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Досліджено зниження шуму транспортних потоків шумозахисними екранами з отвором біля його основи. Розв'язана задача знаходження звукового поля довкола такого шумозахисного екрана. Наведено результати розрахунків ефективності шумозахисного екрана, які показали наявність максимуму зниження шуму. Проведена оцінка впливу ширини отвору на ефективність екрана. Виявлено малу зміну ефективності екрана на низьких частотах при ширині отвору до 0,2 м. Запропоновано спосіб наближення результатів розрахунків до натурних умов

Ключові слова: шумозахисний екран, екран із отвором, ефективність шумозахисних екранів, метод часткових областей, метод кінцевих елементів, звукоізоляція, зниження шуму

Исследовано снижение шума транспортных потоков шумозащитными экранами с отверстием возле его основания. Решена задача нахождения звукового поля вокруг такого шумозащитного экрана. Приведены результаты расчетов эффективности шумозащитного экрана, которые показали наличие максимума снижения шума. Проведена оценка влияния ширины отверстия на эффективность экрана. Выведено малое изменение эффективности экрана на низких частотах при ширине отверстия до 0,2 м. Предложен способ приближения результатов расчета к натурным условиям

Ключевые слова: шумозащитный экран, экран с отверстием, эффективность шумозащитного экрана, метод частичных областей, метод конечных элементов, звукоизоляция, снижение шума

INVESTIGATION OF THE EFFICIENCY OF A NOISE PROTECTION SCREEN WITH AN OPENING AT ITS BASE

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1. Introduction

More and more attention has been recently paid to protection against noise in the world [1]. One of the most effective ways of reducing noise is to set noise protection screens. The most common source of excessive noise worldwide is transportation flows that, according to different data, cover from 50 % to 70 % of settlement territory [2, 3], which leads to the deterioration of hearing, specifically in children [4]. At present, leading countries of the world pay great attention to the construction of new, and the reconstruction of existing, highways, in order to increase intensity of transportation and improve safety of operation. One of the requirements to the safe operation of any construction facilities, which definitely include car and rail routes, is the requirement for "noise protection" [5]. Official normative documents point to the necessity of applying noise protection screens as an effective way to reducing the noise of traffic flows. A procedure for the calculation of efficiency of such screens is quite outdated and does not meet modern requirements for accuracy and reliability [6, 7].

That is why qualitative assessment of the effectiveness of noise protection screens, depending on their design pa-

rameters, as well improving their efficiency, is an extremely important and relevant task.

2. Literature review and problem statement

The biggest disadvantage in the construction of screens in Ukraine is erecting them with openings and gaps of up to 0.5 m (Fig. 1), which leads to a decrease in efficiency of such structures. These gaps are meant for water drainage and removal of other types of sediment from the highways.

The problems of application of noise protection screens and determining their effectiveness were first addressed in the world from the mid-60s of the last century. Underlying these studies are papers [8–10]; however, experimental studies were based on estimating the noise protection screen without influence of the ground. Laboratory studies were later conducted into effectiveness of noise protection screens for point sources of sound with the obtained approximate expressions for assessing efficiency taking into consideration reflection of sound from the surface of the Earth [11, 12]. These studies were based on the theory of geometrical acoustics, which led to the limitation in the

scope of application of the obtained expressions in the field of low and medium frequencies.



Fig. 1. A noise protection screen in the city of Kyiv, with a slit at its base

In paper [13], attention is paid to estimating efficiency of a thick screen with ultimate sound insulation; the results obtained indicate, however, low efficiency. Article [14] reports results of numerical study into passage of sound through an opening in the screen, though in order to get adequate results for other geometry of the problem, it is advisable to have analytical relations. Paper [15] paid attention to the screens of finite length, which made it possible to determine the effect of sound propagation through the ends of the screen. The application of results of this work is possible, however, only for vertical screens and horizontal planes beyond the screen, which is not applicable, for example, to the inclined screens that are placed on bridges.

With the development of computational technology, it became possible to carry out computer simulation of acoustic field around the screen. The most widely used methods are those of boundary areas and finite elements [16–18]. It was shown that the method of boundary areas can be applied to any geometrical system with arbitrary boundary conditions. The time of calculation will be the factor that may limit the complexity of the system, and is suitable for solving external tasks. The finite element method makes it possible to solve internal problems by splitting domains of solutions into elementary particles. A common disadvantage of numerical methods is the uncertainty of error in the calculations. The most common technique to assess the adequacy of computer model is to compare results of the calculations to the field or model experiments, which leads to increased cost and time loss.

The recently developed method in Ukraine implies determining the effectiveness of noise protection screens using a method of partial areas [19]. Paper [20] described estimation of efficiency of acoustically rigid soundproofed screens of arbitrary height and angle of inclination. The results obtained by this method have a good agreement with the results of field measurements [21].

