Numerical Method for Impulse Noise Calculation with Diffuse Sound Reflection

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Abstract. Among the noises occurring in industrial buildings, the impulsive noise affects the human body most detrimentally. Since the impulse noise is not constant in time, when choosing and designing means of reducing it, the changes of spatial-temporal characteristics of sound energy should be calculated after emission by a source of sound pulses. In order to assess the energy characteristics of impulse noise, the article proposed a calculation method based on the ideas of the diffuse character of sound reflection from fencing. Developing the method, a statistical energy model was used, which describes the distribution of reflected energy in closed air volumes in time and space. A direct difference method is proposed to implement the computational model. The principles of the construction of the calculation method are stated and its accuracy is estimated. The assessment of accuracy was carried out by comparative analysis of the calculated and experimental data obtained in the buildings of complex geometric shapes under the action of a pulsed noise source in them. It is established that the calculated decreases of sound pressure levels in time at the calculated points are in good agreement with the experimentally determined decreases, and the error in the calculation of the levels does not exceed 2-3 dB. The obtained accuracy of the calculations is sufficient for the design of building-acoustic means of impulse noise reducing. The method allows making calculations in rooms with any complex space-planning parameters.

1. Introduction

Technological equipment, working in industrial premises, as a rule, creates noise with time-varying sound pressure levels. Impulse noise is quite common among such noises. Such noise consists of one or several successively emitted pulses of sound energy by equipment. Impulse noise is a noise consisting of one or more pulses of sound energy. Impulse noise is considered when the duration of each pulse does not exceed 1 s, and the sound levels measured on the temporal characteristics of “pulse” and “slow” according to GOST 1718-2010 differ by at least 7 dBA. Impulse noise has the most negative impact on the human body \cite{1}. Therefore, estimating impulse noise, an equalization of 5 dB \cite{2} should be added to the obtained values of equivalent sound pressure levels, estimating time-non-constant noise. If it is available, it is necessary to develop more effective means of noise reduction to meet the requirements of the standards.
The selection and estimation of the acoustic efficiency of noise protection means requires acoustic calculations. In the case of impulse noise, the calculations should provide information on the structure of noise at specific points in the room, namely, equivalent sound pressure levels, peak maximum and minimum sound pressure levels, their correlation with each other and with background noise, etc. [3,4]. When determining the noise mode arising from the action of pulsed sound sources, and estimating its compliance with the norms, it is necessary to establish the areas of impact of the impulse noise. The sizes of the zones depend on the space-planning and acoustic characteristics of the premises, the number and location of the pulsed sources, the type of pulses, the level of background noise and a number of other factors. Reliable information about the size of the impulse noise zone and its characteristics within this zone allows us to make a specific targeting of building-acoustic means of reducing impulse noise. For these reasons, developing a method for calculating impulse noise is an important task of building acoustics.

The sound pressure level of the impulse noise at the calculated points is determined by the direct energy of the pulse and its reflected component arising from the reflections of the sound energy of the pulse from the fencing. The formation and distribution of the reflected pulse energy is determined by a large number of factors [5]. The most important among them is the nature of the reflection of sound from fencing [6].

Our studies show that predominantly the reflection of sound from fencing in industrial premises has a mirror-diffuse character. With such reflection, a reflected sound field is formed in the room, which includes two components of sound energy: specular and diffuse [7, 8]. It was found that the dispersion coefficient, which determines the proportion of diffusely scattered energy in the entire energy, coming on the fencing, can be in the range from 0.10 to 0.90 [8].

In order to estimate the non-constant noise, a combined computational model was proposed, taking into account the specular-diffuse reflection character, and a program was developed for its implementation [9]. The calculation of the reflected energy in this case is performed by two methods. Based on the method of geometric acoustics, the mirror component of the reflected energy is determined, and the method, based on the Kuttruf integral equation, determines the diffuse energy.

