N \times Q_R \times Q_\Theta \times Q_{imp} \times Q_F, \quad (1)$$

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.

Equations 2–3 describe Q_N:

$$Q_N = 1 + \frac{L_{NA} - L_0}{50}, \quad (2)$$

for $L_{NA} \geq L_0$ and

$$Q_N = \frac{1}{1 - \frac{L_{NA} - L_0}{50}}, \quad (3)$$

for $L_{NA} < L_0$, where L_0—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 decibels; L_{NA}—A-weighted sound power level, in decibels.

Equation 4 describes Q_R:

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

where r—distance between the workstation and the machine, in metres; Ω—solid angle of radiation, in radians. Q_Θ is defined as

$$Q_\Theta = 1 + \frac{L_{pA} - L_{pAa}}{50}, \quad (5)$$

for $L_{pA} \geq L_{pAa}$ and as

$$Q_\Theta = \frac{1}{1 - \frac{L_{pA} - L_{pAa}}{50}}, \quad (6)$$

when $L_{pA} < L_{pAa}$, where L_{pAa}—averaged A-weighted SPL around the machine at a distance equivalent to the distance between the workstation and the machine, in decibels, L_{pA}—A-weighted SPL at the workstation, in decibels.

Tables 1–2 list values of Q_{imp} and Q_F, respectively.

TABLE 1. Impulse and Impact Noise Index Q_{imp}

L_{Cpeak}	No. of Impulses in 8 h of Work	Q_{imp}
$135 < L_{Cpeak}$	no limit	1.10
$125 < L_{Cpeak} \leq 135$	≤100	1.08
$115 < L_{Cpeak} \leq 125$	≤1000	1.06
$105 < L_{Cpeak} \leq 115$	≤10 000	1.04
$95 \leq L_{Cpeak} \leq 105$	≤100 000	1.02
$L_{Cpeak} \leq 95$	no limit	1.00

Notes. L_{Cpeak}—C-weighted peak sound pressure level (dB).

TABLE 2. Noise Spectrum Index Q_F

$\Delta_{C-A} = L_{pC} - L_{pA}$	Q_F
≤0	1.00
0.1–2.0	1.02
2.1–4.0	1.40
4.1–9.0	1.60
9.1–15.0	1.80
>15.0	1.10

Notes. L_{pC}—C-weighted sound pressure level (dB), L_{pA}—A-weighted sound pressure level (dB).

Each partial index always has a postitive value, it is dimensionless and one is a neutral value. If the value of each index is higher than one, a parameter has an adverse effect on the acoustic climate in the working environment, whereas a value lower than one means that a parameter can improve acoustic conditions. For example, if the value of Q_{GWA} is lower than one, a machine can be considered acoustically safe, whereas if the value of Q_{GWA} is higher than one, the noise emitted by the machine will exceed the admissible value of the SPL at the workstation.

3. EXPERIMENTAL TESTS ON ENGINE-GENERATORS

3.1. Tested Sound Sources

The test programme consisted in measuring the acoustic field around four engine-generators of different power: CMI C-G800 800 W (a two-stroke engine from Eurmate, Germany), CMI C-G2000 2.0 kW (a four-stroke engine from Eurmate, Germany) NT250Up 2.6 kW (a four-stroke engine Nutool, UK) and CMI C-G3500 3.5 kW (a four-stroke engine from Eurmate, Germany) (Figure 1). All those engine-generators were powered with petrol engines and cooled with air, they produced electric current of standardized voltage of 230 V and frequency of 50 Hz. During the work of each engine-generator electric current was produced, supplying the heater with regulated heating power of 350, 700 and 1400 W.

Figure 1. Petrol engine-generators prepared for acoustic measurements.

3.2. Partial Indices

Sound power levels of the engine-generators were determined with the inversion method by modelling the process of vibroacoustic energy radiation through the source to the recipient. If the actual value of sound pressure in measurement points is known, propagation can be reversed to determine the parameters of the sound source [6, 7, 8, 9]. It was assumed that each engine-generator was modelled with one omnidirectional substitute source. The measurements (modelling) were carried out for 10–12 500 Hz. The measurements were made with NI PXI-1042Q (National Instruments, USA), with two NI PXI-4472B modules for 6-channel data registering. Sound pressure was measured with 12 GRAS 40PQ microphones (Figure 2).

Figure 2. A tested engine-generator, a heater and 12 microphones.

Measurements were made with LabVIEW 8.20 software (National Instruments, USA), in which virtual equipment was created to simultaneously register signal from 12 microphones. Then the amplitude and phase of the measurement signal was simultaneusly registered in files. A SVAN 945 sound level meter (Svantek, Poland) was used to determine the other indices; it made it possible to accurately register all sound parameters required for acoustic assessment.