Therefore, there is a need to design the analytical method for calculating a reduction in the levels of sound pressure by noise protection screens with arbitrary angles of inclination of the screen and with a plane beyond the screen. In this case, a mathematical model must take into consideration a possibility of sound penetration through the body of the screen.

3. The aim and objectives of the study

The aim of present study is to determine effectiveness of the noise protection screen with an opening at its base taking into consideration a sound reflection from the ground.

To achieve the set aim, the following tasks have been solved:

- to state and solve a problem on finding a sound field around the screen with an opening near its base using a method of partial areas;
- to identify techniques to adapt the results obtained to a known actual situation;
- to estimate effect of the size of the opening in the screen on its effectiveness.

4. Solution to the problem on a noise protection screen with an opening at its base

A noise protection screen is typically a vertical wall made of solid building materials (such as concrete, brick, glass), or structures in the form of sandwich panels from metal and mineral wool [22]. From the acoustic point of view, all of these materials have a significantly higher acoustic impedance than the air in which sound waves propagate, which is why these materials and structures can be considered acoustically rigid.

The surface of the road, on which automobiles move, is most often made of asphalt or concrete layer, and it can also be considered an acoustically rigid material. As far as the surface beyond the screen is concerned, it can be acoustically rigid (ground, asphalt, concrete, etc.), or it can be absent at all (when a sound source is located on the bridge or a viaduct).

In addition, transportation motion in the present study is considered to be a continuous source of sound whose characteristics do not change lengthwise.

All these conditions and approximations result in a problem whose geometry is shown in Fig. 2.

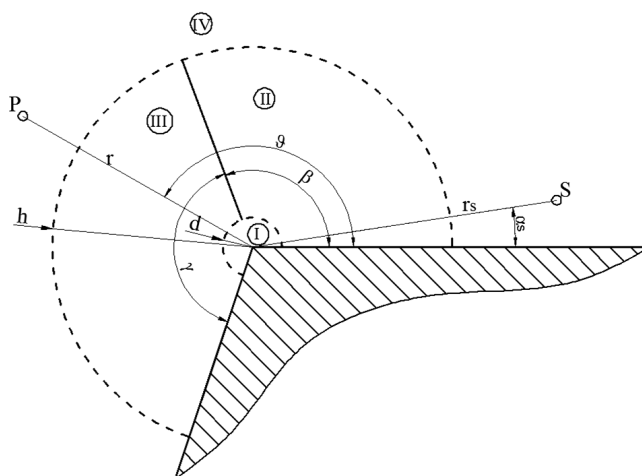


Fig. 2. Estimated geometric model of the noise protection screen with an opening at the base

Problem:

Two acoustically rigid half-planes, one of which is horizontal, the other is inclined, form a dihedral angle with an

angle of disclosure $(\beta+\gamma)$, repeating the surface of the Earth. A sound source S is in the form of an infinitely long cylinder with an infinitely small radius, which operates at zero mode of oscillations and emits a sound wave. This source is at distance r_s from the top of a dihedral angle – the base of the noise protection screen with an opening, and at angle α_s to the horizontal half-plane (road surface). An angle β to the horizontal half-plane is the acoustically rigid, infinitely long band of width $h-d$ – a noise protection screen. The edges of this band are at distance d and h from the top of the dihedral angle. The plane to which the band belongs passes through the top of the dihedral angle. Zone I – an opening through which noise penetrates; zone II – a space to the noise protection screen with a source of noise; zone III – a space of acoustic shadow beyond the screen; zone IV – populated territory to be protected from noise.

It is required to find an acoustic field in arbitrary point P , which is located at distance r from the top of the dihedral angle and at angle θ to the horizontal half-plane, located in zone IV.

As is known [23], the Helmholtz equation for the velocity potential Φ in the polar coordinate system on the plane takes the form:

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

Partial solution will be represented in the form:

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

or

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

where here and below $H_b^{(1)}$, $H_b^{(2)}$, J_b and N_b is the notation of cylindrical functions, namely, by Hankel of the first and second kind, by Bessel and by Neumann, respectively; $k=\omega/c$ is the wave number.

Region I:

Region I is in the form of a sector of the circle with radius d at boundary conditions:

$$\frac{\partial \Phi}{\partial r} = 0 \text{ at } \begin{cases} \alpha = 0, r \leq d, \\ \alpha = \beta + \gamma, r \leq d. \end{cases} \tag{4}$$

We shall apply partial solutions of the form (3). Given the fact that this region contains the origin of coordinates, then the solution using a Neumann function does not match physicality, which is why the second complement in the solution is rejected.

