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# Method for noise calculation under specular and diffuse reflection of sound

# Метод расчета шума при зеркально-рассеянном отражении звука

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**Key words:** production buildings; noise; noise protection measures; noise calculation method; sound reflection from barriers

**Ключевые слова:** производственные здания; шум; шумозащитные мероприятия; метод расчета шума; отражение звука от ограждений

**Abstract.** Selection and designing of noise protection aids in industrial buildings require numerous calculations of energy characteristics typical for noise fields of their facilities. The efficiency of designed soundproof measures is relying on their accuracy. The degree of accuracy is defined by recording completeness in the method of measurement of factors, which affect the processes of noise fields in buildings. One of these factors is the type of sound refection from barriers. The analysis of reflected sound energy distribution revealed that sound reflection in industrial buildings follows mirror-scattered pattern. It forms two reflected fields, mirror-like and diffusely scattered, where reflected sound energy originates and propagates on different principles. The paper offers a combined method for calculation of energy characteristics of such fields; specular reflected energy is calculated by ray tracing, and diffusely scattered one is calculated by a numerical energy method. The paper describes the basic principles for making the combined design model and offers scattering factors of reflexible sound energy that are necessary for the implementation of design model and were obtained from experiments and calculations. The accuracy of the combined method was assessed by a comparative analysis, and experimental and calculation data in production facilities of various proportions. Disagreement between calculations and experiments did not exceed 2 dB. The method fits for solving problems of construction acoustic aids of noise reduction in industrial buildings. Unlike the existing methods, in the proposed method the real process of gradual transition from emerging mirror-reflected energy to diffusely dispersed energy is modeled. At the same time, the method takes into consideration certain acoustic characteristics of each section of enclosure such as sound attenuation coefficient and reflection coefficient. In the suggested form the method allows making calculations of noise in the buildings with any complex space-planning parameters.

**Аннотация.** При выборе и проектировании средств шумозащиты в производственных зданиях выполняются многократные расчеты энергетических характеристик шумовых полей помещений. От их точности зависит эффективность проектируемых шумозащитных мер. Степень точности определяется полнотой учета в методе расчета факторов, влияющих на процессы формирования шумовых полей в помещениях. Одним из них является характер отражения звука от ограждений. В результате анализа распределения отраженной звуковой энергии установлено, что в производственных помещениях отражение звука имеет зеркально-рассеянный характер. В этом случае в них образуются два отраженных поля – зеркальное и диффузно рассеянное, имеющие разные принципы возникновения и распространения отраженной звуковой энергии. Для расчета энергетических характеристик таких полей в статье предложен комбинированный метод расчета, в котором зеркально отражаемая энергия рассчитывается методом прослеживания лучей, а диффузно рассеянная - численным энергетическим методом. Изложены все основные

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принципы построения комбинированной расчетной модели и приведены необходимые для реализации расчетной модели коэффициенты рассеяния отражаемой звуковой энергии, полученные в работе экспериментально-расчетным путем. Точность предложенного комбинированного метода оценена путем сравнительного анализа экспериментальных и расчетных данных в производственных помещениях различных пропорций. В отличие от существующих методов в предложенном методе моделируется реальный процесс постепенного перехода возникающей зеркально отраженной энергии в диффузно рассеянную. При этом метод учитывает конкретные акустические характеристики каждого участка ограждений, а именно его коэффициент звукопоглощения и коэффициент отраженной звуковой энергии. В предложенной форме метод позволяет производить расчеты шума в помещениях с любыми сложными объемно-планировочными параметрами.

## 1. Introduction

Acoustic and economic efficiencies of selecting and designing noise protection aids in industrial buildings depend on the accuracy of calculation methods for noise characteristics that are used for the assessment of noise energy distribution before and after probable use of noise protection aids in industrial buildings. Reliability of noise energy distribution calculation method rests on the extent of the factors that influence the formation of noise fields in the facilities [1]. The most important factor is the type of sound refection from barriers: it influences the accuracy of the calculation method. Calculation results agree with experimental data when the type of sound reflection adopted for the method fits actual conditions of its reflection from the On the contrary, results are unsatisfactory when actual reflection disagrees with the one adopted for design model [1].