Figures 3–6 illustrate the spectra of sound power levels of the engine-generators for different operational conditions (different power produced by the engine-generators). The results made it possible to determine sound power indices of generators. The sound power indices Q_N of the engine-generators ranged from 0.93 to 1.12 (Table 3).

It was assumed that the workstation was located 1 m from the machine. Therefore, the index of distance between the workstation and the machine calculated according to Equation 4 was $Q_R = 0.925$.

Equations 5–6 were used to determine the radiation directivity index Q_Θ. Table 3 presents index values for individual settings of the engine-generators; they were in the 0.93–0.98 range. The values of the noise spectrum index Q_F were determined on the basis of measurements made 1 m from a working engine-generator; they were 1.02–1.06. Global indices Q_{GWA} for

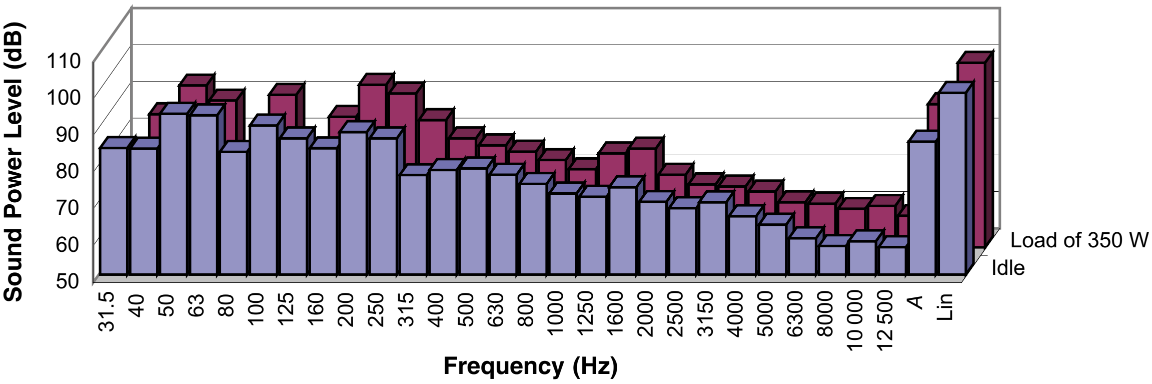

Figure 3. Sound power levels of a CMI C-G800 800 W engine-generator (Eurmate, Germany) for different operational conditions. *Notes*. *A*—*A*-weighted sound pressure level, Lin—linear sound pressure level.

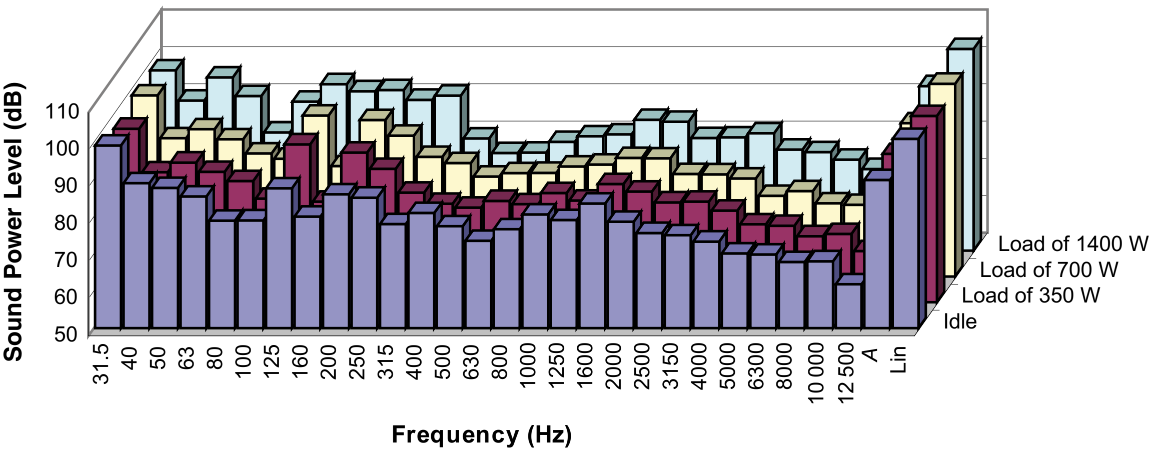

Figure 4. Sound power levels of a CMI C-G2000 2.0 kW engine-generator (Eurmate, Germany) for different operational conditions. *Notes*. *A*—*A*-weighted sound pressure level, Lin—linear sound pressure level.

