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ACOUSTIC SCREEN STRUCTURES, THEIR PROPERTIES FOR NOISE AND VIBRATION REDUCTION

The article presents the research on the reduction of noise and vibrations carried out using screen theory and its implementation in practice. Acoustic screens are divided according to their application and structures. The article deals with the application of screens in practice, gives their theoretical evaluation and analyses influences of their structure and materials. The evaluation of positive and negative acoustic properties of the screens is given. The conclusion is that screen acoustic properties may be improved by including new elements into design of screens, thus increasing their efficiency in reducing noise effect. Theoretical calculations are performed, and the obtained results are analyzed. In conclusion, it is stated that cylindrical, semi-cylindrical or conical elements have to be applied in the screens.

1. Possibilities of screen application

At the present moment in world practice, there are great numbers of various acoustic screens applied for protection against noise and vibrations. Both their purpose and construction may be different. They may be subdivided into several groups, namely, screens for noise reduction, screens for vibration damping, and vibroacoustic screens, which suppress vibrations and noise. Their efficiency is dependent on a great number of various requirements, concerning requirements for materials and their properties, dimensions, etc. One of the most important requirements are vibroacoustic properties of materials. The possible efficiency is calculated according to vibroacoustic parameters of materials, and assumptions are made for dimensions and forms of screen constructions. The construction and form of screens have a more considerable effect on the permeability of noise, i.e. its reduction when en-

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tering the silent side of the screen. In our work [1], we investigated the influence of rigidity of screen walls on sound insulation of acoustic screens. The forms of the screen elements, the final screen construction, as well as the acoustic impedance of the screen, have an impact on the increase of rigidity. At present, however, it is difficult to answer to questions concerning, e.g., how the form of an acoustic screen should look like in order to exhibit vibroacoustic properties needed for the improvement of screen's efficiency in reducing noise and vibrations. In this respect, no consistent opinion exists. Many other requirements are also assumed for the form of screen structure. One of important ones is aesthetical appearance of the screen, as well as ecological requirements. Therefore, it is necessary to apply a comprehensive approach in solving problems concerning acoustic screens.

In this article, we will provide examples of solutions to the mentioned problems.

Our theoretical calculations [1], [2], [3] are based on rigidity increase. However, other vibroacoustic properties of materials and structures also have a strong impact, e.g., various resonances, elasticity, etc. An important requirement, assumed for screens, is the evaluation of the environment in which the screen will be used. One of the more important characteristics of noise and vibration sources propagating in the environment are the spectra of the propagated noise and vibration, which are the functions of power density of noise or vibration in frequency domain. Therefore, this information makes it possible to formulate requirements for the acoustic screen construction.

In some cases, theoretical solutions may give a fundamental idea of how to solve these problems.

In the article, we provide a theoretical justifications for implementation of the proposed measures. On the basis of the theoretical research, the types of screen forms that may improve screen efficiency were determined.

The application of screens for noise and vibration reduction has been known since the time the problem became to important to be ignored. To avoid noise, the first radical attempts were made by isolating high-intensity noise sources from the sources radiating lower noise in the premises.

Acoustic screens in the premises were applied only in the cases, when sound pressure level (expressed in dB scale) of the direct noise source at the point where the noise level was intended to be reduced was much higher than the levels of noise of adjacently located sources and their sound was reflected. Similar conditions were required in order to reduce vibration parameters. The article gives an analysis of screens to be applied for traffic noise reduction. The source under analysis is considered to the noise propagated from the street or highway that introduces a pollution into the people's activity zone and into the inhabited area.

2. Evaluation of screen efficiency

The efficiency of the screens could be determined by experiments or by carrying out calculations.

The efficiency of a manufactured screen can be determined by experiment in the surrounding environment, i.e. by determining the place where the screen would be located, or in the laboratory in the free acoustic field, i.e. in the anechoic chamber.

The best method for evaluation of screens, however, is to apply both methods, i.e. first to calculate various variants of the structure, and after having received the most proper one, to manufacture it and test by experimenting. In order to select and calculate the screens with the required efficiency, able to reduce the level of noise down to the values indicated in the directives, it is required to perform additional research, namely, to determine the characteristics of the noise that is subject to reduction.

To determine the traffic noise characteristics in the streets, roads and in other residential areas where traffic goes through, one can use the equivalent noise levels expressed in dBA.

On the other hand, very important for determining noise characteristics is traffic noise frequency analysis, i.e. the knowledge of characteristics of noise-sound pressure spectral density in the range of audible frequencies.

With the help of these characteristics it is possible to create a noise reduction model, and make calculations that allow us to select the required noise reduction measures, including screens.

