This paper reports studying the reduction of traffic noise by rounded noise protection screens with finite sound insulation, that is, those that can pass sound.

Almost all models of acoustic screens, which are examined by analytical methods, are either direct or such that disregard the passage of sound through the screen, that is, it is assumed that the screen sound insulation is non-finite. This approach made it possible to solve the problem for a simplified model analytically but made it impossible to analyze the required sound insulation of noise protection screens.

In the current paper, the problem of investigating an acoustic field around the screen whose sound insulation is finite has been stated, that is, it was taken into consideration that a sound wave propagates through the body of the screen. In addition, a given problem considers a rounded screen, rather than vertical, which is also used in different countries.

Such a problem was solved by the method of partial domains. This method has made it possible to strictly analytically build a solution to the problem by simplifying it to solving an infinite system of algebraic equations, which was solved by the method of reduction.

The screen model was set by the values of the density and speed of sound in the screen material. This approach has made it possible to change the acoustic impedance of the screen material and thereby change the sound insulation of the screen. That has made it possible to quantify the effect of screen sound insulation on its effectiveness. It has been shown that the efficiency of noise protection screens with finite sound insulation is approaching the efficiency of acoustically rigid screens, provided that the screen's natural sound insulation is 13–15 dB greater than the estimated efficiency of the rigid screen.

The study results could make it possible to more accurately assess the effectiveness of noise protection screens. Determining the screen acoustic efficiency would make it possible to set requirements for its sound insulation characteristics. That could make it possible to select the designs of noise protection screens with minimal physical parameters, such as thickness, weight, etc.

Keywords: rounded noise protection screen, partial domain method, finite sound insulation, noise reduction

REVEALING THE EFFECT OF ROUNDED NOISE PROTECTION SCREENS WITH FINITE SOUND INSULATION ON AN ACOUSTIC FIELD AROUND LINEAR SOUND SOURCES

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1. Introduction

Noise protection screens are one of the most effective means of reducing traffic noise. Screen noise reduction is affected by a large number of factors [1, 2] such as the screen geometric dimensions, the mutual arrangement of the noise source screen and noise protection territory, the screen sound frequency and design, etc.

Among the factors that have been poorly investigated so far is the screen's natural sound insulation. Although it is believed that the sound does not pass through the screen, this is not entirely true. Any screen structure with elastic properties would pass a sound wave. And, accordingly, a sound field behind the screen would consist of the sound waves formed by diffraction through the upper edge of the screen and waves that have passed through the screen.

Noise protection screens can be divided into 3 types by their structure:
– monolithic, made from heavy materials (concrete, brick, stone, etc.);
– sandwich panels, made from two layers of sheet material (steel, aluminum, wooden panels, polycarbonate, etc.) with a gap filled with elastic material;
– sheet materials (polycarbonate, acrylic, wood-chip and fiberglass panels, etc.).

Screens of the last two types are widely used in the world due to the light-weight structure, the possibility to quickly dismantle or replace damaged elements, as well as the relatively low cost of the entire structure. At the same time, such screens have a much smaller mass, hence the lower natural sound insulation, especially in the domain of low frequencies. This causes the sound wave, which propagates from the traffic noise, to partially pass through the screen and enter

the shadow zone. Thus, the sound levels behind the screen increase, which reduces the efficiency of such screens.

Therefore, it is a relevant task to study the effect of screen sound insulation on its capacity to reduce traffic noise. Resolving the issue could help determine the required level of the screen's natural sound insulation, which would not significantly affect its effectiveness.

2. Literature review and problem statement

Study [3] reported the first attempt to analytically solve the problem of finding a field around the screen, which was stated and solved. However, this approach made it possible to find the effectiveness of acoustically rigid vertical screens only, without taking into consideration the reflection of sound from the surface of the earth. That limited the scope of this solution application, especially in the practical design of screens.

Works [4, 5] employed a different approach – the authors built an analytical dependence based on the results of experimental studies. That made it possible to significantly improve the calculation accuracy in terms of practical results. However, there remain unresolved issues related to the effect of the surface of the earth, the angle of inclination of the screen, as well as its soundproof properties, on the effectiveness of the screen.

