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COMPUTER SIMULATION OF THE INDICES OF THE ACOUSTIC ASSESSMENT OF MACHINES

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Two indices of of the acoustic assessment of machines are proposed: a power index and an emission index which enable the potential user to carry out an acoustic assessment of the machine to be installed in the operation room. The worked out indices are functions of several parameters such as e.g. variations of the operational conditions of the machine, or the acoustic properties of the room. The results of the simulation tests, illustrating the effects of the variation of different parameters on the values of the indices of the acoustic assessment, are given.

1. Introduction

The efficiency of an acoustic assessment determines whether a machine, which can be dangerous for man because of excessive noise emission is approved for use or not. The methods that heve been used for the acoustic assessment until now do not take into consideration, among other things,

• the real operation variants of the machine and their duration,

• the parameters of the operation room and their influence on the noise level at a work station.

Furthermore, the sound power level limit values have not been established for most of the machines. In this connection, the principles of the acoustic assessment of machines have not been fully useful in most cases for the machine users. This results, among other things, from the fact that, although the service manual contains data on the sound pressure level at the work station and the sound power level values, it does not provide full information on the machine safety under the operational conditions. Therefore, it is proposed to introduce two alternative indices of the acoustic assessment of machines [1, 3, 6]: a power index and an emission index which enable the potential user of a machine to carry out an acoustic assessment of the machine to be installed in the operation room. The power and the emission indices are functions of the parameters characterizing both the machine and the operation room and influencing the value of the sound pressure level at the work station. In connection with these indices, two new quantities to characterize the noise emitted by a machine are also proposed: the real global A-weighted sound power level and the real global A-weighted sound pressure level caused by the machine at the work station [3, 6].

2. Power index

For a given machine to be installed under specific operational conditions, a power index of the acoustic assessment W_E, in dB, is given as a folowing function:

$$W_E = f_1(C_A, L_W, x, y, z, d, D, L_L), \tag{1}$$

where C_A is the primary acoustic climate in the operation room, L_W is the sound power level of the machine, in dB, x, y, z are the coordinates of the machine location, d is the distance between the machine and the work station, in m, D are the acoustic properties of the operation room, L_L is the admissible value of the equivalent A-weighted sound pressure level at the work station, in dB.

The primary acoustic climate C_A at the point in that the work station of the machine being assessed will be located is composed of sound waves coming from all the original noise sources in the room. This climate is a function of the partial climates produced by the individual noise sources existing up to now and may be expressed by the equivalent A-weighted sound pressure level L'_{Aeq} [4].

The parameter which characterizes the noise of the machine is the sound power level L_W, which may be written as follows:

$$L_W = f_2(n_1, n_2, n_3, \Delta t), \tag{2}$$

where n_1 are non-acoustic parameters which characterize the machine and influence the noise emitted (e.g. rotational speed, motive power), n_2 are parameters which characterize the way of mounting the machine, n_3 are parameters which characterize the operating material, Δt is the time interval in which the sound power level is determined.

By making a synthesis of the parameters n_1, n_2 and n_3 in the specified time intervals Δt_i, it is possible to determine k possible technological-kinematic and structural variants of the operation of the machine during its operation. Each of these variants is characterized by the partial A-weighted sound power level L_{WAi}. Thus, in order to characterize the machine radiation by an energy quantity which is the sound power level, its definition should be extended by the notion of the real global A-weighted sound power level L_{WRGA}; the latter is described by the formula:

$$L_{WRGA} = 10 \lg \frac{1}{\sum\limits_{i=1}^{k} \Delta t_i} \left(\sum_{i=1}^{k} \Delta t_i 10^{0.1 L_{WAi}} \right), \tag{3}$$

where Δt_i is the time duration of the i-th variant of the operation of the source, in s.

In accordance with the relation (1), the machine location in the operation room is determined by the coordinates x, y, z. There are five basic ways of the machine location: suspended in the middle of the room, suspended on the middle of the wall, placed in the middle of the floor, placed on the edge of the surfaces (e.g. of the wall and the floor) or placed in the corner of the room. For each location the characteristic feature is the shape of the radiation surface expressed by the radiation index Q. The values of the radiation index Q for the basic machine locations are given in Table 1 [5].