Then we shall employ boundary conditions for finding the parameters of b, C, D .

$$\begin{aligned} \begin{cases} -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \Big|_{\theta=0} \\ -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \Big|_{\theta=\beta+\gamma} \end{cases} & \Rightarrow \begin{cases} D_b = 0 \\ C_b \sin((\beta + \gamma)b) = 0 \end{cases} \Rightarrow \\ \Rightarrow \begin{cases} D_b = 0 \\ C_b = 0 \\ D_b = 0 \\ \sin((\beta + \gamma)b) = 0 \end{cases} & \Rightarrow \begin{cases} \text{trivial case} \\ D_b = 0, \\ b = \frac{\pi n}{\beta + \gamma}, n = 0, \pm 1, \pm 2.. \end{cases} \end{aligned}$$

Then,

$$\varphi_n(r, \theta) = A_n^{(1)} \cdot J_{\frac{\pi n}{\beta+\gamma}}(kr) \cdot \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right), n = 0, \pm 1, \pm 2... \tag{5}$$

As a result of a finding a partial solution, velocity potential Φ_I for region I can be written down in the form

$$\Phi_I = \sum_{n=0}^{\infty} A_n^{(1)} J_{\frac{\pi n}{\beta+\gamma}}(kr) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right). \tag{6}$$

Region II:

Region II takes the form of a sector of the ring with radius d and h with the following boundary conditions:

$$\frac{\partial \Phi}{\partial r} = 0 \text{ at } \begin{cases} \theta = 0, r > d, \\ \theta = \alpha, r \leq h. \end{cases} \tag{7}$$

We shall apply a partial solution of form (2).

Then we shall use boundary conditions for finding the parameters of b, C, D .

$$\begin{aligned} \begin{cases} -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \Big|_{\theta=0} \\ -C_b \sin(b\theta) + D_b \cos(b\theta) = 0 \Big|_{\theta=\beta} \end{cases} & \Rightarrow \begin{cases} D_b = 0 \\ C_b \sin(\beta \cdot b) = 0 \end{cases} \Rightarrow \\ \Rightarrow \begin{cases} D_b = 0 \\ C_b = 0 \\ D_b = 0 \\ \sin(\beta \cdot b) = 0 \end{cases} & \Rightarrow \begin{cases} \text{trivial case} \\ D_b = 0, \\ b = \frac{\pi n}{\beta}, n = 0, \pm 1, \pm 2.. \end{cases} \end{aligned}$$

Record:

$$\varphi_n(r, \theta) = A_n^{(2)} \cdot J_{\frac{\pi n}{\beta}}(kr) \cdot \cos\left(\frac{\pi n}{\beta} \theta\right), n = 0, \pm 1, \pm 2... \tag{8}$$

After the transforms, similar to the solution to the first region, it is possible to write velocity potential speed Φ_{II} for region II in the form:

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

Region III:

Region III takes the form of a sector of the ring with radius d and h with the following boundary conditions:

$$\frac{\partial \Phi}{\partial r} = 0 \text{ at } \begin{cases} \theta = \beta, r > d, \\ \theta = \gamma, r \leq h. \end{cases} \tag{10}$$

Similar to sector II:

$$\begin{aligned} \Phi_{III} = & \\ = \sum_{n=0}^{\infty} \left[A_n^{(4)} \cdot J_{\frac{\pi n}{\gamma}}(kr) + A_n^{(5)} N_{\frac{\pi n}{\gamma}}(kr) \right] & \cos\left(\frac{\pi n}{\gamma} (\theta - \beta)\right). \end{aligned} \tag{11}$$

Region IV:

Region IV takes the form of an area outside the circle of radius h with the following boundary conditions:

$$\frac{\partial \Phi}{\partial r} = 0 \text{ at } \begin{cases} \theta = 0, r > h, \\ \theta = \beta, r > h. \end{cases} \tag{12}$$

Given the Sommerfeld condition of radiation at infinity, we reject in equation (2) function $H_b^{(2)}(kr)$ because it corresponds to the waves that arrive from the infinity.

$$\Phi_4 = \sum_{n=0}^{\infty} A_n^{(6)} \cdot H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kr) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right). \quad (13)$$

Diffraction field from the source of sound.

For the sake of simplicity, we shall assume that the source of sound is located in zone IV, that is, $h < r_s$.