Therefore, primarily we should have a screen module based on theoretical grounds, develop methodology of efficiency calculation taking into account the design of the screen, i.e. the elements and materials used and planned to be applied in designing of the acoustic screens. Another important parameter of the screen construction is its height.

The world experience in the field of screen application shows that one can apply screens of various designs, as far as materials and dimensions are concerned [1], [2], [3], [4], [5], [6], [7], [8], [9], [10].

The basis for the design of acoustic screen is made of a bearing frame and a sound insulating part with additional sound absorption and protective layers.

The effective screen height is determined by calculations, in accordance to the scheme presented in Fig. 1.

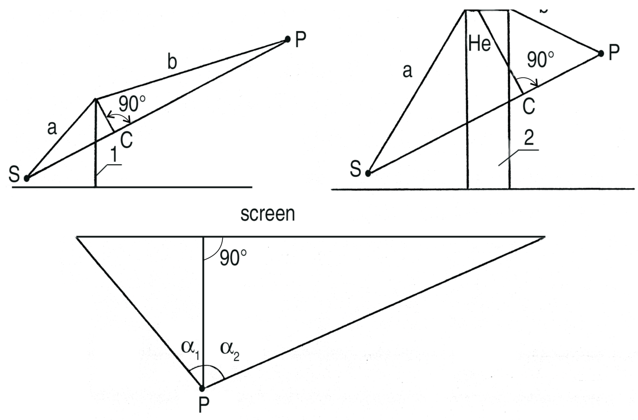

Fig. 1. Calculation schemes for determining the reduction of a noise level behind the screens: 1 – barrier; 2 – building; 3 – embankment; 4 – gap; S – noise source, P – count point, He H – effective height of the screen

3. Calculation of simple screens

In the final calculation, when we have the characteristics of the screen, we should apply the theory of diffraction in order to evaluate the qualitative properties of the screen.

To obtain sound pressure at a certain point P in the zone of the shadow behind the screen, it is necessary to integrate energy radiated by every single elementary volume of the wave front acting as the virtual new point source in the free space above the screen.

Many authors [1], [3], [4], [5], [18] proposed original theories for the analysis of different conditions concerning the propagation of sound waves. These theories, however, are applicable only in simple conditions, which do not exist in reality. On the other hand, such simplicity is good for practical calculations and may be successfully applied in designing screens for noise protection.

Initially, the theory of diffraction was first developed in optics, and was later applied to all the phenomena of diffraction both in acoustics and in other wave processes.

Let's analyze a simplified theory of diffraction by Frenel-Kirchhoff [14]. In Fig. 2, a sound wave from point source S is spreading via the "window" in the infinitely thin barrier, without any penetration of the sound through the barrier. If P is the receiving point, and the dimensions of the window are x_1 and y_1-y_2 in the system of coordinates x, y, on the surface of the barrier, the sound field in point P is expressed as follows:

$$U_{(P)} = B \int_{x_1}^{x_2} dx \int_{y_1}^{y_2} dy \exp\left[ikf(x, y)\right], \tag{1}$$

here $f(x, y)$ is the function of coordinates of the window and of location of the point source S and P; B is the function of geometry of points S and P and of the window, as well as of the wavelength, but here it is considered as a constant on the condition that dimensions of the window are very small in comparison with the distance of points S and P from the barrier, k-is the so-called wave number.

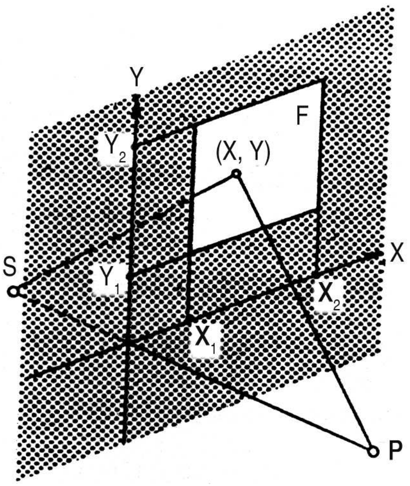

Fig. 2. Infinite plane, X-Y-with a window, S-point source, P-calculated point

Let's assume that coordinates x and y are directed accordingly, x towards u, y towards v. Then, the expression (1) takes the following form:

$$U_{(P)} = iA \int_{u_1}^{u_2} \exp\left(i\frac{\pi}{2}u^2\right) du \times \int_{v_1}^{v_2} \exp\left(i\frac{\pi}{2}v^2\right) dv, \tag{2}$$

$$\int_{0}^{u_1} \exp\left(i\frac{\pi}{2}u^2\right) du = C(u_1) + iS(u_1), \tag{3}$$

$$\left.\begin{aligned} C(u_1) &= \int_0^{u_1} \cos\left(\frac{\pi}{2}u^2\right)du; \\ S(u_1) &= \int_0^{u_1} \sin\left(\frac{\pi}{2}u^2\right)du \end{aligned}\right\} \tag{4}$$

$C(u_1)$ and $S(u_1)$ are known as Frenel integrals. They are very important for solving many problems of diffraction, and their values may be obtained from function tables [19].