Table 1. Values of the radiation index Q for basic machine locations.

Machine location	Radiation surface	Radiation index Q
Suspended in the middle of the room	Spherical	1
Suspended in the middle of the wall	Hemispherical	2
Suspended in the middle of the floor	Hemispherical	2
Placed on the edge of two surfaces	Quarterspherical	4
Placed in the corner	One-eighthspherical	8

The influence of the D factor on sound waves between the machine and the work station may be characterized by the equivalent sound absorption area of the room A in m^2:

$$A = \alpha S, \tag{4}$$

where α is the mean acoustic absorption coefficient determined according to ISO 3744 [7], S is the total area of the surface of the operation room (walls, ceiling and floor) in m^2.

On the basis of the above analysis, the following definition of the power index W_E may be given:

$$W_E = L_{WRGA} - L_{W\mathrm{ref}}\,, \tag{5}$$

where $L_{W\mathrm{ref}}$ is the reference sound power level in dB.

Assuming that the value of the reference sound power level $L_{W\mathrm{ref}}$ should be equal to the maximum value of the A-weighted sound power level of the omnidirectional source installed in the operation room at the place of machine location when the following condition is fulfilled:

• The value of the equivalent A-weighted sound pressure level in the place at that the machine's work station will be located does not exceed the admissible value.

The following final formula determining the power index W_E is obtained:

$$W_E = 10\lg\frac{1}{\sum\limits_{i=1}^{k}\Delta t_i}\left(\sum_{i=1}^{k}\Delta t_i 10^{0.1L_{WAi}}\right) - 10\lg\frac{10^{0.1L_L} - 10^{0.1L'_{A\mathrm{eq}}}}{\dfrac{Q}{4\pi d^2}+\dfrac{4}{A}}\,. \tag{6}$$

The general principle of the acoustic assessment of a machine on the basis of the power index is as follows:

• the machine is acoustically safe (i.e. the equivalent A-weighted sound pressure level at the work station in the operation room during its operation does not exceed the admissible value) if the condition $W_E \le 0\,\mathrm{dB}$ is fulfilled,

• the machine is acoustically dangerous (i.e. the equivalent A-weighted sound pressure level at the work station in the operation room during the operation does not exceed the admissible value) if the condition $W_E > 0\,\mathrm{dB}$ is fulfilled.

3. Emission index

For a given machine to be installed under specific operating conditions, an emission index of the acoustic assessment W_I (in dB), is given as the folowing function:

$$W_I = f_3(C_A,\, L_P,\, d,\, L_L), \tag{7}$$

where L_P is the emission sound pressure level of the machine at the work station (in dB).

The parameter characterizing the noise of the machine is the emission sound pressure level L_P which may be written as a function analogous to the function (2). Therefore the real global A-weighted emission sound pressure level L_{PRGA} is described by the formula:

$$L_{PRGA} = 10\lg \frac{1}{\sum\limits_{i=1}^{k} \Delta t_i} \left(\sum_{i=1}^{k} \Delta t_i 10^{0.1 L_{PAi}} \right), \tag{8}$$

where L_{PAi} is the equivalent A-weighted emission sound pressure level in the i-th variant of the operation, in dB.

Similary to the power index, the following definition of the emission index W_I may be given:

$$W_I = L_{PRGA} - L_{P\mathrm{ref}}\,, \tag{9}$$

where $L_{P\mathrm{ref}}$ is the reference emission sound pressure level, in dB.

Assuming that the value of the reference emission sound pressure level $L_{P\mathrm{ref}}$ should be equal to the maximum value of the A-weighted emission sound pressure level of the omnidirectional source installed in the operating room of the place of the location of the machine when the following condition is fulfilled:

• The value of the equivalent A-weighted sound pressure level at the place of the location of the machine's work station does not exceed the admissible value.