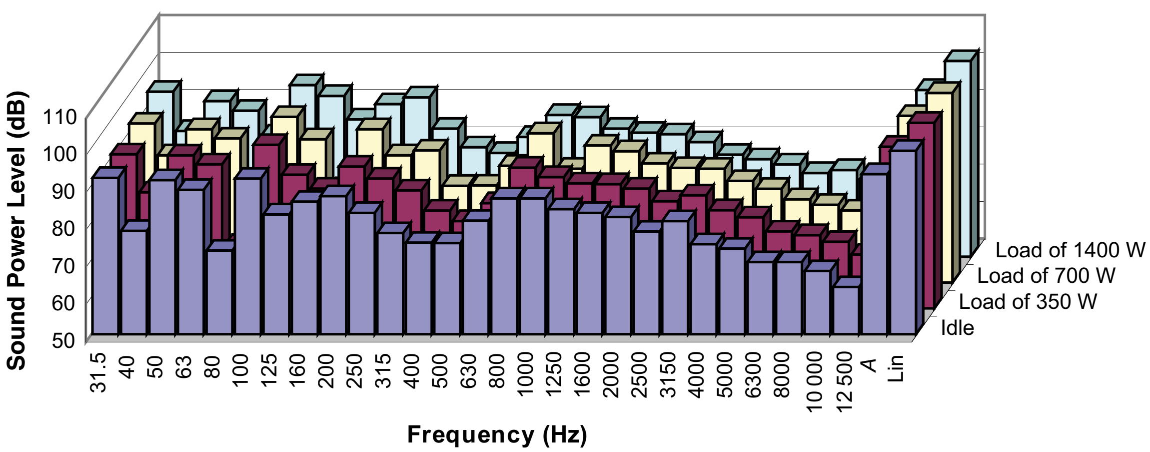

Figure 5. Sound power levels of an NT250Up 2.6 kW engine-generator (Nutool, UK) for different operational conditions. *Notes*. *A*—*A*-weighted sound pressure level, Lin—linear sound pressure level.

each engine-generator ranged from 0.85 to 1.05. When Q_{GWA} is higher than 1.0, noise emitted by a engine-generator at a workstation exceeds the admissible value of *A*-weighted SPL of 85 dB(*A*). The results of noise measurements (*A*-weighted SPLs) at workstations L_{pA} (1 m from generators in simulated in situ conditions) confirm the correctness of the obtained values of Q_{GWA} (Table 3).

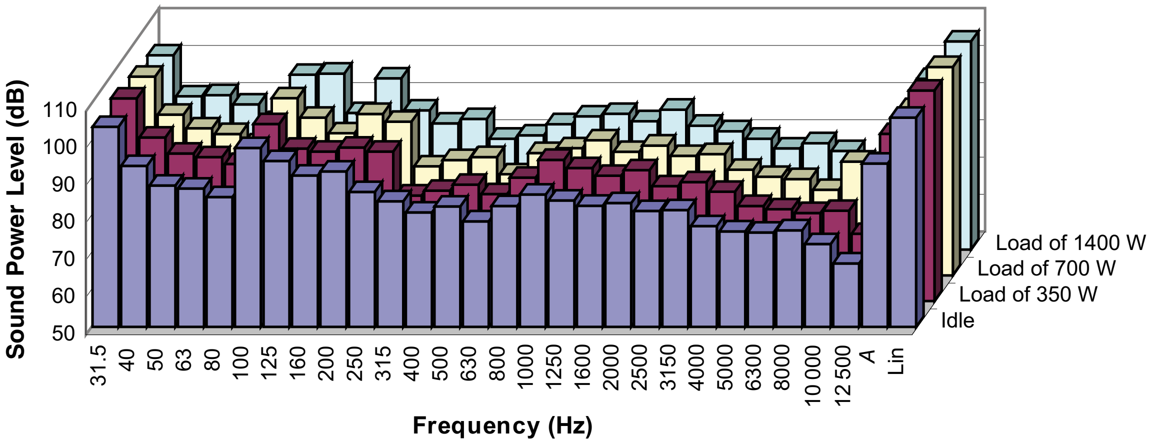

Figure 6. Sound power levels of a CMI C-G3500 3.5 kW engine-generator (Eurmate, Germany) for different operational conditions. *Notes. A*—*A*-weighted sound pressure level, Lin—linear sound pressure level.

TABLE 3. Partial and Global Indices of Engine-Generators

Engine-Generator						
Type	**Power (W)**	Q_N	Q_Θ	Q_F	Q_{GWA}	L_{pA} **(dB)**
CMI C-G800 800 W	0	0.93	0.93	1.06	0.85	74.4
	350	0.98	0.93	1.06	0.89	77.5
CMI C-G2000 2.0 kW	0	1.00	0.97	1.04	1.02	85.4
	350	1.00	0.98	1.04	1.03	85.6
	700	1.02	0.97	1.06	1.03	85.6
	1400	1.09	0.94	1.06	1.05	86.4
NT250Up 2.6 kW	0	1.08	0.96	1.02	0.96	83.8
	350	1.10	0.95	1.02	0.96	84.2
	700	1.09	0.98	1.02	1.02	85.4
	1400	1.12	0.93	1.04	0.98	84.4
CMI C-G3500 3.5 kW	0	1.08	0.98	1.04	0.93	80.2
	350	1.10	0.97	1.04	0.94	80.8
	700	1.09	0.96	1.06	0.97	83.3
	1400	1.12	0.97	1.04	1.00	85.0