Diffraction of the infinite cylindrical sound source of a small wave size on a wedge with acoustically rigid surfaces and angle of disclosure $\beta+\gamma$ is described by expression [17]:

$$\Phi_0 = \frac{\pi i}{2(\beta+\gamma)} \times \begin{cases} \sum_{n=0}^{\infty} \varepsilon_n H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kr_s) J_{\frac{\pi n}{\beta+\gamma}}(kr) \cos\left(\frac{\pi n}{\beta+\gamma} \alpha_s\right) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right), & r < r_s, \\ \sum_{n=0}^{\infty} \varepsilon_n J_{\frac{\pi n}{\beta+\gamma}}(kr_s) H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kr) \cos\left(\frac{\pi n}{\beta+\gamma} \alpha_s\right) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right), & r \geq r_s, \end{cases} \quad (14)$$

where Φ_0 is the potential of oscillatory speed emitted by the source;

$$\varepsilon_n = \begin{cases} 1, & n = 0, \\ 2, & n > 0. \end{cases} \quad (15)$$

Then the field in region IV will be determined as:

$$\Phi_{IV} = \Phi_0 + \Phi_4. \quad (16)$$

We shall write down the terms of field conjugation at boundaries:

– by pressure:

$$\Phi_I = \Phi_{II} + \Phi_{III}, \quad r = d, \quad \theta \in [0, \beta + \gamma], \quad (17)$$

$$\Phi_{IV} = \Phi_{II} + \Phi_{III}, \quad r = h, \quad \theta \in [0, \beta + \gamma]. \quad (18)$$

– by speed:

$$\frac{\partial \Phi_I}{\partial r} = \begin{cases} \frac{\partial \Phi_{II}}{\partial r}, & r = d, \quad \theta \in [0, \beta], \\ \frac{\partial \Phi_{III}}{\partial r}, & r = d, \quad \theta \in [\beta, \beta + \gamma], \end{cases} \quad (19)$$

$$\frac{\partial \Phi_{IV}}{\partial r} = \begin{cases} \frac{\partial \Phi_{II}}{\partial r}, & r = h, \quad \theta \in [0, \beta], \\ \frac{\partial \Phi_{III}}{\partial r}, & r = h, \quad \theta \in [\beta, \beta + \gamma]. \end{cases} \quad (20)$$

Let us substitute expressions (6), (9), (11) and (16), considering (13) and (14), in the conditions of conjugation (17)–(20).

$$\begin{aligned} & \sum_{n=0}^{\infty} A_n^{(1)} J_{\frac{\pi n}{\beta+\gamma}}(kd) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) = \\ & = \sum_{n=0}^{\infty} \left[A_n^{(2)} J_{\frac{\pi n}{\beta}}(kh) + A_n^{(3)} N_{\frac{\pi n}{\beta}}(kh) \right] \cos\left(\frac{\pi n}{\beta} \theta\right) + \\ & + \sum_{n=0}^{\infty} \left[A_n^{(4)} J_{\frac{\pi n}{\gamma}}(kh) + A_n^{(5)} N_{\frac{\pi n}{\gamma}}(kh) \right] \cos\left(\frac{\pi n}{\gamma} (\theta - \beta)\right), \end{aligned}$$

$$\begin{aligned} & \sum_{n=0}^{\infty} A_n^{(6)} \cdot H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kh) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) + \\ & + \frac{\delta_i}{2} \sum_{n=0}^{\infty} \varepsilon_n H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kr_s) J_{\frac{\pi n}{\beta+\gamma}}(kh) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) \cos\left(\frac{\pi n}{\beta+\gamma} \alpha_s\right) = \\ & = \sum_{n=0}^{\infty} \left[A_n^{(2)} \cdot J_{\frac{\pi n}{\beta}}(kh) + A_n^{(3)} N_{\frac{\pi n}{\beta}}(kh) \right] \cos\left(\frac{\pi n}{\beta} \theta\right) + \\ & + \sum_{n=0}^{\infty} \left[A_n^{(4)} J_{\frac{\pi n}{\gamma}}(kh) + A_n^{(5)} N_{\frac{\pi n}{\gamma}}(kh) \right] \cos\left(\frac{\pi n}{\gamma} (\theta - \beta)\right), \end{aligned}$$

$$\begin{aligned} & \sum_{n=0}^{\infty} A_n^{(1)} J'_{\frac{\pi n}{\beta+\gamma}}(kd) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) = \\ & = \sum_{n=0}^{\infty} \left[A_n^{(2)} J'_{\frac{\pi n}{\beta}}(kd) + A_n^{(3)} N'_{\frac{\pi n}{\beta}}(kd) \right] \cos\left(\frac{\pi n}{\beta} \theta\right), \end{aligned}$$

$$\begin{aligned} & \sum_{n=0}^{\infty} A_n^{(1)} J'_{\frac{\pi n}{\beta+\gamma}}(kd) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) = \\ & = \sum_{n=0}^{\infty} \left[A_n^{(4)} J'_{\frac{\pi n}{\gamma}}(kd) + A_n^{(5)} N'_{\frac{\pi n}{\gamma}}(kd) \right] \cos\left(\frac{\pi n}{\gamma} (\theta - \beta)\right), \end{aligned}$$