A little later, the issues of analyzing the effect of sound reflection from the ground were considered in paper [6]; the authors applied the elements of geometric acoustics. Given this, the accuracy of calculation at low frequencies, under this method, was low.

With the development of computer technology, it became possible to conduct computer simulations of the acoustic field around a screen. The most widely used is the method of boundary regions [7] and a finite-element method [8]. This approach has made it possible to find an acoustic field with a different acoustic impedance of screen surfaces and different sound insulation [9]. However, the general disadvantage of numerical methods is the uncertainty of the calculation error. The most common way to assess the adequacy of a computer model is to compare the results of calculations with field or model experiments. However, conducting experiments requires significant material and time costs. Therefore, a strict analytical solution to the problem should remove the above shortcomings.

Recently, a method of partial domains has been proposed for solving the problems of finding an acoustic field in regions of complex shape [10, 11]. The authors of [12] even managed partially to model the finite sound insulation of the screen by making a hole in the screen. However, this approach to simulation of the sound translucent screen has drawbacks, which are primarily associated with the diffraction of the sound wave at the gap.

Study [13] indicates that only some US states have requirements for the necessary sound insulation of screens; the values range from 20 dB to 30 dB. At the same time, no connection between the required sound insulation and screen efficiency was established.

Article [14] also states that the soundproofing setting of the screen is a significant characteristic that can improve the performance of the screen without increasing its height. However, the study was carried out in the field, so does not make it possible to generalize the requirements for the effect of screen sound insulation on its effectiveness.

Therefore, stating and solving a theoretical problem that would be as close as possible to an actual situation could make it possible to reasonably set the requirements for the designs of noise protection screens.

3. The aim and objectives of the study

The aim of this study is to determine the impact of natural screen sound insulation on noise level reduction and screen efficiency. This could make it possible to design such screen structures that, on the one hand, would possess the required sound insulation properties and, on the other hand, be smaller in terms of mass and thickness.

To accomplish the aim, the following tasks have been set:
– to state and solve a mathematical problem that is close to the physical case;
– to build sound fields around noise protection screens and determine the decrease in the sound levels behind screens with different sound insulation.

4. The study materials and methods

To determine an acoustic field around the noise protection screen, we employed the method of partial domains. This method assumes that the acoustic field around a screen is split into several canonical regions for which one can record a solution to the Helmholtz equation. In this case, boundary conditions in each region are used to determine the functional ratios while the conjugation conditions between the regions are applied to find free coefficients.

Since the Helmholtz equation is a differential equation in the partial derivatives of the second order, the boundary conditions and the conjugation conditions are set both for the potential of speed (Φ) and for the first derivative from the coordinate. The physical equivalents of these variables are, respectively, the sound pressure and oscillation velocity.

The result of solving the problem is a non-finite system of algebraic equations to be solved by the method of reduction. Since the satisfactory coordination of sound fields within different regions necessitates keeping a large enough number of unknowns (from 300 to 600) and, accordingly, the equations of the system, the problem is solved in the programming environment MATLAB. This environment makes it possible to perform calculations for a large array of points around the screen. To plot charts, we selected a 0.1 m step between points both horizontally and vertically.

5. Stating and solving a theoretical problem

5. 1. Physical model

A noise protection screen, in terms of the shape of its cross-section, may take the form of both a rectangle (vertical or inclined) and a more complex shape, including a sector of the ring (Fig. 1). The material from which the screen is made must possess high sound insulation properties so that sound does not penetrate through the screen. However, in practice, screens are often made from light materials and structures that have low sound insulation, especially in the low-frequency zone. Such materials and structures include polycarbonate, acrylic, glass, sandwich panels, etc. The soundproofing of such screens is comparable to the theoretical efficiency of noise protection screens. Thus, the effect of sound passing through the screen on the acoustic field outside the screen is significant.

The surface of the road over which vehicles move is most often made of asphalt or concrete coating, so it can be considered an acoustically rigid material. The surface behind the screen is also horizontal and acoustically rigid.

In addition, traffic in the current study is considered as a continuous source of sound whose characteristics do not change along the entire length.

All these conditions and approximations lead to the problem whose geometry is shown in Fig. 1.