Notes. Q_N—sound power index, Q_Θ—radiation directivity index, Q_F—noise spectrum index, Q_{GWA}—global index, L_{pA}—*A*-weighted sound pressure level. CMI C-G800 800 W—a two-stroke engine-generator from Eurmate, Germany; CMI C-G2000 2.0 kW—a four-stroke engine-generator from Eurmate, Germany; NT250Up 2.6 kW—a four-stroke engine-generator Nutool, UK; CMI C-G3500 3.5 kW—a four-stroke engine-generator from Eurmate, Germany.

4. SIMULATION TESTS OF INDICES

During the simulation tests of the global index, partial indices were tested first: the sound power index Q_N, the index of distance between the workstation and the machine Q_R and the radiation directivity index Q_Θ. Figure 7 illustrates the results of the simulation of Q_N of the machine. According to Equations 2–3 a decrease in the sound power level of the machine entails a decrease in Q_N. The model value of Q_N decreases from 1.40 to 0.71 when the sound power level of the machine decreases respectively from 110 to 70 dB.

Figure 8 presents the results of simulation tests of Q_R as a function of the distance; an increase in the distance between the workstation and the machine results in a decrease in Q_R. Moreover, for distances longer than 2 m, the index is constant, Q_R = 0.8. The distance of 0.71 m indicated in Figure 8 corresponds to Q_R = 1, which corresponds, in turn, to

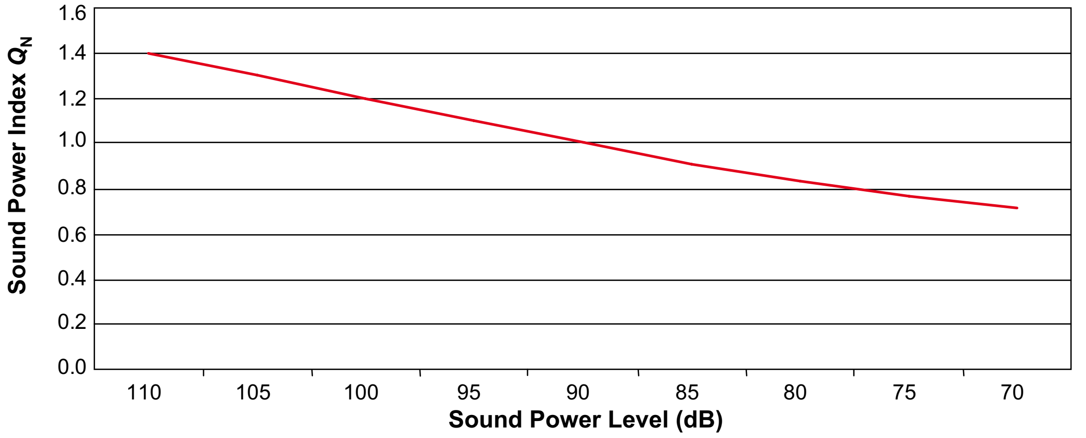

Figure 7. Influence of sound power level on the sound power index Q_N.

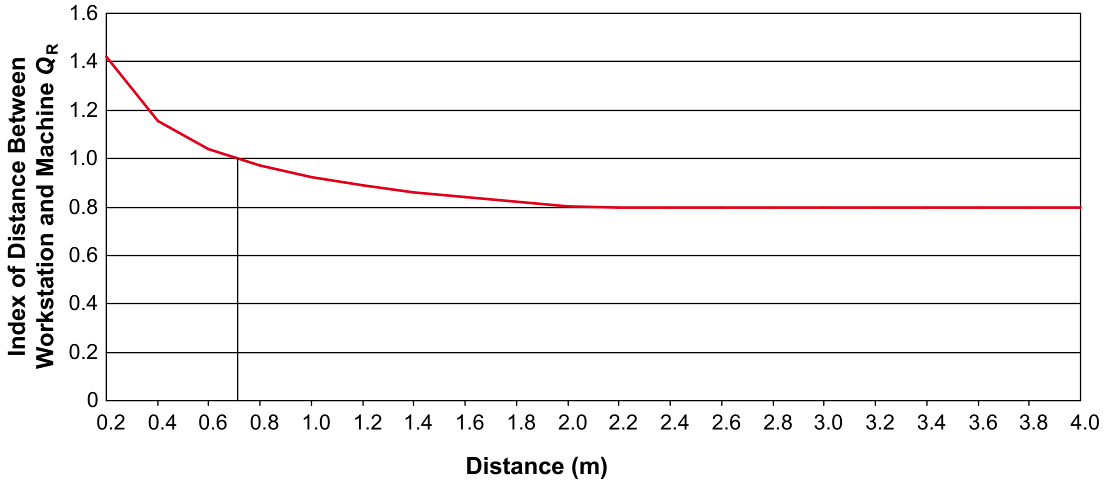

Figure 8. Influence of distance on the index of distance between the workstation and the machine Q_R.