$$\begin{aligned} & \sum_{n=0}^{\infty} A_n^{(6)} J'_{\frac{\pi n}{\beta+\gamma}}(kh) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) + \\ & + \frac{\delta_i}{2} \sum_{n=0}^{\infty} \varepsilon_n H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kr_s) J'_{\frac{\pi n}{\beta+\gamma}}(kh) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) \cos\left(\frac{\pi n}{\beta+\gamma} \alpha_s\right) = \\ & = \sum_{n=0}^{\infty} \left[A_n^{(2)} J'_{\frac{\pi n}{\beta}}(kh) + A_n^{(3)} N'_{\frac{\pi n}{\beta}}(kh) \right] \cos\left(\frac{\pi n}{\beta} \theta\right), \end{aligned}$$

$$\begin{aligned} & \sum_{n=0}^{\infty} A_n^{(6)} J'_{\frac{\pi n}{\beta+\gamma}}(kh) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) + \\ & + \frac{\delta_i}{2} \sum_{n=0}^{\infty} \varepsilon_n H_{\frac{\pi n}{\beta+\gamma}}^{(1)}(kr_s) J'_{\frac{\pi n}{\beta+\gamma}}(kh) \cos\left(\frac{\pi n}{\beta+\gamma} \theta\right) \cos\left(\frac{\pi n}{\beta+\gamma} \alpha_s\right) = \\ & = \sum_{n=0}^{\infty} \left[A_n^{(4)} J'_{\frac{\pi n}{\gamma}}(kh) + A_n^{(5)} N'_{\frac{\pi n}{\gamma}}(kh) \right] \cos\left(\frac{\pi n}{\gamma} (\theta - \beta)\right). \end{aligned}$$

By using the property of orthogonality of harmonic functions, we shall obtain an infinite system of equations, which is solved by the method of reduction with finding 240–480 unknown coefficients A_n depending on frequency.

5. Analysis of the obtained results

Based on the solution given in the previous chapter, we developed software in the Matlab programming environment. Results of calculations and their analysis is given below.

5.1. Approximation of calculation results to the actual situation

To run an analysis of results of solving the problem, we performed calculations at frequencies 63 Hz, 125 Hz, and 250 Hz, corresponding to the averaged geometrical frequencies of octave bands.

Fig. 3 shows acoustic field around an acoustically rigid vertical noise protection screen of height 5 m with an opening at the base of the screen of width 0.25 m. The sound source is at a distance 10 m from the screen that corresponds to a typical situation that is observed for automobile roads in Ukraine.

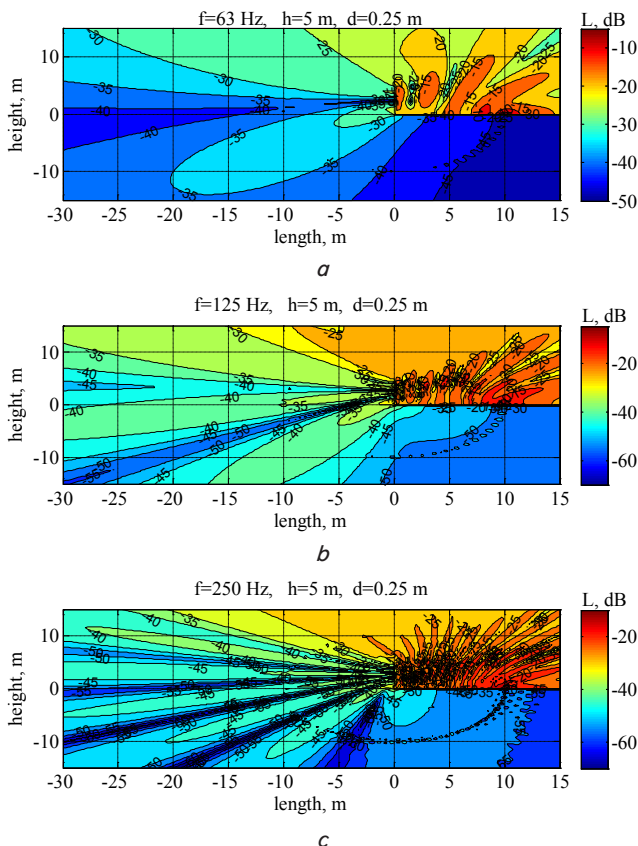


Fig. 3. Acoustic field around an acoustically rigid vertical screen of height 5 m with an opening of width 0.25 m at different frequencies: *a* – 63 Hz; *b* – 125 Hz; *c* – 250 Hz

Fig. 3 shows that at all frequencies, beyond the screen, there is a sharp change in the levels of sound pressure. This is due to the interference of sound waves that passed over the top edge of the screen and through the opening in its lower part. However, results of measurements at actual objects did not reveal such a drastic change in the levels of sound pressure. The reason for this is that the transportation flow as the source of noise is noisy with a continuous spectrum, which is why it is advisable to analyze efficiency of the screen taking this fact into consideration.