Sound reflection from barriers depends on complicated dimensional dependencies that rely on the surface shape, material structure, angle of sound incidence and other parameters. This makes exact description of type of the sound reflection from barriers a problem difficult to solve [2]. The existing method of calculations uses two ideal models of sound reflection – mirror-like and diffuse ones.

Mirror reflection is considered to observe the equality between incidence and reflection angles of sound rays from barriers. It is encountered when sound reflects from surfaces of size much greater that the length of waves that fall on them, whose irregularities are much smaller than the lengths [2, 3]. Now, mirror sound reflection form barriers can be found in design models based on geometric theory of facilities acoustics [4, 5]. Such models calculate noise via the method of apparent sources with its main provisions established in the first half of the 20$^{th}$ century [6], and the ray tracing method, M. Schreder offered initially for research of halls acoustics [7], and later adapted it to other problems, including noise calculation in industrial facilities [8].

The practice of noise calculations for industrial buildings most often uses design models and appropriate methods of implementation based on vision of diffuse type of sound reflection from barriers. Diffuse reflection implies total dissipation of reflected energy in accordance with the directional pattern that cosine dependence approximates by Lambert law. In terms of design models based on distribution of reflected sound energy, two design models appear definable. The first one employs classical theory of diffused sound field, that obeys the conditions of energy distributing uniformly throughout the volume of the facility and isotropic arrival of reflected sound rays to any point of the facility [9, 10]. This model is a base for developing statistic methods for solving practical problems of noise control in buildings with proportional facilities, e.g. in residential buildings [11, 12]. The second one rests on the notion that diffused sound reflection creates quasi-diffused sound fields in the facilities; they, unlike ideal diffused fields do not obey the feature of uniform energy distribution in the volume, but do keep the feature of isotropic angular directivity of sound rays that arrive to any point of the volume [13]. Such fields are formed in industrial facilities of large volume. As directed flows of reflected sound energy exist in quasi-diffused fields, the methods developed for noise calculations are based on statistical energy approach to estimation of reflected sound fields [14]. These methods are used in solving the practical problems at manufacturing companies, buildings and facilities of various purpose [15, 16].

Similar energetic approach to estimation of reflected sound energy distribution in facilities is also used in foreign practice [17–23]. In [17–23], a mathematical model for the distribution of sound energy in rooms with diffuse reflection of sound from walls is used. It is based on the idea that particles diffuse in a medium containing spherical scattering objects, and the assumption that the density gradient of the reflected sound energy and the density of its flux in the reflected sound field have a stable connection. The studies confirmed the possibility of using this model to solve various practical problems.

We analyzed the influence the type of sound reflection from barriers has on the accuracy of calculation methods. Comparing the calculations obtained by methods that employ mirror and diffused models of reflection with the data of experiments held in production facilities of various proportions and various sound absorbing characteristics showed that the actual nature of sound reflection carries traits of both mirror-like and diffused models of reflection. It was found that, as compared to the experimental data, the calculated levels of sound pressure in the mirror model were higher in the area furthest from the source, while in the diffused model, they were lower.

From the results of this comparative analysis, we found the necessity of a new method of calculation that would employ a mixed mirror-diffused model of sound reflection, when one part of energy is reflected under the mirror model, while the other one is scattered diffusely under the Lambert's law.

As a result, a reflected sound field of the facility forms two components for the reflected energy density, mirror-like and diffused, that obey different laws of formation. Mirror component depends on reflections of mirror-like part of rays, while the diffused one depends on the part of energy that converts into diffused energy while reflection of rays. The mirror component is defined by reflections of mirror-like elements of the rays, and diffusive element is defined by energy which transits at reflections of mirror rays from enclosures to dispersed energy. Thus, the calculation of energy characteristics of such a field needs the method for separate finding of mirror-like and diffused components. The process should consider for continuous transition of some mirror energy to diffused energy. Finally, the calculated levels of sound pressure are to be found from superposition principle from the sum of densities of direct sound energy, mirror and diffused components of reflected energy density:

$$L_i = 10\lg\left[\left(\varepsilon_i^{dir} + \varepsilon_i^{mir} + \varepsilon_i^{dif}\right)c / I_0\right], \tag{1}$$

where $\varepsilon_i^{dir}, \varepsilon_i^{mir}, \varepsilon_i^{dif}$ are densities of direct sound energy, mirror-like and diffused components of reflected sound energy in *i*-th designed point of the facility volume; $I_0$ means intensiveness of sound at the threshold of hearing; *c* means velocity of sound in the air.