When using such a combined model, considerable computational resources are required and a significant computational time is required. Therefore, the model is more suitable for research purposes than for solving practical problems of noise control. On its basis, it is possible, for example, to analyze the influence of the scattering coefficients on the ratio of the energies of the specular and diffuse components in the reflected sound field and their change over time, to study the reverberation time separately for the specular and diffuse components and in general for the whole reflected sound field, and also a number of other tasks.

The studies based on the combined model showed that when the scattering coefficients of the reflected energy are more than 0.20, the magnitude of the reflected energy and its change over time are mainly determined by the diffusely reflected component. This makes it possible to apply simpler methods in the calculations of noise and the design of noise protection devices. Such methods are based on the ideas of the diffuse nature of the reflection of sound from fencing.

In this regard, the purpose of this work is to develop a method for calculating impulse noise, which is based on the idea of the diffuse reflection of sound from fencing. During its development, the following tasks were solved: numerical calculation model and difference method for its implementation were proposed; experimental estimation of the proposed method was made by comparing the results of calculations and experiments in rooms of complex geometric shape.

2. Methods
Since, when working in a room of a time-non-constant noise source, there is a change in the reflected sound energy in time and space of the room, we, in the case of diffuse reflection of sound from fencing, propose to use a statistical energy model [10] to calculate the space-time changes in reflected noise. The model is built on the basis of the ideas that in the reflected quasi-diffuse sound field there is
a link between the flow density \( \bar{q} \) and the density gradient of the reflected sound energy \( \varepsilon \), represented as

\[
\bar{q} = -\eta \cdot \text{grad} \varepsilon,
\]  

(1)

where \( \eta \) - coupling coefficient of flow density and density gradient, determined by the formulation [11]

\[
\eta = 0.5c \cdot \bar{l},
\]  

(2)

\( c \) – sound velocity in the air; \( \bar{l} \)– average free path of reflected sound rays in the room.

In this case, the distribution of sound energy in a closed room is described by a second-order partial differential equation.

\[
\frac{\partial \varepsilon}{\partial t} - \eta \nabla^2 \varepsilon + cm_a \varepsilon = F_{(r,t)},
\]  

(3)

where \( \nabla^2 \) – Laplace operator; \( m_a \) – spatial attenuation coefficient of sound in air; \( F_{(r,t)} = W(1 - \bar{a})/dv \)–amount of radiated reflected sound energy per volume \( dv \); \( W \)–source power; \( \bar{a} \) – average sound absorption coefficient of a room.

Solving equation (3), it is possible to obtain the distribution of reflected energy over the space of the room at any time interval.

The certainty of the solution of equation (3) is provided by specifying the boundary and initial conditions.

The boundary conditions in accordance with (1) are

\[
q_{(r,t)} \cdot \bar{n} = -\eta \frac{\partial \varepsilon}{\partial n} \bigg|_S = \gamma \varepsilon_{(r,t)} \bigg|_S,
\]  

(4)

where \( \gamma \) - coefficient of transfer of reflected energy at the boundaries of the room, determined according to [12] by formulation

\[
\gamma = \frac{c \alpha_s}{2(2 - \alpha_s)},
\]  

(5)

\( \alpha_s \) – sound absorption coefficient on the surface area of the room \( S \).

Finally, taking into account (2) and (5), the boundary conditions can be represented as

\[
\frac{\partial \varepsilon}{\partial n} \bigg|_S = -\frac{\alpha_s}{(2 - \alpha_s)} \varepsilon_{(r,t)} \bigg|_S.
\]  

(6)

The initial conditions are determined by the information about the initial distribution of the reflected sound energy in the room.

\[
\varepsilon \bigg|_{t=t_0} = f(x_1, x_2, x_3).
\]  

(7)

The approaches similar to the presented computational model were later proposed in foreign papers [13–19]. The models are based on ideas about the diffuse propagation of reflected sound energy, similar to the Brownian motion of molecules [20].