The following final formula determining the power index W_I is obtained:

$$L_{PRGA} = 10\lg \frac{1}{\sum\limits_{i=1}^{k} \Delta t_i} \left(\sum_{i=1}^{k} \Delta t_i 10^{0.1 L_{PAi}} \right) - 10\lg \frac{10^{0.1 L_L} - 10^{0.1 L'_{\mathrm{Aeq}}}}{1 + 4\dfrac{2\pi d^2}{A}}\,. \tag{10}$$

The general principles of the acoustic assessment of the machine on the basis of the emission index are as follows:

• the machine is acoustically safe (i.e. the equivalent A-weighted sound pressure level at the work station in the operation room during the operation does not exceed the admissible value) if the condition $W_I \le 0\,\mathrm{dB}$ is fulfilled,

• the machine will acoustically dangerous (i.e. the equivalent A-weighted sound pressure level at the work station in the operation room during its operation exceeds the admissible value) if the condition $W_I > 0\,\mathrm{dB}$ is fulfilled.

4. Distance correction

On the basis of formula (10) it is possible to calculate the value of the emission index W_I only for such a distance d between the machine and the work station for which the real global A-weighted emission sound pressure level L_{PRGA} from the machine at the work station was determined at laboratory conditions. Because the real global A-weighted emission sound pressure level by the machine at the work station depends on the distance between the machine and the latter, it was necessary to modify formula (10) for the simulation tests. Therefore, a distance correction DC, in dB, was introduced, which takes into account the drop in the emission level with the variation of the distance.

The fact that the emission level of the source is determined by the sound pressure level is the starting-point for working out the distance correction DC. For the sound pressure level of the source, it is possible to assume that its value in the free field (in the far field) is inversely proportional to the square of the distance from the source. At the same time, it is possible to accept that this relation is valid for the indoor environment if the measurement points are located in the area restricted by the limiting distance, i.e. at the distance from the source at which the sound intensity determined by the reverberant field and the sound intensity determined by the free field are in equilibrium. Consequently, assuming that if the range of the variability of the distance between the assessed machine and the workstation is within the area restricted by the limiting distance, the distance correction DC in dB is described by the formula:

$$\mathrm{DC} = -20\lg\frac{d_1 + \Delta d}{d_1}\,, \tag{11}$$

where d_1 is the distance between the machine and the work station at which the real global A-weighted emission sound pressure level was determined experimentally, in m, Δd is the change of the distance between the machine and the work station in relation to the distance d_1.

Thus, the formula modified for the simulation tests, which makes the determination of the value of the emission index W_I possible, is:

$$W_I = L_{PRGA} + DC - 10\lg\frac{10^{0.1L_L} - 10^{0.1L'_{\mathrm{Aeq}}}}{1 + 4\dfrac{2\pi(d_1+\Delta d)^2}{A}}\,. \tag{12}$$

5. Simulation test results of the power index

The influence of the distance d between the machine and the work station and the radiation index Q is presented in Fig. 1. This figure shows that an increase in the distance between the machine and the work station as well as in the value of the radiation index cause a decrease of the value of the power index.

Simulation test results showing the influence of the primary acoustic climate L'_{Aeq} in the operation room and the distance d between the machine and the work station are presented in Fig. 2. In this case, on the basis of the results obtained it is possible to state that an increase of the value of the power index is followed by an increase of the

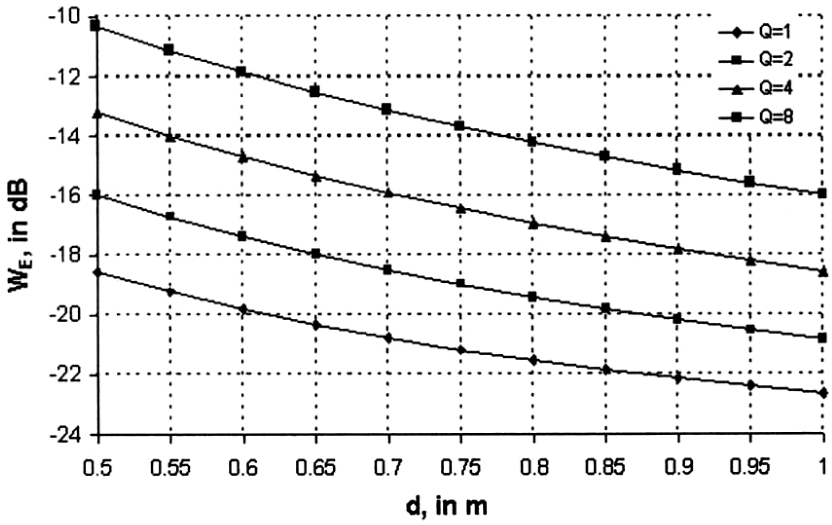

Fig. 1. Influence of the distance d and the radiation index Q on the power index W_E ($A = 54\,\mathrm{m}^2$, $L'_A\mathrm{eq} = 35.4\,\mathrm{dB}$, $L_L = 85\,\mathrm{dB}$, $L_{WRGA} = 84.7\,\mathrm{dB}$).