According to the above, the article aims to develop a noise calculation method, which takes into consideration a mirror-dispersed type of sound reflection from enclosure. During its development the following tasks were accomplished: the accounting model for forming of the reflected sound field was proposed; this model also takes into consideration the constant transition of mirror-reflected energy to diffusely scattered energy; the definition of the coefficient of dispersion of energy reflected from enclosure for typical groups of industrial buildings was done by experimental calculations, the experimental assessment of the combined method by comparing the results of experiments and calculations in production buildings of various geometrical proportions was made.

A practical use of the combined method is supported with the computer program that can estimate noise mode in facilities and acoustic efficiency of noise reduction aids designed.

## *2. Methods*

In the combined method offered, densities of direct sound and mirror-like component are calculated with a ray tracing method. The method has been selected because it finds direct and reflected energies as well as the part of the energy that converts into diffused energy during reflections of mirror rays. A diffused component of reflected energy is calculated with numerical statistical energy method, developed earlier for estimation of diffusedly reflected energy distribution in a quasi-diffused sound field [13, 14].

The backbone of the combined calculation method consists in the following.

A sound source, in accordance with its directional pattern, irradiates the amount of rays found probabilistically, each of them carrying a part of sound energy of the source. Each ray is tracked up to a calculated point with account to its contacts with barrier surfaces. During reflection from surface, the part of energy remained after ray energy absorption reflects under mirror law, while other follows diffused Lambert's law. The energy reflected under the mirror law is tracked until the next act of reflection, when, after reflection, mirror energy converts into diffused one. Each ray is tracked until it completely loses its energy due to absorption at surfaces, attenuation in the air and conversion of some mirror energy into diffused one. Thus, all rays that come from the source are tracked, with summarized direct and mirror reflected energies of all rays that pass the calculated point. Energy distribution of diffusedly scattered rays is estimated with numerical statistical energy method. What follows are the main principles of plotting the combined calculation method.

As numerical method is employed for the calculation of diffused component of reflected energy, at first all the volume of facility is broken down elementary volumes, where the nature of diffusely reflected energy density's change can be accepted as linear [13].

Then, densities of direct sound energy $\varepsilon_i^{dir}$ and of mirror reflected energy $\varepsilon_i^{mir}$, that arrive to each *i*-th elementary volume, can be obtained from the formulas

$$\varepsilon_i^{dir} = \sum_{k=1}^{K} W_{ki}^{dir} \Big/ cS_{red}, \quad (2)$$

$$\varepsilon_i^{mir} = \sum_{k=1}^{K} W_{ki}^{mir} \Big/ cS_{red}, \quad (3)$$

where $W_{ki}^{dir}$ is an energy of direct sound each *k*-th ray transmits per a unit of time into *i*-th elementary volume

$$W_{ki}^{dir} = \frac{W}{N} \exp\left(-m_a R_{ki}\right), \quad (4)$$

$W_{ki}^{mir}$ is a sound energy brought per a unit of time by each *k*-th mirror reflected ray that enters the *i*-th volume

$$W_{ki}^{mir} = \frac{W}{N} \exp\left(-m_a R_{ki}\right) \prod_{p=1}^{P} \left[(1-\alpha_p)(1-\beta_p)\right]^{D_p}, \quad (5)$$

*W* is sound power of the source, W; *N* is a number of rays going out of the source; $m_a$ is space coefficient of sound attenuation in the air, m$^{-1}$; $R_{ki}$ is a distance *k*-th ray passes from between the sound source and the *i*-th elementary volume, m; $\alpha_p$ is a coefficient of sound absorption of *p*-th barrier surface, to where the tracked ray fell; *P* is a total amount of reflection acts of *k*-th ray from all surfaces it encounters during propagation to distance $R_{ki}$ up to *i*-th elementary volume; $D_p$ is number of incident acts of *k*-th ray to *p*-th surface during its propagation to distance $R_{ki}$; $\beta_p$ is a part of mirror diffusely scattered energy of *k*-th ray after its reflection from *p*-th surface of barrier; *k* is a number of rays that pass through the elementary volume; $S_{red}$ is a reduced sectional area of elementary volume. In case, when all the volume of the facility is broken down elementary volume shaped as cubes or parallelepiped, square $S_{red}$ is taken as a square of cross section of the sphere equal in volume to elementary cube or parallelepiped.