In our case, in order to establish the initial conditions, we can assume that the action of a broadband omnidirectional noise source located at a point with coordinates \( x_1^0, x_2^0, x_3^0 \), is represented as a sequential emission of sound energy pulses at an infinitely small time interval \( \partial \tau \). The pulse energy involved in the subsequent formation of the reflected sound field comprises\( W(1 - \bar{a})\partial \tau \). With an infinitely small \( \partial \tau \) with a sufficient approximation, we can assume that the radiated energy pulse is initially distributed near the source in a small volume \( V_{\text{nc}} \), respectively; the initial conditions have the form

\[
\begin{cases}
\varepsilon = \frac{W(1 - \bar{a}) \partial \tau}{V_{\text{nc}}}; x \in V_{\text{nc}}, \\
\varepsilon = 0; x \notin V_{\text{nc}}.
\end{cases}
\]  

(8)
It is proposed to use the direct difference method to implement the computational model consisting of a parabolic equation (3) with boundary and initial conditions (6) and (8).

In this case, the entire volume of the room is divided into a number of elementary volumes $dv$. For each volume, the reflected energy balance equations are written. The obtained equations allow the difference method to calculate the sound energy density values in all elementary volumes at all subsequent time intervals $dt$, that is, to estimate the change in sound energy density at all points of the volume under the action of a time source of time energy that is not constant in sound energy regime in the premises of both simple and complex in shape and disproportionate in geometric proportions.

The calculation scheme of the method is presented below using the example of a two-dimensional model of premises. Two-dimensional models correspond to flat and long rooms, widespread both in civil (office premises, auditoriums, corridors, etc.) and in industrial buildings. A feature of these rooms is that sound energy, changing significantly in the horizontal plane, varies little in height in flat rooms [21] or in cross section in long rooms [22]. This circumstance allows the use of a two-dimensional computational model of the noise field and thereby significantly reduces the complexity of calculations.

In the case of a two-dimensional model, the room, for which the solution is determined, is divided into elementary volumes in the form of parallelepipeds with sides $\Delta x$, $\Delta y$ and a height equal to the height of the room $h$ (Figure 1). For each volume, the net points are determined. It is more convenient to take parallelepiped with a square net of the base $\Delta x=\Delta y=\Delta$ for programming. For each volume, the equations of the balances of the reflected energy are written, including the densities of the flow of reflected energy between adjacent volumes and the flow densities at the volume boundaries.

In general, the reflected energy balance equation for a volume with a noise source is

$$\Delta V \varepsilon_{ij}^{t+dt} = \Delta V \varepsilon_{ij}^t + W(1 - \varepsilon_{ij}) \cdot dt - \Delta^2(q_{in} + q_{in'}) dt - \Sigma_4 q_{i\pm1,j\pm1} S dt,$$

where $\Delta V = h\Delta^2$ — volume of an elementary parallelepiped; $q_{in}, q_{in'}$ — densities of sound energy flows through the lower and upper edges of the parallelepiped (floor and ceiling of the room); $q_{i\pm1,j\pm1}$ — flow density through the side surfaces of the parallelepiped; $S = h\Delta$ — side surface area.

The flow densities $q_{i\pm1,j\pm1}$ (Figure 1, a) between volumes $i, j$ and volumes $i\pm1, j\pm1$ with regard to relation (1) are defined as

$$q_{i\pm1,j\pm1} = \frac{c_{\pi,\gamma} (\varepsilon_{ij} - \varepsilon_{i\pm1,j\pm1})}{\Delta},$$

For the side surfaces of the volumes that coincide with the surfaces of the room (see Figure 1, b), the calculation of the flow density is performed using the formulas

$$q_{(\alpha)}_{jk} = \frac{c_{\alpha,\gamma} \varepsilon_{ij}}{2(2-\alpha_{ijk})}; q_{(\alpha)}_{jk} = \frac{c_{\alpha,\gamma} \varepsilon_{ij}}{2(2-\alpha_{ijk})},$$

where $\alpha_{ijk}$, $\alpha_{ijk}$ — sound absorption coefficients of $k$-surfaces of $i, j$ elementary volume.