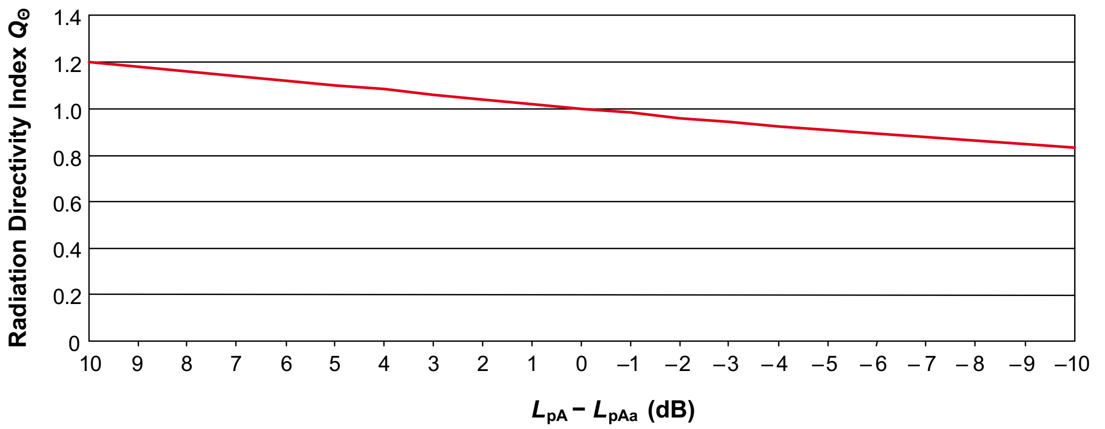

Figure 9. Influence of the difference between the sound pressure level at the workstation and averaged sound pressure level around the engine-generator on the radiation directivity index Q_Θ.

workstations at which SPL = 85 dB provided that $Q_N \times Q_R \times Q_\Theta = 1$. Assuming that $Q_N \times Q_R \times Q_\Theta = 1$, $Q_R = 1.2$ (corresponding to the distance of ~0.38 m), *A*-weighted SPL = 95 dB, the admissible value will be exceeded by 10 dB. On the other hand, a decrease in distance of up to 0.2 m will result in *A*-weighted SPL exceeding the admissible value by 20 dB ($Q_R = 1.4$).

Another partial index, the radiation directivity index Q_Θ, provides information on the suitability or unsuitabiliy of the location of the workstation in relation to the radiation directivity properties. It is defined by the difference between SPL measured at the workstation and average SPL around the machine at the same distance as the workstation. Figure 9 illustrates the dependency of Q_Θ as a function of that difference.

The dependencies of Q_N and Q_R are mirrored directly by the value of the global index Q_{GWA}. Figure 10 illustrates the influence of *r* on Q_{GWA} for selected combinations of Q_N and Q_Θ. Figure 11 illustrates the influence of *A*-weighted