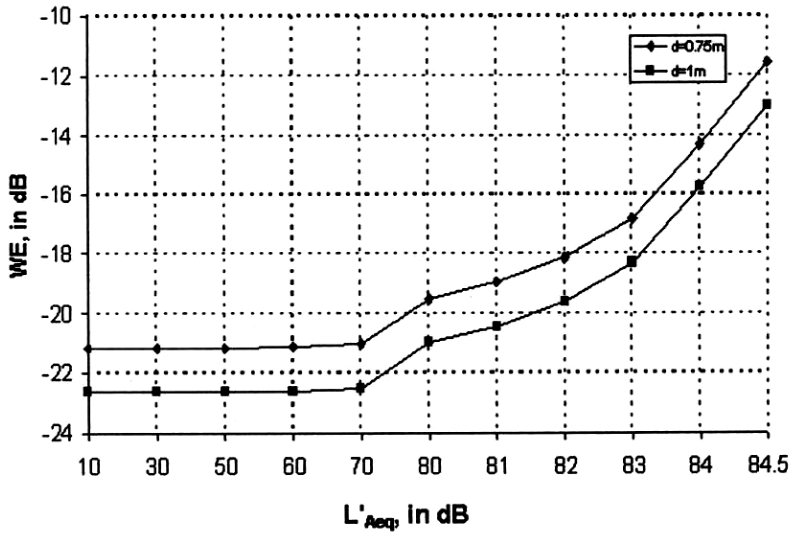

Fig. 2. Influence of the primary acoustic climate L'_{Aeq} and the distance d on the power index W_E ($A = 54\,\mathrm{m}^2$, $Q = 1$, $L_L = 85\,\mathrm{dB}$, $L_{WRGA} = 70.5\,\mathrm{dB}$).

equivalent A-weighted sound pressure level characterizing the primary acoustic climate in the operation room and the reduction of the distance between the machine and the work station. At the same time, the results show that the influence of the equivalent A-weighted sound pressure level characterizing the primary acoustic climate, are especially significant if the difference between the admissible value of the equivalent A-weighted sound pressure level at the work station and the value of the equivalent A-weighted sound pressure level characterizing the primary acoustic climate this level, is less than 15 dB (e.g. in the case when the admissible value of the equivalent A-weighted sound pressure level at the work station is 85 dB, the influence of the equivalent A-weighted sound pressure level characterizing the primary acoustic climate is significant if its value exceeds 70 dB).

Figure 3 presents the influence of the equivalent sound absorption area of the operation room A and the distance d between the machine and the work station on the

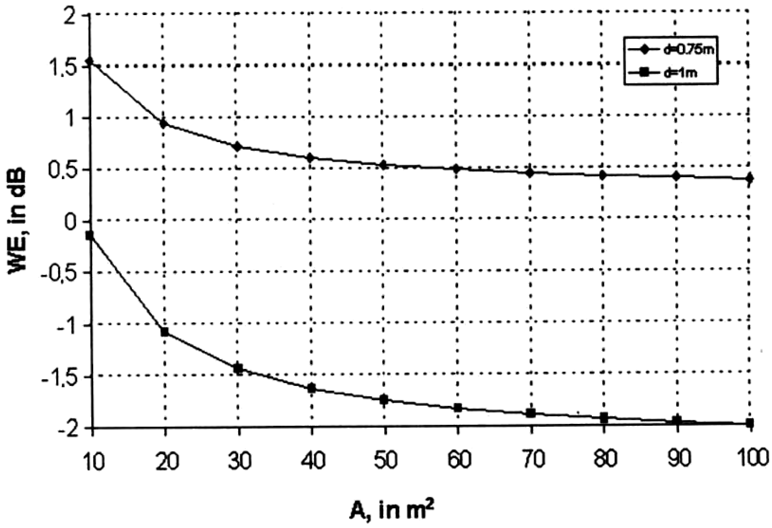

Fig. 3. Influence of the equivalent sound absorption area of the room A and the distance d on the power index W_E ($Q = 8$, $L'_{A\mathrm{eq}} = 35.4$ dB, $L_L = 85$ dB, $L_{WRGA} = 85$ dB).