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Figure 1. Schemes for the compilation of sound energy balance equations for elementary volumes $\Delta V$: a) - internal; b) - bordering with the side surfaces of fencing.
Density of flows through the floor and ceiling of the room are determined by the formulas
\[ q_{i,j,un} = \frac{ca_{i,j,nn}}{2(1 - \sigma_{i,j,nn})}, \quad q_{i,j,mn} = \frac{ca_{i,j,mn}}{2(1 - \sigma_{i,j,mn})} \tag{12} \]
where \( \sigma_{i,j,nn}, \sigma_{i,j,mn} \) – sound absorption coefficients of the floor and ceiling within the \( i, j \) elementary volume.

Taking into account formulas (10) - (12), equation (9) has the form
\[ \varepsilon_{i,j}^t \left[ 1 - \frac{(4-k)c\Delta t}{2\Delta^2} - \frac{c}{2h} \left( \frac{\alpha_{i,mn}}{2-\alpha_{i,mn}} + \frac{\alpha_{i,mn}}{2-\alpha_{i,mn}} \right) dt - \sum_k \frac{ca_{j,k}dt}{2\Delta(1-\alpha_{j,k})} \right] + \frac{p(1-\alpha)dt}{\Delta^2h} + \frac{cT}{2\Delta^2} \sum_{k} \varepsilon_{i+1,j,k}^t + \varepsilon_{i,j}^t \Delta t \tag{13} \]
where \( k \) is the number of side surfaces of the \( i, j \) volume, which are the surfaces of the room.

The resulted equation (13) describes the change in time of the density of the reflected sound energy from a pulse within the limits of \( i, j \) elementary volume.

The accepted scheme for the calculation of non-stationary processes is conditionally stable. The studies of the stability of the numerical solution of problems with parabolic equations [23], including equations of type (3), made it possible to determine the limiting time interval \( dt \), which ensures the stability of the solution. In this case, it is determined by the formulation
\[ dt \leq \frac{\Delta^2}{2y} = \frac{\Delta^2}{ct} \tag{14} \]

A computer program was developed to implement the proposed method. The method of calculation and the program implementing it allow one to study changes in the energy characteristics of the noise field of the premises during the work of sources with variable sound power, including pulsed sources.

### 3. Results and discussion

In order to evaluate the proposed calculation method, a comparative analysis of the calculated and experimental data in rooms of complex and simple form with different geometric proportions under the action of a pulsed noise source was performed. The study was carried out in octave frequency bands.

The equipment for experimental studies included sources of sound energy, a set of noise-measuring instruments and device for measuring the reverberation time. In the experiments, OED-SP-012-600 omnidirectional sound source (dodecahedron) was used. The power of the dodecahedron in the frequency range 63-8000 Hz was 90 dB and higher. The source directivity did not exceed \( \pm 5 \) dB. During the measurement, the equipment of LLC “Company OKTAVA+” was used, which allows recording and analyzing the sound energy characteristics of the noise in the rooms. The method of measuring sound pressure levels corresponded to 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 form and proportions of the rooms.

The studies were carried out in the absence of equipment in the rooms and other elements that dissipate sound in order to exclude collateral factors that in one way or another affect the accuracy of the results.

The calculations were performed using a specially developed computer program that allows the author to run any calculations by the proposed method.

The results of the comparative analysis showed the adequacy of the computational model and the numerical method that implements it to the actual conditions for the formation of the reflected sound field. The method makes it possible to objectively assess the spatial and temporal changes in the noise in the rooms when the pulsed sound sources act in them.