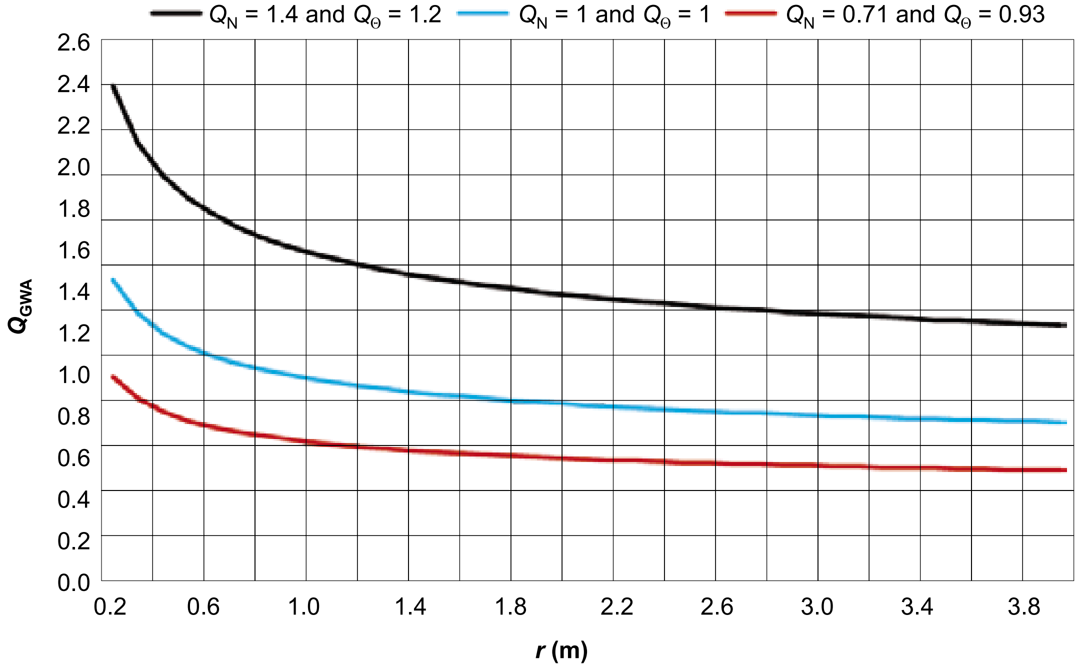

Figure 10. Influence of the distance between the workstation and the engine-generator *r* on the global index Q_{GWA}.

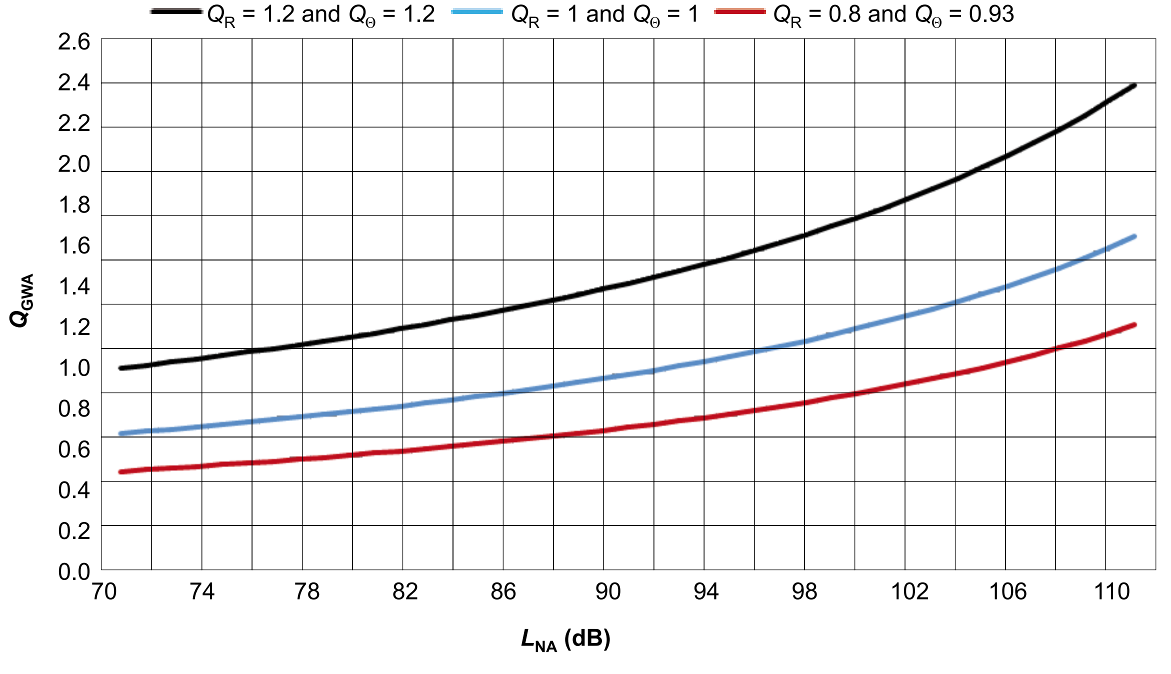

Figure 11. Influence of the *A*-weighted sound power level L_{NA} on the global index Q_{GWA}.

sound power level on Q_{GWA} for different combinations of partial indices Q_R and Q_Θ.

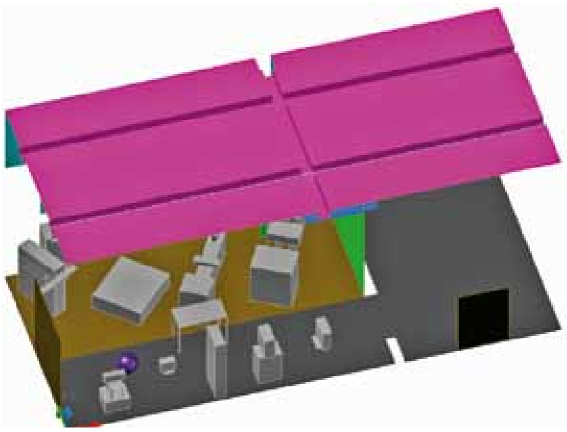

Figure 12. Model of a workshop (violet sphere indicates the tested engine-generator).

The distribution of the global index Q_{GWA} in a room was analysed with Raynoise[1] version 2.0. This software was used to model the workshop, where the engine-generators were tested (Figure 12).