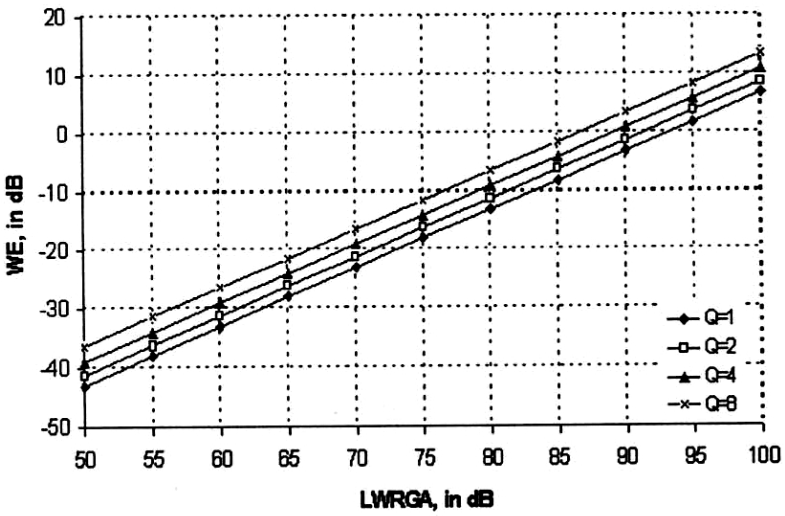

Fig. 4. Influence of the real global A-weighted sound power level L_{WRGA} on the value of the power index W_E ($A = 54\,\mathrm{m}^2$, $d = 1$ m, $L'_{A\mathrm{eq}} = 35.4$ dB, $L_L = 85$ dB).

value of the power index W_E. On the basis of the results obtained it is possible to state that an increase of the value of the equivalent sound absorption area of the operation room causes a decrease in the value of the power index. The most significant influence of the changes of the values of the equivalent sound absorption area of the room on the changes of the values of the power index is observed in the region below $70\,\mathrm{m}^2$. At the same time, the acoustic assessment result will be more favourable if the distance between the machine and the workstation is greater.

The influence of the changes of the values of the real global A-weighted sound power level L_{WRGA} on the value of the power index W_E is presented in Fig. 4. This figure shows that an increase in the value of the real global A-weighted sound power level causes a linear increase of the value of the power index.

6. Simulation test results of the emission index

Figures 5 and 6 present the simulation test results of the emission index W_I as a function of the real global A-weighted emission sound pressure level from the machine at the work station L_{PRGA} and the change of the distance between the machine and the work station Δd. The test results obtained in this case show that an increase in the value of the emission index is followed by an increase in the value of the real global A-weighted emission sound pressure level of the machine at the work station and the reduction of the distance between the machine and the work station. At the same time, there is a linear relation between the emission index and the value of the real global A-weighted emission sound pressure level of the machine at the work station.