Fig. 1 shows that all the airspace around the screen was split into four regions. The distribution of the regions implies that one can record a solution to the Helmholtz equation for them, as well as satisfy boundary conditions.
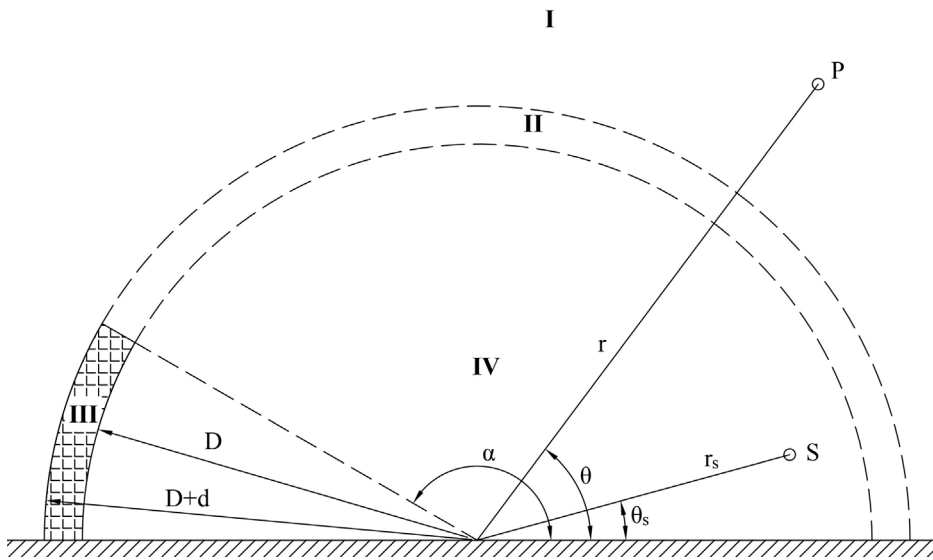

Fig. 1. Estimated geometric model of noise protection screen with finite sound insulation

5. 2. Problem statement

There is a half-space limited to an acoustically rigid surface. Within this half-space, there is a noise protection screen formed by the sectors of two non-finitely long cylindrical surfaces with a common axis, located on the surface of an acoustically rigid half-plane. One end of the screen is also located on the acoustically rigid plane, the other, at angle α, is acoustically rigid. In the cross-section perpendicular to the axis of the cylinders, the screen takes the shape of a sector of the ring with an internal radius R and a thickness of d with an opening angle α.

The sound source is S, in the form of a non-finitely long cylinder with a non-finitely small radius, operating at zero oscillation mode and emitting a sound wave. This source is located at a distance of r_S from the axis of the cylindrical surfaces and at angle α_S to the acoustically rigid plane.

The environment around the screen has density ρ and sound speed c.

It is required to find an acoustic field at arbitrary point P, which is at arbitrary distance r from the axis of the cylindrical surfaces and at arbitrary angle θ to the horizontal plane.

5. 3. Solving a problem

Given the geometry of the problem, we shall place the polar coordinate system at point O, which coincides with the axes of the cylindrical surfaces.

As is known from [15], the Helmholtz equation for the speed potential Φ in the polar coordinate system takes the following form:

$$\frac{\partial^2 \Phi}{\partial t^2} - c^2 \left[\frac{1}{r}\left(\frac{\partial}{\partial r} r \frac{\partial \Phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \theta^2}\right] = 0. \tag{1}$$

The partial solution is represented in the following form:

$$\varphi_b(r,\theta) = \left[A_b H_b^{(1)}(kr) + B_b H_b^{(2)}(kr)\right] \times$$
$$\times \left[C_b \cos(b\theta) + D_b \sin(b\theta)\right], \tag{2}$$

or

$$\varphi_b(r,\theta) = \left[A_b J_b(kr) + B_b N_b(kr)\right] \times$$
$$\times \left[C_b \cos(b\theta) + D_b \sin(b\theta)\right], \tag{3}$$

where hereafter $H_b^{(1)}$ $H_b^{(2)}$ J_b and N_b are the designations of cylindrical functions, namely, Hankel, of the 1st and 2nd kind, Bessel, and Neuman, respectively; $k=\omega/c$ is the wavenumber. Moreover, the use of any solution is arbitrary and depends on the boundary conditions and geometry of the problem.