The distribution of SPLs of the tested engine-generators in the industrial hall, 1.5 m above the floor, was simulated. Figures 13–14 show the distribution of SPL and *A*-weighted SPL of the CMI C-G800 800 W engine-generator, which was under no load (idling).

The distribution of the values of Q_{GWA} was analysed for the engine-generators in relation to the location of the workstation in the workshop. Figure 15 illustrates the distribution of Q_{GWA} of the CMI C-G800 800 W engine-generator. Depending on the location of the workstation the

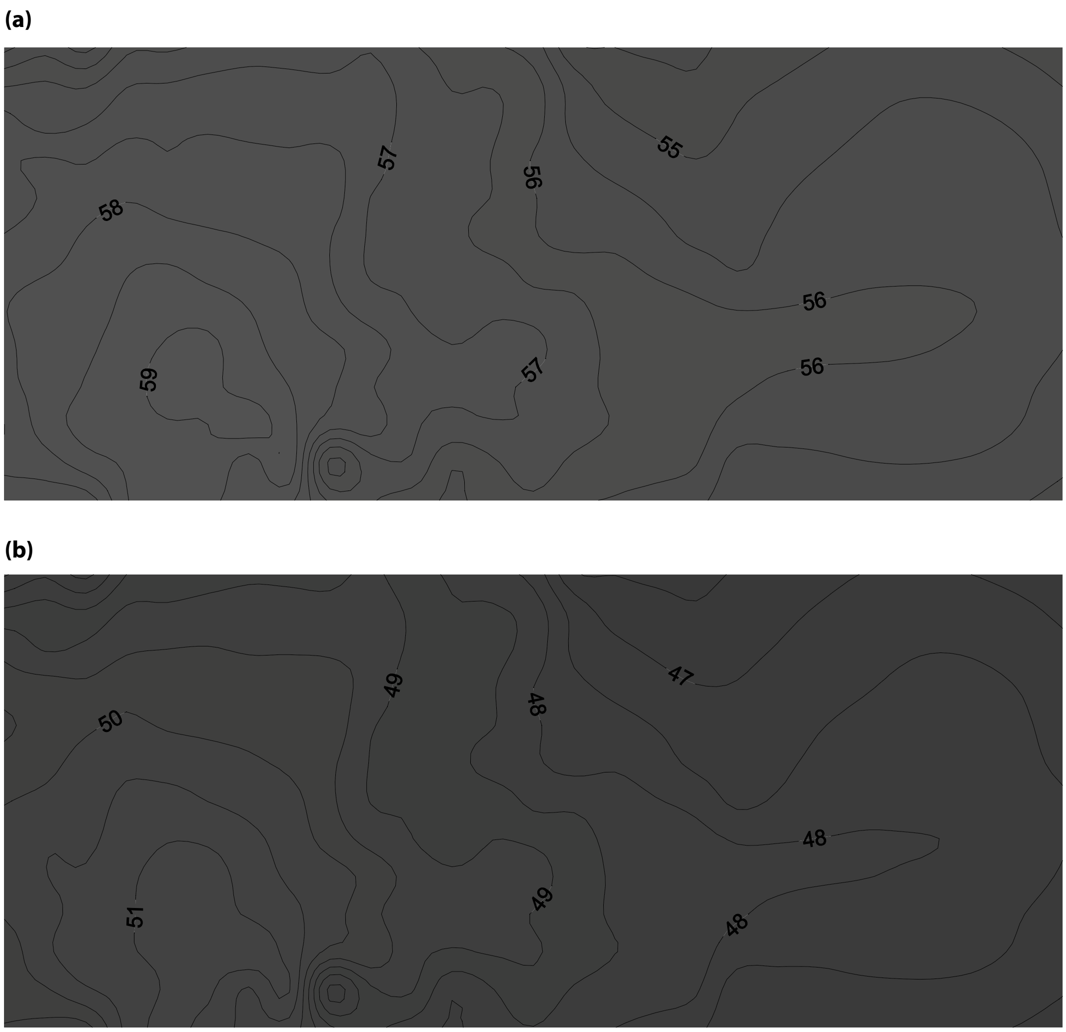

Figure 13. Distribution of sound pressure level, in decibels, in the workshop: (a) 4000 Hz, (b) 8000 Hz.