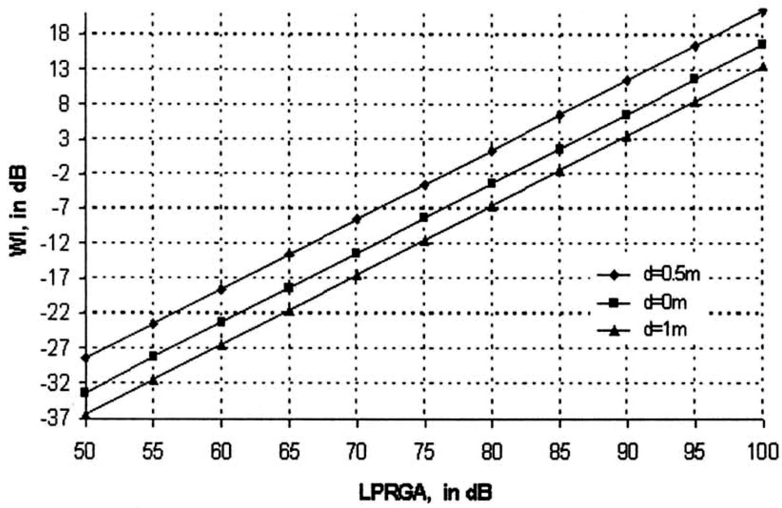

Fig. 5. Influence of the real global A-weighted emission sound pressure level L_{PRGA} on the value of the emission index W_I ($A = 54\,\mathrm{m}^2$, $L'_{\mathrm{Aeq}} = 35.4\,\mathrm{dB}$, $L_L = 85\,\mathrm{dB}$).

Simulation test results showing the influence of the primary acoustic climate L'_{Aeq} in the operation room and the change of the distance between the machine and the work

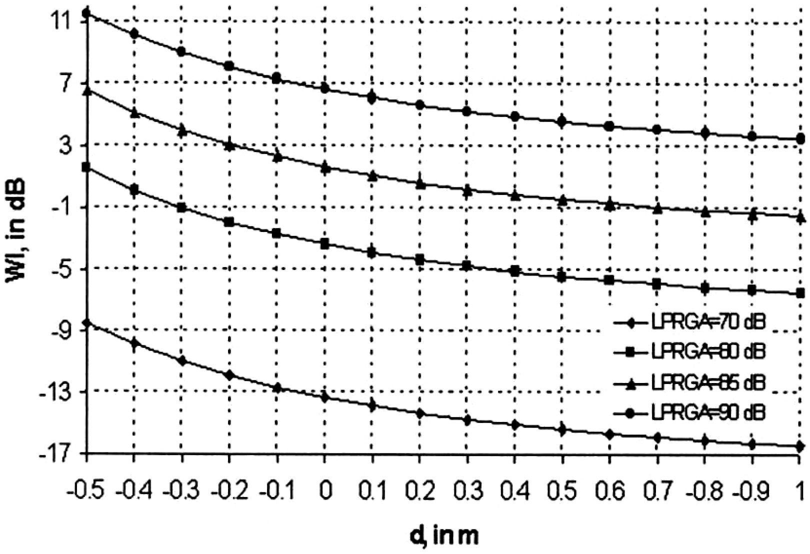

Fig. 6. Influence of the change of the distance Δd on the value of the emission index W_I ($A = 54\,\mathrm{m}^2$, $L'_{\mathrm{Aeq}} = 35.4\,\mathrm{dB}$, $L_L = 85\,\mathrm{dB}$).

station Δd are presented in Fig. 7. On the basis of the results obtained it is possible to state that an increase of the value of the emission index is followed by increase in the equivalent A-weighted sound pressure level characterizing the primary acoustic climate in the operation room. In the same way as in the case of the power index, this influence of the equivalent A-weighted sound pressure level characterizing the primary acoustic