Region I.

Region I takes the form of a region outside a circle with a radius $D+d$ under the following boundary conditions:

$$\frac{\partial \varphi}{\partial \theta} = 0$$

at

$$\begin{bmatrix} \theta = 0, r > D+d, \\ \theta = \pi, r > D+d. \end{bmatrix} \tag{4}$$

For this region, we shall apply the solution to the Helmholtz equation in the form of (2). In this solution, the function $H_b^{(1)}$ describes the waves diverging from the coordinate origin; the function $H_b^{(2)}$ – waves coming from infinity.

Given the condition of Sommerfeld radiation at infinity, the function $H_b^{(2)}(kr)$ can be rejected in equation (2) because, according to the geometry of region I, there are no waves coming from infinity.

Then, to meet the conditions at the boundary, $\theta=0$ and $\theta=\pi$.

$$\begin{bmatrix} -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \big|_{\theta=0} \\ -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \big|_{\theta=\pi} \end{bmatrix} \Rightarrow \begin{bmatrix} D_b = 0 \\ C_b \sin(\pi b) = 0 \end{bmatrix} \Rightarrow$$

$$\Rightarrow \begin{cases} \begin{cases} D_b = 0 \\ C_b = 0 \\ D_b = 0 \\ \sin(\pi b) = 0 \end{cases} \end{cases} \Rightarrow \begin{cases} \text{a long case,} \\ \begin{cases} D_b = 0, \\ b = n, \ n = 0,\pm 1,\pm 2... \end{cases} \end{cases}$$

Record:

$$\varphi_n(r,\theta) = \tilde{A}_n^{(1)} \cdot H_{\pi n}^{(1)}(kr) \cdot \cos(\pi n \cdot \theta), \quad n = 0,\pm 1,\pm 2... \tag{5}$$

The full solution to the equation is composed of the full sum of the partial solutions.

In addition, since the multipliers $\tilde{A}_n^{(1)}$ are unknown, it is possible to divide each term of the amount by $H_{\pi n}^{(1)\prime}\left[k(D+d)\right]$;

this would simplify the expressions when the conjugate conditions are met:

$$\Phi_1 = \sum_{n=0}^{\infty} A_n^{(1)} \frac{H_{\pi n}^{(1)}(kr)}{H_{\pi n}^{(1)\prime}[k(D+d)]} \cos(n\theta). \tag{6}$$

Region II.

Region II takes the shape of a sector of the ring with radii D and $D+d$ under the following boundary conditions:

$$\frac{\partial \varphi}{\partial \theta} = 0 \text{ at } \begin{bmatrix} \theta = 0, D+d \geq r > D, \\ \theta = \alpha, D+d \geq r > D. \end{bmatrix} \tag{7}$$

Suppose that the screen boundary at $\theta = \alpha$ is acoustically rigid.

Employ solutions (3) to the Helmholtz equation. Then, to meet the conditions at the boundary, $\theta = 0$ and $\theta = \alpha$.

$$\begin{bmatrix} -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \big|_{\theta=0} \\ -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \big|_{\theta=\alpha} \end{bmatrix} \Rightarrow \begin{bmatrix} D_b = 0 \\ C_b \sin(\alpha b) = 0 \end{bmatrix} \Rightarrow$$

$$\Rightarrow \begin{cases} \begin{cases} D_b = 0 \\ C_b = 0 \end{cases} \\ \begin{cases} D_b = 0 \\ \sin(\alpha b) = 0 \end{cases} \end{cases} \Rightarrow \begin{cases} \text{a long case,} \\ \begin{cases} D_b = 0, \\ b = \frac{\pi n}{\alpha}, \ n = 0, \pm 1, \pm 2\ldots \end{cases} \end{cases}$$

Record:

$$\varphi_n(r,\theta) = A_n^{(2)} \cdot J_{\frac{\pi n}{\alpha}}(kr) \cdot \cos\left(\frac{\pi n}{\alpha} \cdot \theta\right) +$$

$$+ A_n^{(3)} \cdot N_{\frac{\pi n}{\alpha}}(kr) \cdot \cos\left(\frac{\pi n}{\alpha} \cdot \theta\right), \qquad n = 0, \pm 1, \pm 2\ldots \tag{8}$$