Density of diffusedly reflected energy $\varepsilon_i^{dif}$ in the combined method is calculated with the numerical energy method that implements a mathematical model presenting distribution of density energy in quasi-diffused sound field as an equation of second order partial derivatives

$$\eta \nabla^2 \varepsilon^{dif} - c m_a \varepsilon^{dif} = 0 \quad (6)$$

with boundary conditions

$$\bar{q}\Big|_{dS} = \beta(1-\alpha) I\Big|_{dS} - \frac{c \cdot \alpha}{2(2-\alpha)} \varepsilon^{dif}\Bigg|_{dS}. \quad (7)$$

In expressions (6) and (7), $\eta = 0.5 c l_{\text{cp}}$ a coupling coefficient for flow density and density gradient of diffusedly reflected energy in quasi-diffused sound field [13]; $l_{\text{cp}}$ is a length of mean free run of diffusedly reflected sound rays; $\alpha$, $\beta$ are coefficients of sound absorption and scattering of mirror energy at the considered element of *dS* surface; *I* is intensiveness of direct and reflected mirror sound energy with regard to incident angle of sound rays that fall on element *dS*.

The first member in the right part of boundary conditions (7) define entering of diffusedly scattered energy into the volume of facility from the surface of element *dS* when mirror rays fall on it. The second member define intensiveness of absorption of diffusedly scattered energy that falls on element *dS*.

In the case of a numerical decision of equation (6) with boundary conditions (7) each elementary volume $V_{i,j,d}$ (see Figure 1) receives an equation for balance of diffusedly reflected sound energy per unit of time. Total distribution of density of diffusedly reflected energy is obtained by doing the system of algebraic equations.

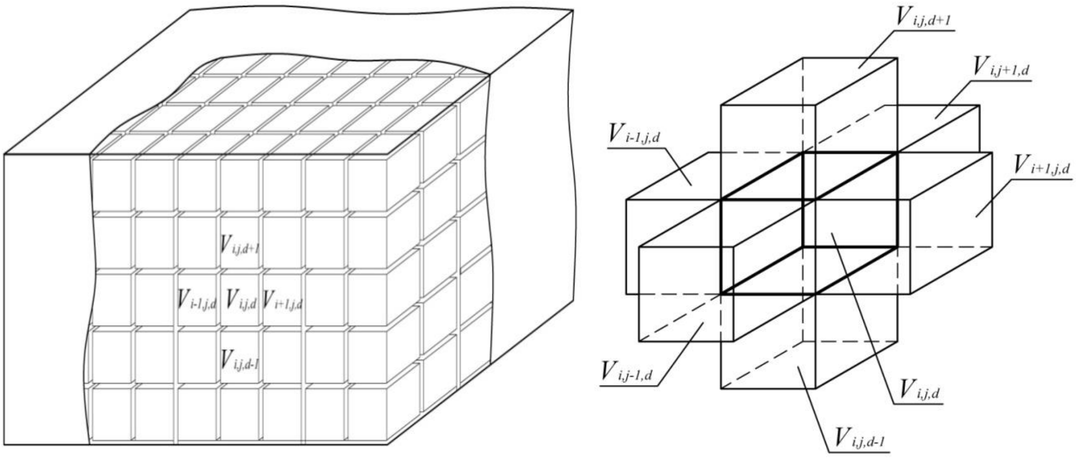


**Figure 1. Patterns of facility breaking into elementary volumes**

Balance of reflected energy for each *i,j,d*-th elementary volume with regard to absorption of sound in the air is generally written as

$$\sum_{n=1}^{N} q_n S_n + \sum_{m=1}^{6-N} W_m^{dif} - \sum_{m=1}^{6-N} q_{(\alpha)m} S_m - c m_a \varepsilon_{i,j,d}^{dif} V_{i,j,d} = 0. \quad (8)$$

