Combined Method for Calculating Non-Continuous Noise in Industrial Buildings

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Abstract. In multi-storey industrial buildings, technological processes are widespread, whereby a non-continuous in time noise regime is formed in rooms. When choosing and designing means of noise protection in these cases, multiple calculations of the energy characteristics of the noise fields of premises are performed. The effectiveness of the designed noise protection measures depends on their accuracy. The degree of accuracy is determined by the completeness of accounting in the method for calculating the factors affecting the formation of noise fields in rooms. One of them is the nature of the reflection of sound from fences. As a result of the analysis of the distribution of the reflected sound energy, it was found that in industrial premises the reflection of sound has a specularly scattered character. In this case, two reflected fields are formed in them - specular and diffusely scattered, having different principles of the appearance and dispersion of reflected sound energy.

To calculate the energy characteristics of such fields, a combined calculation method is proposed in the article. Considering that the premises in industrial multi-storey buildings have a regular rectangular shape, in the proposed method, the specularly reflected energy is calculated by the method of imaginary sources, and the diffusely scattered energy is calculated on the basis of the Kuttruff integral equation. All the basic principles of building a combined computational model are stated. The accuracy of the method was assessed by comparative analysis of experimental and calculated data in rooms with a regular geometric shape.

In contrast to the existing methods, the proposed method simulates the real process of the transition of the arising specularly reflected energy into the diffusely scattered one. In this case, the method takes into account the specific acoustic characteristics of each section of the fence, to be exact, its sound absorption coefficient and the scattering coefficient of reflected sound energy. In the proposed form, the method makes it possible to calculate non-continuous noise in rooms with a regular geometric shape, typical of multi-storey industrial buildings.

1. Introduction

In multi-storey industrial buildings, for example, light industry, commonly, technological processes are carried out in which a non-continuous in time noise regime occurs in the premises. To provide them with regulatory requirements for the noise factor, it is necessary to develop noise protection measures.

The acoustic and economic efficiency of the selection and design of noise protection equipment depends on the accuracy of the methods for calculating the energy characteristics of noise used to
assess the distribution of sound energy in rooms before and after the possible use of noise protection measures. The degree of reliability of the assessment of the distribution of sound energy depends on the completeness of accounting in the adopted method for calculating the factors affecting the formation of noise fields in rooms [1]. The most significant factor affecting the accuracy of the calculation is the nature of the sound reflection from the fences. The calculation results coincide with the experimental data in those cases when the nature of sound reflection adopted in the development of the method corresponds to the real conditions of its reflection from fences. Vice versa, the results become unsatisfactory if the actual reflection does not correspond to the one adopted in the calculation model [2]. The exact description of the nature of the sound reflection from the fences is difficult to accomplish [2]. Therefore, in practice, while calculating the ideal specular and diffuse models of sound reflection are used.

In case of specular reflection, equality of the incidence angles and reflection of sound rays from fences are observed. It is performed when sound reflects from surfaces, the dimensions of which are much larger than the lengths of the waves incident on them, and the dimensions of the irregularities on them are significantly less than these lengths [3,4]. At this point, specular reflection of sound is implemented in calculation models developed on the basis of the geometric theory of room acoustics. Within these models, for the calculation of noise, the method of imaginary sources was proposed, the main provisions of which were developed in the first half of the 20th century [5], and also the method of ray tracing, first proposed by M. Schroeder for studying the acoustics of halls [6]. Later it was modified for noise calculations in industrial premises [7].

An analysis of the possibility of using these methods to assess the energy characteristics of non-continuous in time noise has shown that the method of imaginary sources is the most appropriate for calculating noise in rooms with a regular shape. It has a simpler computation procedure and is easily algorithmic.

While calculating the noise, the most widely used calculation models and methods based on the concept of the diffuse nature of sound reflection from fences. Diffuse reflection assumes complete scattering of the reflected energy in accordance with the directional diagram according to Lambert's law. There are various calculation models based on the concept of diffuse scattering of reflected sound energy.

The first model is based on the classical theory of a diffuse sound field, in which the uniformity of energy distribution over the volume of the room and the isotropy of the arrival of reflected sound beams at any point in the room are observed [8]. On its basis, statistical methods have been developed that are used to solve practical problems of combating noise in buildings with commensurate premises, for example, in residential buildings [9]. In the second calculation model, it is assumed that in rooms with diffuse reflection of sound, quasi-diffuse sound fields are formed, in which, unlike an ideal diffuse field, the uniformity of the energy distribution over the volume is not observed, but the sign of isotropy of the angular directivity of sound rays arriving at any point in the volume is preserved. [10]. Such fields are formed in large production facilities. Since there are directed streams of reflected sound energy in quasi-diffuse fields, methods have been developed for calculating constant noise based on a statistical energy approach to assessing reflected sound fields [11]. These methods are used to solve practical problems in buildings and structures for various purposes. Similar energy methods are also used in foreign practice. [12-18].