Following the transforms similar to the solution for the first region, one can write down the speed potential Φ_{II} for region II in the following form:

$$\Phi_{II} = \sum_{n=0}^{\infty} \left[A_n^{(2)} \cdot \frac{J_{\frac{\pi n}{\alpha}}(kr)}{J_{\frac{\pi n}{\alpha}}(kD)} + A_n^{(3)} \frac{N_{\frac{\pi n}{\alpha}}(kr)}{N_{\frac{\pi n}{\alpha}}(kD)} \right] \cos\left(\frac{\pi n}{\alpha} \theta\right). \tag{9}$$

Region III.

Region III predetermines a noise protection screen; it also takes the shape of a sector of a ring with radii D and $D+d$ and the opening angle π-α under the following boundary conditions:

$$\frac{\partial \varphi}{\partial r} = 0 \text{ at } \begin{bmatrix} \theta = \alpha, D+d \geq r > D, \\ \theta = \pi, D+d \geq r > D. \end{bmatrix} \tag{10}$$

Apply solution (3) to the Helmholtz equation (1).

Following the transforms similar to the solution for the first region, one can write down the speed potential Φ_{III} for region III in the following form:

$$\Phi_{II} =$$

$$= \sum_{n=0}^{\infty} \left[A_n^{(4)} \frac{J_{\frac{\pi n}{\pi-a}}(k_1 r)}{J_{\frac{\pi n}{\pi-a}}(k_1 D)} + A_n^{(5)} \frac{N_{\frac{\pi n}{\pi-a}}(k_1 r)}{N_{\frac{\pi n}{\pi-a}}(k_1 D)} \right] \cos\left[\frac{\pi n}{\pi-\alpha}(\Theta - a)\right]. \tag{11}$$

where $k = \omega / c_1$.

Region IV.

Region IV is a half-circle of radius D under the following boundary conditions:

$$\frac{\partial \Phi}{\partial r} = 0 \text{ at } \begin{bmatrix} \theta = 0, r \leq D, \\ \theta = \pi, r \leq D. \end{bmatrix} \tag{12}$$

Since region IV hosts the origin of coordinates, we shall also use solution (3) to the Helmholtz equation.

Given that the Neumann function (N) at the origin coordinates approaches the minus of infinity, and the Bessel function (J) – unity, we discard the term $B_b N_b(kr)$ in solution (3) because the field at the coordinate origin is finite. Then following the mathematical transforms, we obtain:

$$\Phi_4 = \sum_{n=0}^{\infty} A_n^{(6)} \cdot \frac{J_{\pi n}(kr)}{J'_{\pi n}(kD)} \cos(\pi n \theta). \tag{13}$$

Diffraction field from a sound source.

For clarity, we assume that the sound source is in zone IV, that is $r_S < D$.

The diffraction of a non-finite cylindrical sound source of small wave dimensions at a wedge with acoustically rigid surfaces and an angle of opening π is described by the following expression given in [16]:

$$\Phi_0 = \frac{i}{2} \begin{cases} \sum_{n=0}^{\infty} \varepsilon_n H_n^{(1)}(kr_s) J_n(kr) \cos(n\theta_s) \cos(n\theta), \ r < r_s, \\ \sum_{n=0}^{\infty} \varepsilon_n J_n(kr_s) H_n^{(1)}(kr) \cos(n\theta_s) \cos(n\theta), \ r \geq r_s, \end{cases} \tag{14}$$

where Φ_0 is the potential of the oscillation velocity emitted by the source;

$$\varepsilon_n = \begin{cases} 1, \ n = 0, \\ 2, \ n > 0. \end{cases}$$

Then the field in region I would be defined as:

$$\Phi_{IV} = \Phi_4 + \Phi_0. \tag{15}$$

Write the conjugation conditions for fields at the boundaries.

Since the Helmholtz equation is a differential equation of the 2nd order, the conjugation of the regions must be performed according to the speed potential – which corresponds to the sound pressure, and the first derivative from the speed potential – corresponding to the oscillation velocity of the particles of the medium.