Here, $q_n$ is densities of diffused energy flows between *i,j,d*-th volume and adjacent contacting volumes through surfaces $S_n$, that connect them, W/m$^2$; $W_m^{dif}$ is a diffuse component of sound energy that enters *i,j,d*-th volume after reflection of rays from *m*-th surface of this volume of square $S_m$, being barrier surface of facility, W; $q_{(\alpha)m}$ is a density of diffuse energy flow that is absorbed at *m*-th surface of *i,j,d*-th volume, being a barrier surface for the facility of square $S_m$, W/m$^2$; N is a number of elementary volumes that contact with *i,j,d*-th volume; 6-*N* man a number of facets of *i,j,d*-th volume, being barrier surface of the facility; $V_{i,j,d}$ is a volume of an elementary parallelepiped, m$^3$; $\varepsilon_{i,j,d}^{dif}$ is a density of diffusedly reflected energy in *i,j,d*-th volume, J/m$^3$.

For the inner volume not contacting with barriers and equipment, the balance of reflected energy is written as

$$\sum_{n=1}^{6} q_n S_n - c m_a \varepsilon_{i,j,d}^{dif} V_{i,j,d} = 0. \quad (9)$$

Final members of equations (8) and (9) show losses of energy in *i,j,d*-th volume because of its absorption in the air.

Densities of energy flows $q_n$ are defined as

$$q_n = -\eta\left(\varepsilon_{i,j,d}^{dif} - \varepsilon_n^{dif}\right)/h_n. \quad (10)$$

where index $n \in \{i-1, j, d; i+1, j, d; i, j-1, d; i, j+1, d; i, j, d-1; i, j, d+1\}$; $h_n$ means a distance between centers of *i,j,d*-th volume and contacting volumes in direction characterized by index *n*.

Density of flows $q_{(\alpha)m}$ is obtained from the formula

$$q_{(\alpha)m} = \frac{\alpha_m \cdot c\varepsilon_{i,j,d}^{dif}}{2(2-\alpha_m)}, \quad (11)$$

where $\alpha_m$ means coefficient of sound absorption of *m*-th surface *i,j,d*-th volume.

Value $W_m^{dif}$ is a sum of energies of rays that converted to reflected diffused component when rays reflect from *m*-th surface *i,j,d*-th volume, that make a part of facility barrier surface. In accordance with formulas (4) and (5) and given the ray incidence angle on the surface, $W_m^{dif}$ is calculated by the formula

$$W_m^{dif} = \beta_m (1-\alpha_m)\left[\sum_{k=1}^{K}\frac{W}{N}\exp(-m_a R_{ki,j,d})\cos\theta_{mi,j,d} + \right.$$
$$\left. + \sum_{k=1}^{K}\frac{W}{N}\exp\left(-m_a R_{ki,j,d}\right)\cos\theta_{mi,j,d}\prod_{p=1}^{P}\left[\left(1-\alpha_p\right)\left(1-\beta_p\right)\right]^{D_p}\right], \qquad (12)$$

where $K$ is a number of direct rays or mirror reflected rays, that fell on $m$-th surface $i,j,d$-th volume, being a barrier surface; $\beta_m$ is a portion of diffusedly scattered energy of $k$-th ray after its reflection from $m$-th barrier surface $i,j,d$-th volume; $\theta_{mi,j,d}$ is an incident angle of $k$-th ray that falls on $m$-th surface in $i,j,d$-th volume.

A complicated problem in use of combined method of calculation consists in finding the scattering coefficient of reflected sound energy β. We based on experimental research and appropriate calculations to set coefficients β for typical groups of facilities in production buildings (see Table 1). Similar research is now being held for other groups of industrial and civil buildings not included in Table 1.