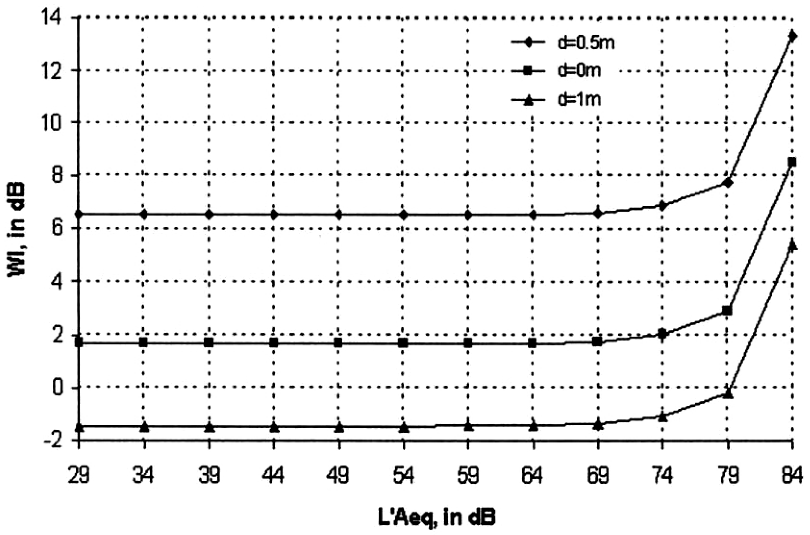

Fig. 7. Influence of the primary acoustic climate $'_{\mathrm{Aeq}}$ and the change of the distance Δd on the value of the emission index W_I ($A = 54\,\mathrm{m}^2$, $L_L = 85\,\mathrm{dB}$, $L_{PRGA} = 85\,\mathrm{dB}$).

climate is especially significant if the difference between the admissible value of the equivalent A-weighted sound pressure level at the work station and the value of the equivalent A-weighted sound pressure level characterizing the primary acoustic climate is less than 15 dB.

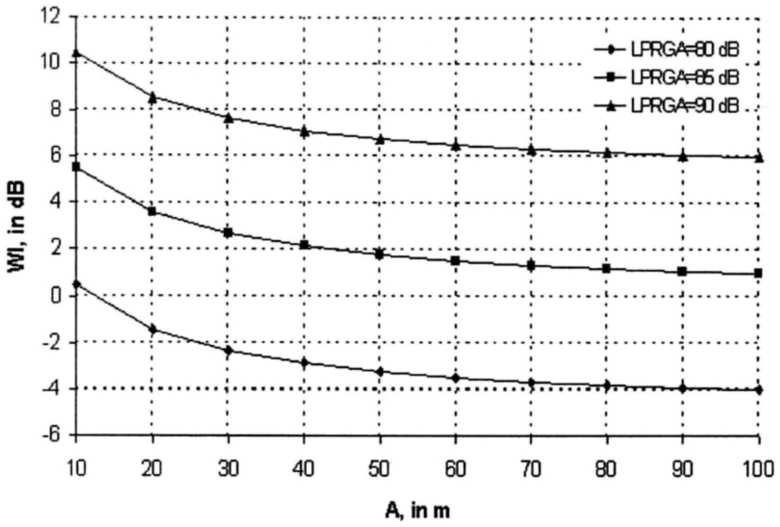

Fig. 8. Influence of the equivalent sound absorption area of the operation room A on the value of the emission index W_I ($L'_{\mathrm{Aeq}} = 35.4$ dB, $L_L = 85$ dB, $d = 1$ m).

Figure 8 presents the influence of the equivalent sound absorption area of the operation room A. The test results obtained show that an increase in the value of the equivalent sound absorption area of the operation room causes a decrease of the value of emission index.

7. Summary

The simulation test results are consistent with the experimental tests results [4], with the general principles of sound wave propagation and with the noise control methods. Sample results of the assessment of different noise sources using the power and emission indices (assuming that $L_L = 85$ dB), cofirmed by the measured values of the equivalent A-weighted sound pressure levels ($L_{\mathrm{Aeq}M}$), are given in Tables 2 and 3.

Table 2. Results of assessments using the power index.

Noise source	drill		centrifuge	
L_{WRGA}, in dB	84.7		73.2	
d, in m	0.75	1	0.5	1
W_E, in dB	0.52	−1.78	−7.6	−13
$L_{\mathrm{Aeq}M}$, in dB	85.5	84.2	75.6	74.8

Table 3. Results of assessments using the emission index.

Noise source	grinder		mixer	
L_{PRGA}, in dB	78		68.8	
A, in m^2	5.7	13.3	5.7	13.3
W_I, in dB	0.3	−2.4	−13	−14.5
$L_{\mathrm{Aeq}M}$, in dB	89	82.2	74.1	70.1

It is possible to achieve a favourable acoustic assessment result (i.e. the value of the assessment index is not greater than 0 dB) in the following ways:

• by reducing the noise emission of the machine and, by decreasing thereby the real global A-weighted sound power level (the real global A-weighted emission sound pressure level), and

• by shaping suitably the operational conditions, i.e. by increasing the equivalent sound absorption area of the operation room, changing the machine location in the room, by increasing the distance between the machine and the work station and decreasing the equivalent A-weighted sound pressure level characterizing the primary acoustic climate.

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