In addition to the calculation models considered above, in the practice of estimating the distribution of diffusely scattered energy, a numerical method based on the Kuttruff equations is used [19], which refers to the Fredholm integral equations of the second kind [20].

An analysis of the possibilities of using the considered calculation models and methods showed that to estimate the non-continuous in time noise generated by diffuse reflection of sound, a numerical method based on the integral Kuttruff equation should be used.

The analysis of the influence of the nature of sound reflection from fences on the accuracy of calculation methods is performed. Comparison of calculations obtained by methods using specular or diffuse reflection models with experimental data in industrial premises of different proportions and
with different sound-absorbing characteristics showed that the real nature of sound reflection simultaneously carries signs of specular and diffuse reflection models. Based on the analysis, it has been established that to assess the non-constant, a new calculation method is required, in the development of which a mixed specular-scattered model of sound reflection should be used, when one part of the energy is specularly reflected, and the other is diffusely scattered in accordance with Lambert's law. With this reflection, two components of the reflected energy density are formed in the sound field of the room - specular and diffuse. They have different patterns of formation. The specular component is determined by the reflections of the specular part of the rays, and the diffuse component is determined by the energy that passes into the scattered energy during reflections of the specular rays from the fences. Therefore, to calculate the energy characteristics of such a field, a calculation method should be used in which the specular and diffuse components are determined separately. In this case, the constant transition of part of the specular energy into diffuse one must be taken into account. The final result of calculating the sound pressure levels of variable noise will be determined at the calculated points at any time $\tau$ by the sum of the densities of the direct sound energy, the specular and diffuse components of the reflected energy density

$$L_{\tau i} = 10 \log \left( \frac{E_{\tau i}^{\text{dir}} + E_{\tau i}^{\text{mir}} + E_{\tau i}^{\text{diff}}}{I_0} \right),$$

where $E_{\tau i}^{\text{dir}}$, $E_{\tau i}^{\text{mir}}$, $E_{\tau i}^{\text{diff}}$ - density of direct sound energy, specular and diffuse components of reflected sound energy at the $i$-th calculated point of the volume of the room at time $\tau$; $I_0$ - sound intensity at the threshold of audibility; $c$ - the speed of sound in air.

This article presents a combined method for calculating non-continuous noise, taking into account the specularly scattered nature of sound reflection from fences. In its development, a calculation model of the formation of a reflected sound field was used, which takes into account the partial transition of specularly reflected energy into diffusely scattered energy. An experimental assessment of the proposed combined method was carried out by comparing the results of experiments and calculations in production facilities of a regular shape with their various geometric proportions.

2. Methods

In the proposed combined method, the calculation of the specular component of the reflected noise is performed by the method of imaginary sources. The choice of the method is justified by the fact that it allows to determine the specularly reflected energy and, at the same time, to establish its part that transforms into diffuse energy during reflections. To calculate the diffuse component of the reflected energy, a numerical method for solving the Kuttruff equation is used, which was previously developed to estimate the distribution of diffusely reflected energy in a constant sound field and used by us to estimate the coupling coefficient between the flux density and the gradient of the reflected energy density in a quasi-diffuse sound field [21].

The point of the proposed combined calculation method is as follows.

First, the energy density of the direct sound and the density of the specular component of the reflected noise are determined. This is due to the fact that their energy is the primary source for the formation of diffusely reflected sound energy. Then the diffusely scattered energy is calculated and the sound pressure levels of the non-continuous noise are calculated using formula (1).

The calculation of the density of direct energy arriving at the $i$-th calculated point from a source of non-continuous in time noise is usually not difficult, and especially when the source is a point source with a known radiation factor. For example, for a point source that emits energy uniformly into a sphere, the value of the direct energy density will be determined at the calculated moment $\tau$ by the formula
where $R_i$ - distance from source to $i$-th calculated point; $m_a$ - spatial attenuation coefficient of sound in air; $W_t$ - variable acoustic power of the source, taking into account the delay in arrival at the calculated point of the radiated energy, $t = \tau - R/c$. Here and below, the quantities $t$ and $\tau$ refer to the same time interval, however, the first quantity relates to the emission of energy by a sound source, and the second determines the observation time.