[1] http://www.lmsintl.com/raynoise

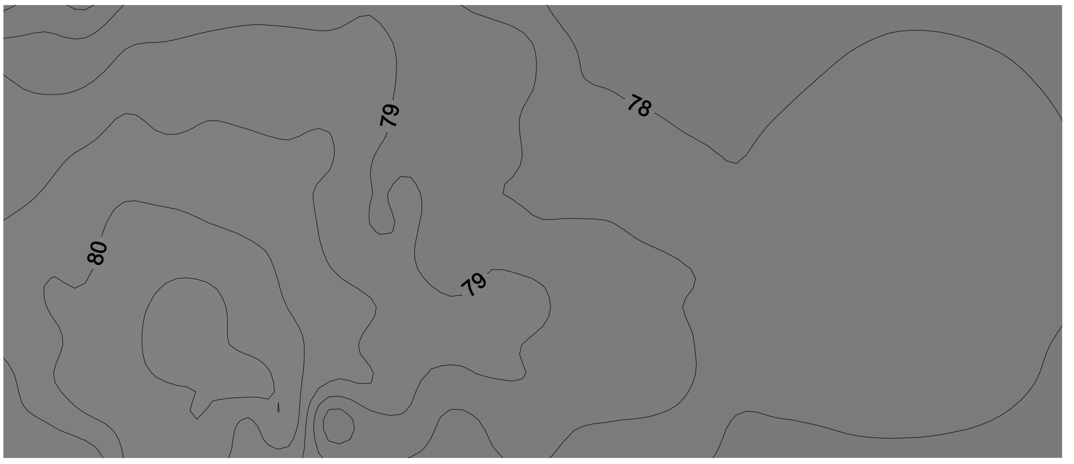

Figure 14. Distribution of the *A*-weighted sound pressure level, in decibels, in the workshop.

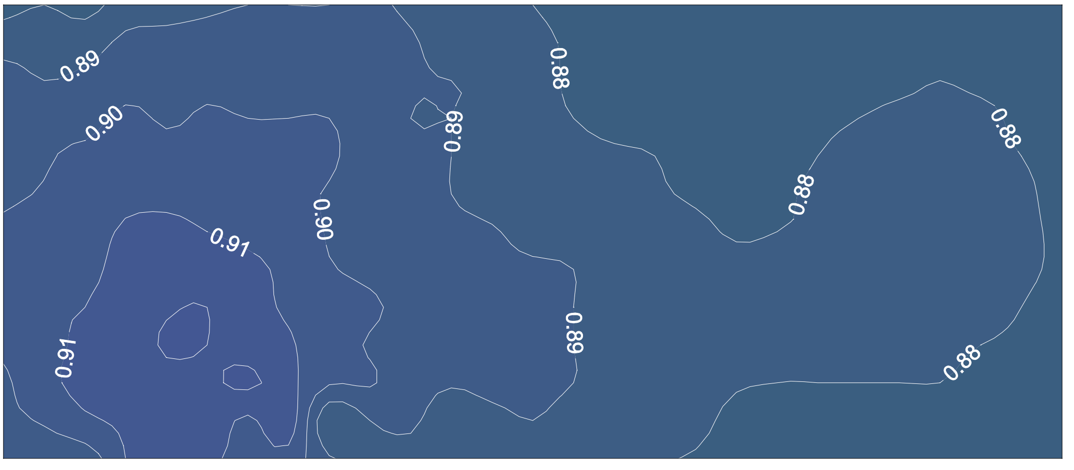

Figure 15. Distribution of the global index Q_{GWA} in the workshop.

noise of the engine-generator affects the values of the global index. The value of Q_{GWA} is often critical in the vicinity of the machine.

5. CONCLUSIONS

The global index Q_{GWA} was developed for acoustic assessment of machinery. It is a function of partial indices.

Partial indices can be divided, among others, into indices depending on a given machine only (e.g., the sound power index Q_N) and indices depending on the location of a machine in an industrial hall (e.g., the index of distance between the workstation and the machine Q_R). Each partial index is always positive, dimensionless, and 1 is a neutral value. If the value of each index is higher than 1, a parameter has an adverse effect on the acoustic climate of the working environment. A value lower than 1 indicates that a parameter can improve acoustic conditions.

If the value of the global index of acoustic quality is lower than 1, the machine is acoustically safe, whereas if the value of the global index is higher than 1, noise emitted by the machine exceeds admissible values of SPL at the workstation. The installation of such a machine in an industrial hall is a hazard for employees who are not directly involved in its operation, too.

The determined values of the global indices of the tested engine-generators were confirmed by the results of *A*-weighted SPL measurements at workstations of the engine-generators. The simulation tests results are consistent with the experimental ones, with the general principles of sound wave propagation and with noise control methods.

Software for predicting noise emission of machinery was developed and verified. It supports correct location of machinery in industrial rooms on the basis of the global index Q_{GWA}. That software can be used for

- determining the distribution of the global index in sections of limited cubicoid areas, a typical shape of an industrial hall with the use of statistical prediction method of SPL in the room;
- visualizing the working conditions to assess partial indices influencing the value of the global index, taking into account several machines at the same time;
- optimizing the location of machines and workstations to minimize the harmful effects of noise with the use of a genetic algorithm, using the value of the global index to calculate adaptation.

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