***Table 1. Recommended values of scattering coefficients β***

| No. | Characteristics of the facility | Examples of facilities | Scattering coefficient |
|---|---|---|---|
| 1 | Empty facilities and facilities of simple shape with flat containing surfaces | Air ducts, channels, crosses, tunnels | 0.1 |
| 2 | Empty facilities with forms of facility slightly distorted from flat surfaces | Corridors, empty facilities without equipment | 0.2 |
| 3 | Facilities of simple form with flat ceiling and equipment installed | Production facilities in multistoreyed buildings | 0.3-0.4 |
| 4 | Facilities with complicated ceiling and equipment installed | Production facilities in onestoreyed buildings | 0.5-0.8 |
| 5 | Facilities of complicated from with many equipment, including large-size pieces, and scattering elements at the ceiling | Production facilities in onestoreyed buildings | 0.9-1.0 |

## 3. Results and Discussion

To estimate the accuracy of the combined method offered, we did a comprehensive comparative analysis of experimental and calculated data in industrial facilities of various proportions.

The experimental research was held in proportional facilities that, in accordance with [5] have not more than 5 ratio between the largest and the smallest size, in long facilities where ratio between length $D$, height $H$ and width $G$ make $D/H$>5, $G/H$<4, and in flat facilities with $D/H$>5, $G/H$≥4 size ratio. All facilities were of regular rectangular shape. During experiment, long facilities contained no equipment. Proportional and flat facilities had several pieces of equipment.

The hardware support of experiments included sources of sound energy, a set of noise metering instruments and metering equipment for reverberation time. The experiment employed noise source IOSh-1A produced by Etalon plant, and omnidirectional sound source (dodecahedron) OED-P-012-600. Sound power of source IOSh-1A in frequency range 63-8000 Hz was not less than 80 dB, dodecahedron power was 90 dB and more. Directivity index of sources was not more than ±5 dB. Some measurements were made with the equipment by Bruel & Kjaer, while other measurements were made with the equipment by Kompania OKTAVA+ OOO that affords recording and analysis of time and energy characteristics of noise in the facilities. The measurement methods of sound pressure levels agreed with GOST 12.1.050-86. The number and layout of measurement points in facilities fit the requirements of reflected energy distribution analysis in terms of sound reflection type and facilities proportions influence on it.

The calculations were made by the specially designed computer program that can apply combined method for calculations with any values of β in the range between β=0 (fully mirror reflection) and β=1.0 (fully diffused scattering).

The analysis proved that in proportional facilities noise may be calculated with methods that employ both mirror and diffused reflection of sound from barriers. Results of calculations with statistic and geometry methods agree with experimental data. The example is shown in Figure 2. It is seen that experimental and calculated data in the zone furthest from the noise source differ not more than ±1.5 dB. Potential analysis of geometry method for rays tracking and numerical statistical energy method proves that in proportional facilities of complicated forms or when numerous repetitive calculations are required, numerical method is more attractive in terms of efficiency, as it offers faster performance (see Figure 2) for the same accuracy.

Figure 3 shows the results of calculations and an experiment held in long facilities of corridor type. It can be seen that for mirror model of reflection (β=0) calculations are much higher, and for diffused model (β=1) they are much lower. The results closest to the experiment were obtained for mirror-diffused reflection, when β=0.2, that fits well with the data of Table 1.

Calculated characteristics and experimental levels of sound pressure obtained in typical flat facility without equipment are shown in Figure 4. It is seen that like in case of long facilities, the mirror model of reflection increases calculated levels, while diffused model reduces them. As before, the calculation with mirror-diffused reflection with β=0.2 brings the most satisfactory results.

Generally, the results of the comparative analysis demonstrate that evaluation of the noise mode required the calculation methods that are based on the mirror-diffused reflection of sound from barriers and, in particular, the combined method of calculation presented in this paper.

The suggested method is substantially different from the previously developed accounting models based on formal combinations of geometrical and statistical methods: they offered using the imaginary source method, which takes into account the remaining part of reflected energy [13]. Such approach was also suggested in foreign practice [24, 25]. In this case, to define the first reflection the method of ray tracing is used instead of the imaginary source method. The said methods formally consider the separation of mirror- and diffusely reflected energy and, accordingly, their accuracy is defined by the accuracy of this separation. Unlike them, in the suggested combined method the constant process of transition of the mirror energy to energy dispersed at certain parts of enclosure while taking into account their position regarding the noise source and acoustic characteristics of the surface is shown. Numerical realization of the combined accounting model allows conducting calculations for buildings of any complexity.