By pressure:

$$\Phi_I = \Phi_{II} + \Phi_{III}, \ r = D+d, \ \theta \in [0, \pi], \tag{16}$$

$$\Phi_{IV} = \Phi_{II} + \Phi_{III}, \ r = D, \ \theta \in [0, \pi]. \tag{17}$$

By speed:

$$\frac{\partial \Phi_I}{\partial r} = \frac{\partial \Phi_{II}}{\partial r}, \ r = D+d, \ \theta \in [0, \alpha], \tag{18}$$

$$\frac{1}{\rho c} \frac{\partial \Phi_I}{\partial r} = \frac{1}{\rho_1 c_1} \frac{\partial \Phi_{III}}{\partial r}, \ r = D+d, \ \theta \in [\alpha, \pi], \tag{19}$$

$$\frac{\partial \Phi_{IV}}{\partial r} = \frac{\partial \Phi_{II}}{\partial r},$$

$$r = D, \quad \theta \in [0, \alpha], \tag{20}$$

$$\frac{1}{\rho c} \frac{\partial \Phi_{IV}}{\partial r} = \frac{1}{\rho_1 c_1} \frac{\partial \Phi_{III}}{\partial r},$$

$$r = D + d, \quad \theta \in [\alpha, \pi]. \tag{21}$$

By fitting expressions (6), (9), (11), (13) to (15) to conjugation conditions (16) to (21) and using the properties of orthogonal functions, as described in [11, 12], one can obtain a non-finite system of algebraic equations relative to unknown $A_n^{(1)} - A_n^{(6)}$, which is solved by the method of reduction.

6. Decrease in the sound levels behind a screen with different sound insulation

The result of this study is that it was possible to build a strict analytical solution to the problem of finding a sound field around a screen with partial impedance. This allows us to evaluate the effectiveness of the screen:

$$dL = 20 \lg \left(\frac{p_{with}}{p_{out}} \right), \tag{22}$$

where p_{with} is the sound pressure when using a screen, determined by the speed potentials $\Phi_I - \Phi_{IV}$ – (6), (10), (12), (14) in the appropriate region; p_{out} is the sound pressure in the absence of a screen, determined by the speed potential of the sound source Φ_0 (15).

Compare the results of calculating the efficiency of a screen with different impedance characteristics, which has different sound insulation.

In this case, all screens would be the same in their geometric parameters, and the upper screen edge would be at the same distance from the sound source.

In this case, to simulate the noise signal, we shall calculate the sound fields for 25 frequencies [12], which are evenly distributed in the octave band:
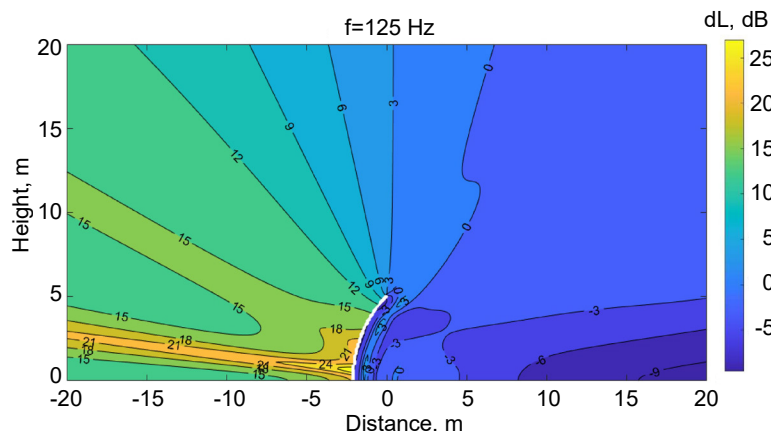
$$\overline{p} = \sqrt{\sum_{i=1}^{25} \left[p(f_i) \right]^2}, \tag{23}$$

where $p(f_i)$ is the field of sound pressure at the i-th frequency within the one-octave band, Pa; $\overline{p}$ is the average sound pressure in the octave frequency band, Pa.

Let the screen height be 5 m, screen curvature radius D=7.07 m, with angle α=135°.