For this purpose, one should build an acoustic field not for only one frequency, but for the resulting field, for several frequencies. As shown by numerical studies, it is sufficient to find the total field of 25 frequencies, uniformly distributed over octave band, to consider the resultant acoustic field to be a field of noise signal (Fig. 4).

Fig. 4 shows that the sharp change in the sound pressure levels in the field beyond the screen has disappeared, which unambiguously brings the result obtained to the actual situation. However, the most informative is not the field of sound pressure levels but rather the efficiency of a noise protection screen, which is determined from expression

$$\Delta L = L_0 - L_1, \tag{21}$$

where L_0 are the sound pressure levels without a screen, dB; L_1 are the sound pressure levels with a screen, dB.

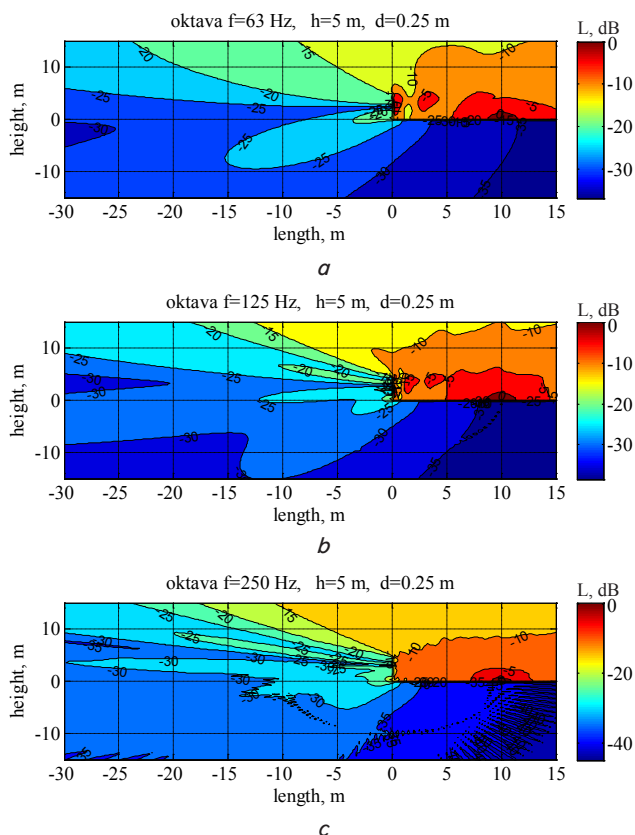


Fig. 4. Acoustic field around an acoustically rigid vertical screen of height 5 m with an opening of width 0.25 m in various octave bands with the averaged geometrical frequencies: *a* – 63 Hz; *b* – 125 Hz; *c* – 250 Hz

5. 2. Dependence of efficiency of the screen on the size of the opening

Fig. 5 shows charts of change in the efficiency of a noise protection screen for sound frequency and height of the estimated point at different size of the openings. One can see that the efficiency of the screen depends on the size of the opening, and the smaller the opening, the higher the efficiency that improves over a wide range of heights of the estimated point. However, there is a region of interferential interaction between the sound, which passed through the opening, and the sound that passed over the top edge of the screen. In this region, with a decrease in the opening of the screen the efficiency is also reduced. This pattern is observed also at various distances of the estimated point from the screen (Fig. 6).

Results of calculations have shown that at a change in the size of the opening from 0.1 m to 0.2 m, its effectiveness changes by no more than 0.5 dB. Thus, we can assume that the presence of the opening in the lower part of the screen the size up to 0.2 m will not lead to a significant reduction in its efficiency at low frequencies, but at the same time will facilitate the removal of sediments from the highways.