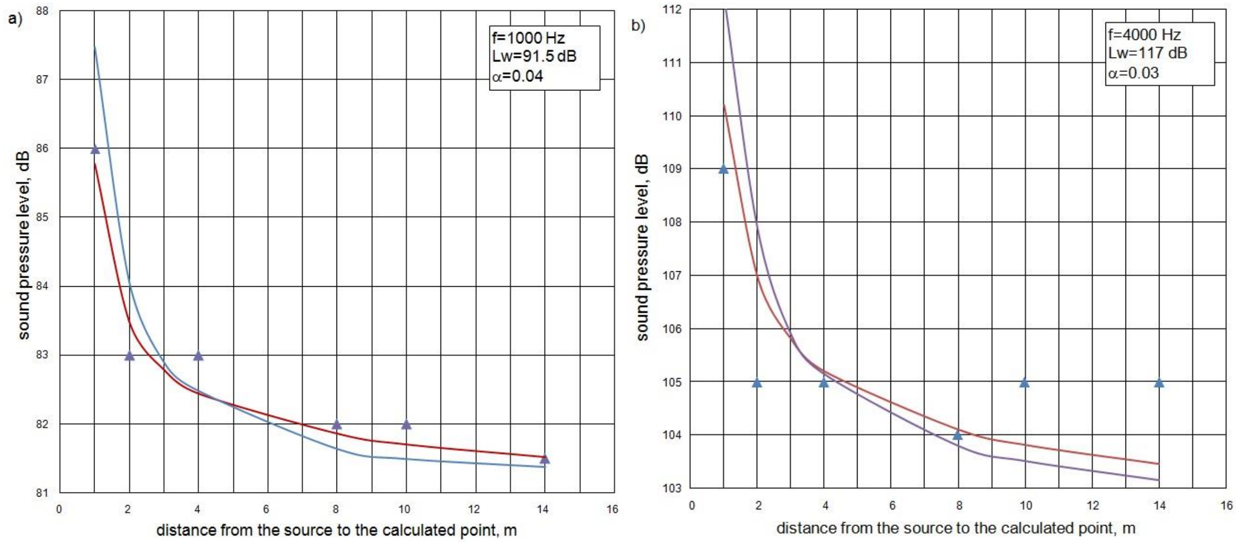


**Figure 2. Experimental and calculated levels of sound pressure in proportional 18×15×4.5 m facility: ▲ – experimental data; ▬▬ – calculation with β=1 (fully scattered reflection); ▬▬ – calculation with β=0 (fully mirror reflection)**