Below there is an example of a comparative analysis of the experimental and calculated data for a production U-shaped room during work of a pulsed sound source. The scheme of the room is shown in Figure 2. All dimensions in the diagram are given in meters. The height of the room is 5m.
The results of the analysis are given for an octave band with $f=2000$ Hz. The sound absorption coefficient of all room surfaces equals $\alpha=0.10$. Peak noise source power is 99 dB; the frequency of the source is 1; pulse duration 0.4 s; time between pulses is 0.6 s.

Figure 3 shows the results of calculations and experimental data at design point 1. It can be seen that the divergences between the results of calculations and the experiment do not exceed 3.0 dB.

Implemented computer simulation showed the ability to make studies of changes in time and space of the room reflected sound energy.

The results of the calculation of the sound field parameters in the calculated points of the room are shown in Table 1. It can be seen that the sound field during the operation of a pulsed sound source is very uneven. The maximum sound level in the calculations at points 1 and 6 differs by 13.2 dB, and the minimum level is only 3 dB. It is also seen that the initial unevenness of the sound field after switching off the source is equalized over time. The indicators of uneven attenuation of sound energy can be the difference between maximum and minimum noise levels $\Delta L$ in the time interval $\Delta t$ between pulses, as well as the average attenuation rate of sound energy that is calculated according to the formula

$$m = \frac{\Delta L}{\Delta t}, \text{ dB/c.}$$

(15)
All the data, obtained on the basis of calculations and experiment, are given in Table 1.

**Table 1.** Results of determining the parameters of the sound field in the room under the action of a pulsed sound source.

| Studied characteristics         | Calculation point number | 1   | 2   | 3   | 4   | 5   | 6   |
|---------------------------------|--------------------------|-----|-----|-----|-----|-----|-----|
| Maximum noise level, calculated |                          | 86.5| 83.8| 81.4| 77.8| 74.7| 73.3|
| dB                              | experimental             | 88.0| 85.0| 82.0| 80.0| 76.0| 75.0|
| Minimum noise level, calculated |                          | 66.6| 66.6| 66.3| 65.5| 65.4| 63.6|
| dB                              | experimental             | 71.0| 79.0| 69.0| 69.0| 68.0| 68.0|
| Difference between the maximum  |                          | 19.9| 17.2| 15.1| 12.3| 10.3| 9.7 |
| and minimum levels, dB          | experimental             | 17.0| 15.0| 13.0| 11.0| 8.0 | 7.0 |
| Sound energy attenuation rate,  | calculated               | 33.2| 28.7| 25.2| 20.5| 10.3| 9.7 |
| dB/s                            | experimental             | 28.3| 25.0| 21.7| 18.3| 13.3| 11.7|

Thus, the proposed numerical method for calculating impulse noise based on the statistical energy model, which assumes the diffuse character of sound reflection from fencing, is sufficient for practical calculations of accuracy. The method allows estimating the spatial and temporal characteristics of noise in rooms of various shapes and geometric proportions. In contrast to the method that takes into account the mirror-diffuse character of the reflection of sound from fencing [9], it requires less computational resources and has a higher speed.

4. Conclusions

The performed studies and the obtained results allow us to draw the following conclusions:

1. If a reflected sound field forms in a production room where the diffusely scattered component of the reflected sound energy predominates, computational models based on the idea of diffuse sound reflection from fencing are applied to calculate the energy characteristics of time-non-constant noise.

2. The proposed statistical energy model of the reflected sound field and the enhanced method of its implementation, when a pulsed noise source work, can be applied for specular-diffuse reflection of sound from fencing under conditions when the coefficient of dissipation of reflected energy exceeds 0.20. Similar conditions are provided in most industrial premises.

3. The conducted comparative analysis of the calculated and experimental data confirmed the adequacy of the proposed calculation model and the numerical method for its implementation to the conditions for the formation and distribution of reflected sound energy when pulsed noise sources are applied in production facilities. The error of calculations in rooms with complex shapes does not exceed ± 3.0 dB. The numerical method is suitable for calculating noise and designing noise protection in rooms with non-constant noise regime.

5. References

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