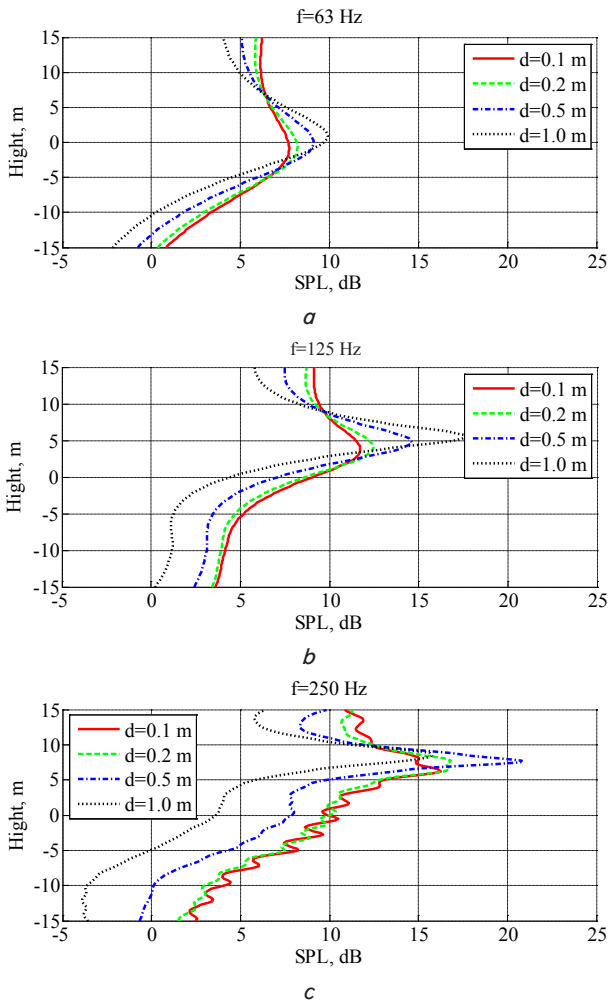


Fig. 5. Effectiveness of the noise protection acoustically rigid screen of height 5 m with an opening of width d at a distance 30 m beyond the screen depending on frequency: $a - 63$ Hz; $b - 125$ Hz; $c - 250$ Hz

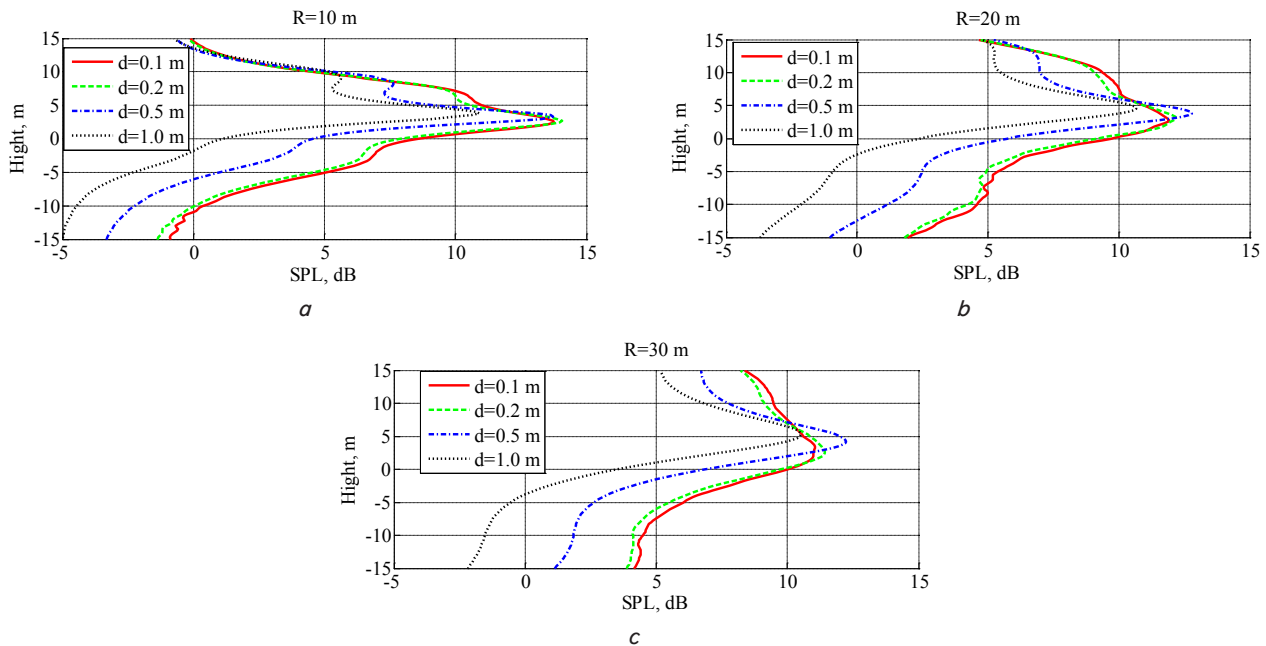


Fig. 6. Effectiveness of the noise protection acoustically rigid screen of height 5 m with an opening of width d at frequency 125 Hz, depending on distance to the screen: $a - 10$ m; $b - 20$ m; $c - 30$ m

6. Discussion of results of simulation and calculation of the noise protection screen with an opening at its base

The problem solved makes it possible to find the levels of effectiveness of noise protection screens, taking into consideration the presence of slits through which sound penetrates the region of shadow. Such a mathematical model can be considered to be a model of the screen with ultimate soundproofing.