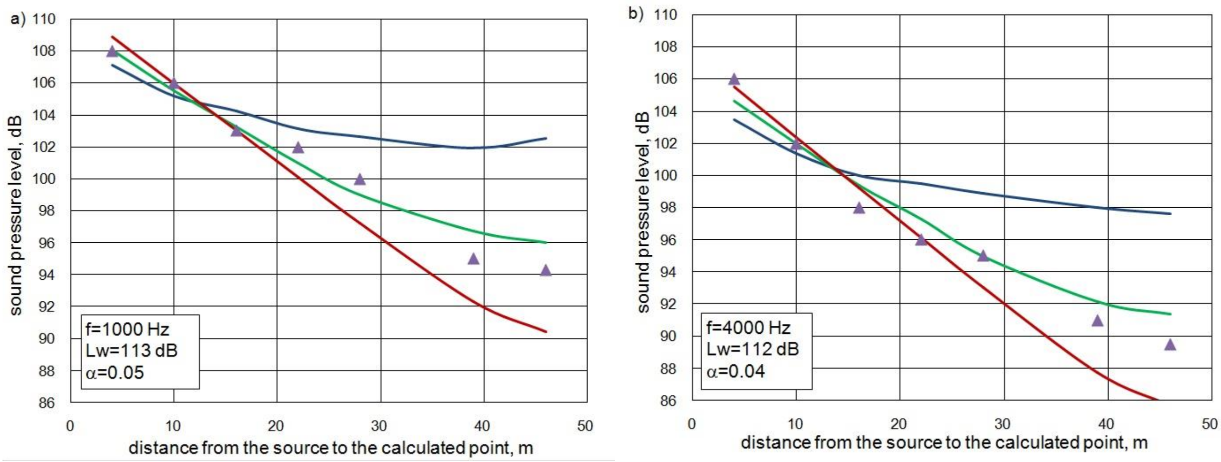


**Figure 3. Experimental and calculated levels of sound pressure in long 49.6×2.5×3.5 m facility:**
**▲ – experimental data; – calculation with β=1 (fully scattered reflection);**
**– calculation with β=0 (fully mirror reflection);**
**– calculation with β=0.2 (mirror-diffused model of reflection)**

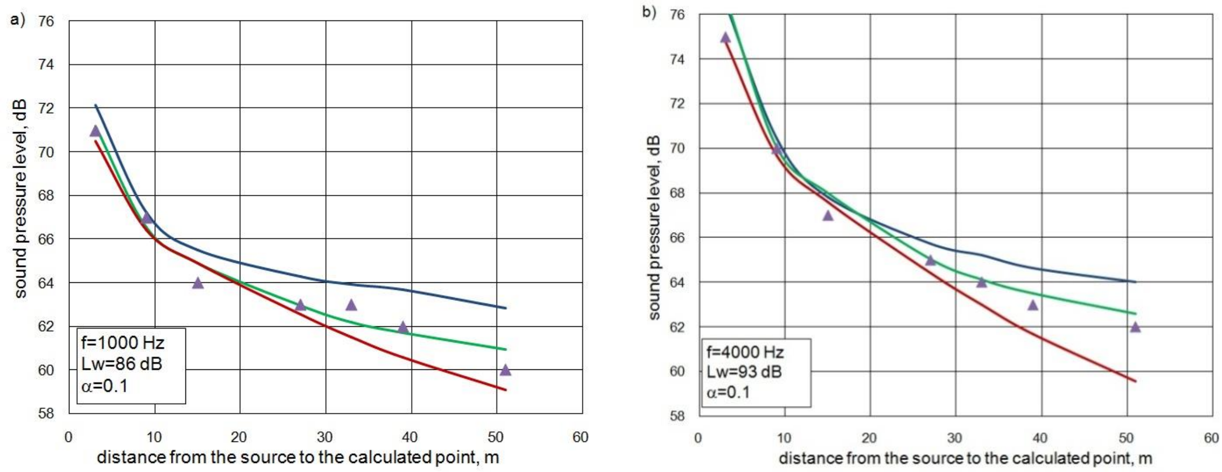


**Figure 4. Experimental and calculated levels of sound pressure in flat 72×36×6 m facility:**
**▲ – experimental data; – calculation with β=1 (fully scattered reflection);**
**– calculation with β=0 (fully mirror reflection);**
**– calculation with β=0.2 (mirror-diffused model of reflection)**

## *4. Conclusions*

The research done and the results obtained lead to the following conclusions:

1. The accuracy in the calculating levels of sound pressure in facilities depend on the extent the calculation method accounts for the actual type of sound reflection from barriers. In industrial facilities, the sound reflection from barriers has distinctive mirror-diffused type.

2. Calculation of noise in industrial facilities with mirror-diffused type of sound reflection requires the use of the developed combined method of calculations based on the ray tracing method for estimation of mirror energy distribution, and the numerical statistical energy method for estimation of diffused-scattered energy.

3. The accuracy of the combined calculation method depends largely on the reliability of finding the scattering coefficientβ. Its value depends on the structure of the enclosure surfaces, on the presence in the premises of the sound-scattering equipment, the shape and proportions of the rooms. This paper gives values of scattering coefficients β for the most typical groups of production facilities. An additional research of values β for other groups of facilities not mentioned in the Table 1 is required.

4. The method offered and the software for its implementation can estimate noise mode in production facilities for any scattering coefficient β in the range between β=0 (fully mirror scattering) and β=1 (fully diffused scattering). Error for calculation of the most difficult cases is not more than ±2.0 dB that

fits the required accuracy of practical calculations for estimation of noise mode and development of construction-acoustic aids of noise reduction in production buildings.

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