The determination of the specular component of the density of the reflected sound energy is carried out by the method of imaginary sources, taking into account the transition during reflections of a part of the specular energy into diffusely scattered energy. In this case, the loss of specular energy occurs due to its partial absorption on the surface, which has a sound absorption coefficient $\alpha$, as well as due to the scattered part of its energy at the surface scattering coefficient $\beta$. The decrease in the specular energy in this case is conveniently estimated by one value of the "conditional" sound absorption coefficient, determined by the expression

$$\alpha_{con} = 1 - (1 - \alpha)(1 - \beta) = \alpha + \beta - \alpha \beta. \quad (3)$$

Since the coefficient $\beta$ is almost impossible to determine for each individual surface, in the calculations it is taken to be the same for all surfaces of the room. Our preliminary studies show that in long rooms such as corridors, the coefficient $\beta$ in the calculations can be taken equal to $\beta = 0.2$, and in rooms with a regular geometric shape with a flat ceiling and in the presence of technological equipment in them, equal to $\beta = 0.3 - 0.4$. In this case, the calculation of the specular component of the reflected sound energy is performed by the expression

$$\varepsilon_{\tau i}^{np} = \frac{W_t}{4\pi R_i^2 c} \exp(-m_a R_i), \quad (2)$$

$$\varepsilon_{\tau i}^{mnq} = \sum_{m=0}^{m=\infty} \sum_{n=0}^{n=\infty} \sum_{q=0}^{q=\infty} \frac{W_t \prod_{j=1}^{j=j} (1 - \alpha_{con})^{k_j} \cdot \exp(-m_a r_{mnq})}{r_{mnq}^2}, \quad (4)$$

where $r_{mnq}$ - distance to the calculated point from the imaginary source of the $mnq$ order ($m + n + q \neq 0$); $k_j$ - the number of contacts of a ray from an imaginary source with the $j$-th surface of the room; $W_t$ - the sound power of the source, taking into account the delay in the arrival of the beam from the imaginary source of the $mnq$ order, $t = \tau - r_{mnq}/c$; $\alpha_{con}$ - conditional sound absorption coefficient of the $j$-th surface, determined by formula (3). In this case, the value of $\alpha_{con}$ is the same for each $j$-th surface.

After determining the density of the specular component of the reflected sound energy, the density of the diffusely scattered energy of the reflected noise is calculated using the Cuttruff equation. The calculation method is as follows.

All surfaces of the room in accordance with the scheme in Figure 1 are divided into areas $ds$. The dimensions of the areas are taken so that the energy density within them is sufficiently uniform. The absorption and reflection coefficients of sound energy by surfaces are considered to be diffuse, and the reflection of scattered energy from surfaces is determined by the Lambert cosine dependence.
Figure 1. Scheme for calculation using the Kuttruff equation.

At the beginning of the calculation, the intensities of the direct and specularly reflected energies incident on each elementary area $d s'$ are found using the method of imaginary sources

$$I_{d s', t}^0 = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \sum_{q=0}^{\infty} W_{t - r_{mnq}} \prod_{j=1}^{k} (1 - \alpha_{con})^{k_j} \exp(-m r_{mnq}) \cos \theta_{mnq}$$

where $\theta_{mnq}$ – angle of incidence of sound waves from the source of $mnq$ order to the fence element $d s'$. For direct sound at $m=n=q=0$ the coefficients are $k_j = 0$.

Intensity calculations should be done for a time interval $t \in \{t_s, t_e\}$, where $t_s = \tau - 2T_{rev}$ – start of the calculation, $t_e = \tau$ – end time of the calculation, $T_{rev}$ – standard reverberation time in the tested room. Such a beginning is taken on the basis that all the later total energy of imaginary sources received from portions of energy emitted by the source earlier than time $t_s$ will have an order of magnitude less than the energy that arrived at the calculated point at time $t_e$ during time $2T_{rev}$. It should be noted that the value of $2T_{rev}$ is accepted rather conditionally, and therefore, in specific design conditions, it can be taken as another larger or smaller value relative to $2T_{rev}$. Our preliminary calculations showed that the error in the results of calculating the density of sound energy due to the adoption of $2T_{rev}$ instead of, for example, $6T_{rev}$, is less than 1%. The calculation of the sound energy density within this interval is performed at regular intervals. The time step between calculations depends on the nature of the change in the power of the sound source during this period, the required accuracy of the calculations, as well as on other factors, including the time of the calculations.

Next, the calculation of the diffuse component of the energy incident on the area $d s'$ from all other areas $d s$ is performed and the intensity value $I_{d s', t}$ is determined by the expression

$$I_{d s', t} = \int l_{d s, t - r/c} \left(1 - \alpha_s \right) \cos \theta_1 \cos \theta_2 d s + I_{d s', t}^0 \left(1 - \alpha_s \right) \beta,$$
where \( I_{ds,t} \) is the intensity of the sound energy incident on the area \( ds \), determined by the contributions of the scattered energy reflections from all other sections of the fences, taking into account time delays, other symbols are explained in Figure 1.