The data obtained show a decrease in the efficiency of the screen with an increase in the width of the opening due to the fact that part of the sound energy passes through this opening because of which the levels of sound pressure in the region of shadow behind the screen increase.

Applying a method of partial areas to solve this problem made it possible to search for solutions not only for the vertical, but also for the inclined screen with different width of the opening. The use of this solution allowed us to set an arbitrary inclination angle of the plane beyond the screen, in contrast to the DLSM method [15]. At the same time, this method is purely analytical, based on known solutions of the wave equation. This circumstance has an unquestionable advantage over numerical methods, such as the method of boundary areas and the method of finite elements [16–18], in which the accuracy of obtained results is unknown and can be found only at the stage of experimental verification.

However, the application of this solution to the problem is somewhat limited for high frequencies (>1000 Hz). This is due, first, to the need of solving a system of equations of the higher order and, second, the accuracy of calculation of the Bessel functions of high order ($n > 100$) for large arguments ($kr > 100$) decreases, which leads to false results. That is why, in order to improve results of the calculation, it is necessary to apply known asymptotic approximations [24].

The present studies could be used in the design of noise protection screens, as well as to estimate the effectiveness of screens with an opening which are located on bridges and at variable height of terrain. Our method of calculation has shown that for the points beyond the screen, below road level, the efficiency of the screen decreases dramatically.

In future, this method can be improved to determine efficiency of the screen with ultimate sound protection and length, as well as to analyze effectiveness of impedance screens.

7. Conclusions

1. We stated and solved the problem on determining effectiveness of the noise protection screen with an opening at its base, which made it possible to estimate effectiveness of the noise protection screen for frequencies up to 1000 Hz and for distances between the source of noise and the screen up to 15 m.

2. When performing calculations, a drastic change was revealed in the sound pressure levels around the screen,

which is not observed under actual conditions. A procedure is provided to adjust results of the calculations by increasing the number of estimated frequencies in each octave band. It allowed us to obtain the more uniform sound field and thus we can assume that the source of sound has a noise, rather than tonal, character.

3. As a result of the performed calculation, we identified a region with maximum efficiency of the noise protection screen. It is shown that the efficiency of the screen of height 6 m decreases by the magnitude of up to 7 dB when width of the opening increases by up to 1 m. We detected anomalous dependence of the width of the opening on efficiency of the screen in the region of interferential interaction. It was also established that the width of the opening to 0.2 m significantly affects efficiency of the screen in a low frequency region.

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Розглянуто задачу визначення нестационарного температурного поля в захищеній металевій конструкції в умовах пожежі. Визначено вогнезахисну ефективність покриття, нанесеного на металеву пластину, нагріту під час нестандартного температурного режиму за умови неідеального теплового контакту. Використовуючи розроблену математичну модель розрахунку температури та експериментальні дані, визначено вогнезахисну ефективність покриття

Ключові слова: нестационарне температурне поле, металева конструкція, конвекційний теплообмін, вогнезахисна ефективність покриття

Рассмотрена задача определения нестационарного температурного поля в защищенной металлической конструкции в условиях пожара. Определена огнезащитная эффективность покрытия, нанесенного на металлическую пластину, нагретую во время нестандартного температурного режима при условии неидеального теплового контакта. Используя разработанную математическую модель расчета температуры и экспериментальные данные, определена огнезащитная эффективность покрытия

Ключевые слова: нестационарное температурное поле, металлическая конструкция, конвективный теплообмен, огнезащитная эффективность покрытия

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RESEARCH INTO NON-STATIONARY TEMPERATURE FIELD IN THE PROTECTED METALLIC STRUCTURE UNDER CONDITIONS OF FIRE

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1. Introduction

At all stages of capital construction or reconstruction of objects of any designation it is required to take into account the ability of metallic building structures to maintain their properties under fire conditions, particularly, to ensure the necessary fire resistance limit.

It is known that in order to improve the limit of fire resistance of structures, they are treated with fire-retarding substances. One of the means to protect metallic structures from fire is the application of special coatings on their surfaces, bloating under the influence of high temperature of fire with the formation of a heat insulation layer.

To analyze the processes and phenomena that occur during fire, it is necessary to apply methods of general physics, chemistry, thermophysics, thermodynamics, mechanics of solids, mathematics, etc. By employing a complex of these disciplines, it is possible to study and describe complex phenomena that accompany the start and development of fire, that is, to model a process that takes place there [1].

In the practice of calculating a temperature problem during fire, it is as a rule necessary to solve the problem of nonstationary thermal conductivity. Under conditions of fire, a situation that most often occurs involves heating of the wall on the one hand, and the presence of convective heat exchange with the surrounding medium, on the other hand.