The sound source would be located at a horizontal distance of 1 m from the upper edge of the screen. Such a distance would determine the high level of screen efficiency, which could make it possible to more clearly determine the effect of the screen natural sound insulation R, dB, on its effectiveness ΔL, dB.

The screen effectiveness at $R \to \infty$, derived when solving the problem using the MATLAB programming environment, is shown in Fig. 2.
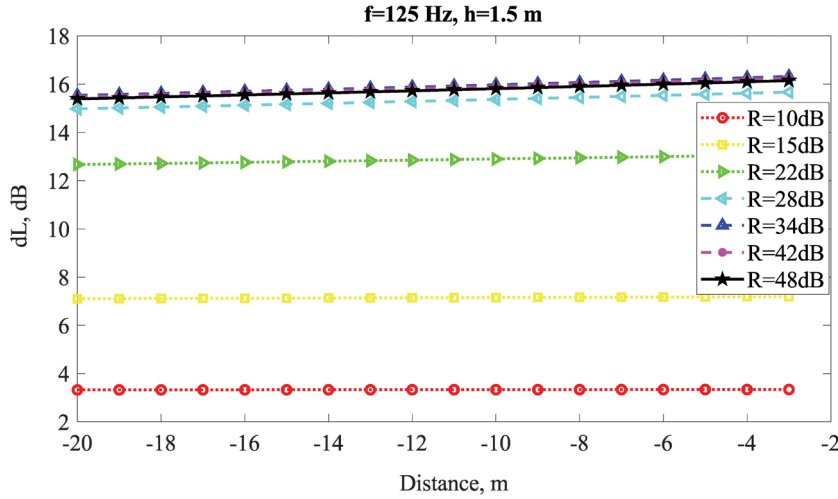

Fig. 2. The efficiency of a rounded acoustically rigid noise protection screen with a height of 5 m

In this case, the screen's natural sound insulation is determined from expression (24):

$$R = -10 \lg \frac{I_{out}}{I_{in}}, \tag{24}$$

where I_{in} is the intensity of the sound falling on the screen, W/m²; I_{out} is the intensity of the sound that has passed through the screen, W/m².

Sound energy losses when passing the screen occur at two boundaries: air–screen and screen-air (25).

$$I_{out} = I_{in} \cdot T_{air-bar} \cdot T_{bar-air}, \tag{25}$$

where $T_{air-bar}$ is the coefficient of sound passing by intensity through the air–screen boundary; $T_{bar-air}$ is the coefficient of sound passing by intensity through the screen–air boundary.

It is known from [17] that the coefficients of passing are determined from the ratio $\xi = \rho_1 c_1 / \rho c$:

$$T_{air-bar} = T_{bar-air} = \frac{4\xi}{(1+\xi)^2}. \tag{26}$$

Then, taking into consideration expressions (24) to (26), we obtain:

$$R = -20 \lg \left(\frac{4\xi}{(1+\xi)^2} \right). \tag{27}$$

By changing the screen settings ρ_1 and c_1 (Table 1), one can adjust the natural sound insulation of the screen and determine its effect on reducing the sound levels behind the screen (Fig. 3, 4).

Table 1

The relationship between screen impedance and sound insulation

$\rho c \cdot 10^{-3}$, kg/m³	0.4216						
$\rho_1 c_1 \cdot 10^{-3}$, kg/m³	4.216	8.432	21.08	42.16	84.32	210.8	421.6
ξ	10	20	50	100	200	500	1000
R, dB	10	15	22	28	34	42	48