It should be noted that the numerical calculation of sound intensities according to expression (6) is a laborious task that requires significant amounts of memory to store the results. The number of unknowns in this case is equal to the product of the number of elementary sections of the fences and the number of layers in the time interval \( t \in [t_s, t_{e}] \), which depend on the reverberation time and the degree of time discreteness of the calculation.

Finally, the density of diffusely reflected energy at the \( i \)-th calculated point from a source with variable sound energy at time \( \tau \) is determined by the spatial and temporal distribution of the intensity of the reflected sound energy from the elements of the fences and is calculated by the formula

\[
\varepsilon_{ri} = \int_0^T I_{ds,t}(1 - \alpha_s \cos \theta_2) \frac{ds}{2\pi r_s^2 c} \exp(-m_\alpha r_s)
\]

where \( t = \tau - r_s/c \) – moment of emission of scattered reflected energy from the surface \( ds \); \( r_s \) - distance from an elementary barrier element \( ds \) to the calculated point.

Finally, the sound pressure levels are determined by formula (1).

3. Results and discussion

To assess the accuracy of the proposed method, a comparative analysis of experimental and calculated data obtained in long and flat industrial premises was carried out. All rooms had a regular rectangular shape. During the experiment, equipment was absent in long rooms. In flat rooms, the amount of equipment was negligible.

The experimental research hardware included sources of sound energy, a set of noise-metering instruments, and equipment for measuring the reverberation time. An omnidirectional sound source (dodecahedron) OED-P-012-600 was used in the experiments. The sound power of the source in the frequency range 63-8000 Hz was 90 dB and higher. The source directivity index did not exceed \( \pm 5 \) dB. The measurements were carried out using the equipment of LLC “Company OCTAVA +”, which allows recording and analyzing the temporal and energy characteristics of noise in rooms. The sound pressure level measurement technique was in accordance with GOST 12.1.050-86. The choice of the number and position of measurement points in the rooms met the requirements of analyzing the distribution of reflected energy from the standpoint of the influence on it of the nature of sound reflection and the proportions of the rooms.

The calculations were carried out using a specially developed computer program that allows calculations by the combined method for any values of \( \beta \) in the range \( \beta=0 \) (completely specular reflection) to \( \beta=1.0 \) (completely diffuse scattering).

Figures 2 and 3 show the results of calculations and experiments in a long corridor-type room and in a flat room in the octave band with a geometric mean frequency of 2000 Hz. The suspended ceiling in the hallway has a sound absorption coefficient of 0.5, and the rest of the fence surfaces is 0.1. In a flat room, the average sound absorption coefficient of all fences was 0.15; in both cases, an energy pulse of 0.5 seconds duration was simulated. In the corridor, the calculated point was in the near field at a distance of 4 m from the source. In a flat room, the distance between the source and the point where the sound pressure levels were measured was 20 m. It can be seen that the calculations for the specular reflection model \( \beta=0 \) are significantly overestimated, while for the scattered model \( \beta=1 \) are underestimated. The closest results to the experiment were obtained for specularly scattered reflection, when \( \beta=0.2 \).

In general, the results of the comparative analysis indicate the need when assessing the noise mode to use calculation methods, which are based on the idea of mirror-scattered reflection of sound from fences and, in particular, the combined calculation method presented in this article.
Figure 2. Experimental and calculated sound pressure levels in a long room with dimensions 49.6×2.5×3.5 m

Figure 3. Experimental & calculated sound pressure levels in a flat room with dimensions 72×36×6 m

4. Conclusions
The performed studies and the obtained results allow to draw the following conclusions:

1. The accuracy of calculations of sound pressure levels in rooms depends on the accounting rate of the real nature of sound reflection from fences while using the calculation method. In industrial premises, the reflection of sound from fences has a delineated mirror-diffuse reflection pattern. The scattering of specular sound energy reflected from fences depends on the nature of the fence surfaces, the presence of equipment in the premises, and the shape and proportions of the premises. For typical industrial premises of multi-storey buildings, the values of the scattering coefficients $\beta$ are given in this article. Additional studies of the values of $\beta$ are needed for other rooms in these buildings.

2. When calculating noise in multi-storey industrial premises with a specular-scattered character of sound reflection from fences, the developed combined calculation method should be used, based on
the use of the method of imaginary sources to estimate the distribution of specular energy, and a numerical method for solving the Kuttruff integral equation to estimate the diffuse-scattered energy.

3. The proposed method and a computer program for its implementation make it possible to assess the noise regime in industrial premises of the correct geometric shape at any value of the scattering coefficient $\beta$ within the range from $\beta=0$ (completely specular reflection) to $\beta=1$ (completely diffuse scattering). The calculation error in the most difficult cases does not exceed $\pm2.0$ dB, which corresponds to the required accuracy of practical calculations when assessing a variable noise regime and developing construction-acoustic means for noise reduction in industrial buildings.

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