f=125 Hz, h=1.5 m

Fig. 3. Dependence of the screen efficiency *dL*, dB, on its natural sound insulation *R*, dB (the height of the estimated point is 1.5 m)
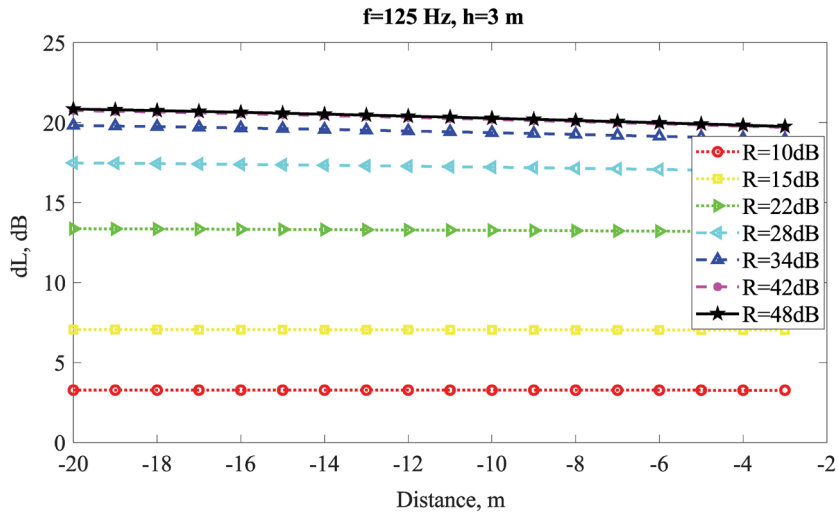
f=125 Hz, h=3 m

Fig. 4. Dependence of the screen efficiency *dL*, dB, on its natural sound insulation *R*, dB (the height of the estimated point is 3 m)

Fig. 2, 3 show that at small screen sound insulation ($R<22$ dB) the screen efficiency is small. And only at sound insulation $R=28–34$ dB, efficiency reaches its maximum value of 15–16 dB.

Fig. 4 shows that the maximum screen efficiency is 20–21 dB, and is achieved at the screen natural sound insulation of at least 34 dB.

7. Discussion of results of studying the effect of sound insulation of the screen on its effectiveness

The use of a given analytical solution has its advantages in assessing the accuracy of calculations as keeping a different number of system terms enables the calculation of the field with the required accuracy. As our numerical experiment has shown, the number of elements required by the system depends on frequency, and the higher the frequency, the more equations the system must contain. The maximum number of equations in the system was 600.

Owing to the introduction of an actual screen thickness (region III), it was possible to explicitly set the acoustic impedance of the medium. Modeling the sound translucence of the screen by changing the impedance of the screen material in such a case is justified since the effectiveness of the screen in general was analyzed. The integrated indicator used was the value of the natural sound insulation of the screen *R*.

The use of expression (23) has made it possible to simulate the acoustic field of a noise sound source, which has also allowed us to find a sound field (Fig. 2) without a pronounced interference pattern, as shown in works [11, 18]. Thus, the resulting dependences of screen efficiency on distance fully correspond to the results of full-scale acoustic measurements [14, 19].

However, the application of the method of partial domains to solve the set problem has its drawbacks and limitations.

First of all, this is cumbersome enough mathematical reasoning, which does not make it possible to quickly change the geometry of the noise protection screen. In addition, as mentioned above, high frequencies necessitate maintaining a greater number of equations, which makes it impossible to perform calculations for high frequencies ($f>1,000$ Hz) [11, 12]. Therefore, the method of partial domains should be employed to conduct low- and medium-frequency analysis. For a high-frequency analysis of the efficiency of noise protection screens, it is advisable to apply other numerical methods, such as a finite-element method or a boundary region method.

It is clear that the different thickness of the screen material, as well as fastening conditions, would also affect its sound insulation and, thereby, its effectiveness, as shown in work [19]. However, the merit of the current study is that it has been found that the screen's efficiency within ±1 dB from the maximum possible is achieved provided that the natural sound insulation of the screen *R* is 13–15 dB higher than its effectiveness (Fig. 3, 4). This makes it possible to select such a design for the predefined screen efficiency that could meet the requirement for natural sound insulation.

In the future, it is necessary to conduct laboratory measurements of the effectiveness of screens with finite sound insulation, as well as check the result under full-scale conditions.

8. Conclusions

1. Owing to the application of the method of partial domains, it was possible to solve the set problem for a wide range of frequencies (up to 1,000 Hz), as well as different thicknesses and sound insulation of screens. The transition from the tonal sound source to the noise one has made it

possible to obtain a uniform sound field (without an interference card), which is observed in practice.

2. Based on the calculation results, the effect of the screen's natural sound insulation on its effectiveness was revealed. It has been shown that the screen's efficiency reaches its maximum values (16–22 dB) provided that the screen's natural sound insulation is 13–15 dB higher than efficiency.

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