These values are illustrated by the Cornu spiral shown in Fig. 3.

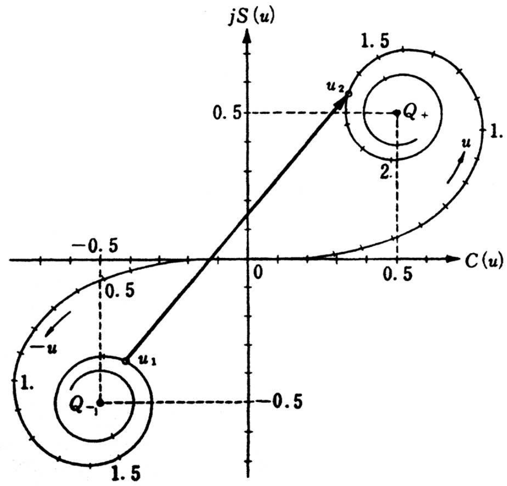

Fig. 3. The Cornu spiral

The value u means the length of the spiral line between the points.

$$\left.\begin{aligned} \mathrm{C}(0) = \mathrm{S}(0) &= 0, \\ \mathrm{C}(\infty) = \mathrm{S}(\infty) &= \pm 0.5. \end{aligned}\right\} \tag{5}$$

The complex value $\int_{u_1}^{u_2} \exp\left(i\frac{\pi}{2}u^2\right)du$ represents a vector from u_1 to u_2. Its absolute value and the angle between it and the real axis correspond to the amplitude and the phase angle, respectively.

Let's make an assumption that points S and P are in free space without any screen; then, from expression (2) we get

$$u_1 - \infty, v_1 = -\infty, u_2 = +\infty \text{ and } \infty$$
$$v_2 = +\infty \text{ and then } U_0 = -iA(1-i)^2 = 2A.$$

The factor of diffraction can be determined as follows

$$[DF] = \frac{U_{(p)}}{U_0} = \frac{-i}{2}\int_{u_1}^{u_2} \exp\left(i\frac{\pi}{2}u^2\right)du \times$$
$$\times \int_{v_1}^{v_2} \exp\left(i\frac{\pi}{2}v^2\right)dv = \frac{-1}{2}\{C(u_2) - C(u_1) + \tag{6}$$
$$+i[S(u_2) - S(u_1)]\}\{C(v_2) - C(v_1) + i[S(v_2) - S(v_1)]\}.$$

The sound field in point P, after the sound wave has passed through the window, represents the factor of diffraction (DF) in the free-space field.

Here we analyze a semi-infinite thin screen with the point source. In the simplest case, a semi-infinite flat screen is installed between points S and P; as the values $u_1 = -\infty$, $u_1 = +\infty$ are substituted into expression (6), we receive:

$$DF = \frac{-i}{2}(1+i)\left\{\left[\frac{1}{2} - (v_1)\right] + i\left[\frac{1}{2} - S(v_1)\right]\right\}. \tag{7}$$

Noise reduction by means of a semi-infinite screen is expressed as $\Delta L_{1/2}$, dB:

$$\Delta L_{1/2} = -10\lg|DF|^2 = -10\lg\frac{1}{2}\times$$
$$\times\left\{\left[\frac{1}{2} - C(v_1)\right]^2 + \left[\frac{1}{2} - S(v_1)\right]^2\right\}. \tag{8}$$

here the value in the braces corresponds to the square of the absolute value of the vector from v_1 to Q, Fig. 3.

The curve in Fig. 4 is the graph of calculation results obtained from equation (8). The areas of negative and positive values correspond to the position of point P in the shade zone and out of the acoustic shade, respectively.

Equation (8) derived from the theory of diffraction in optics has a simplified form, so it very clearly illustrates the physical essence of the phenomenon. Unfortunately, application of optical diffraction principles does not ensure the same accuracy in acoustics. In optics, the length of waves is very low, at the same time the distance between the source and the barrier and the observer is high enough compared to the wavelength. The conditions in acoustics are quite different; therefore when designing acoustic structures and screens it is recommended to apply empirical data.

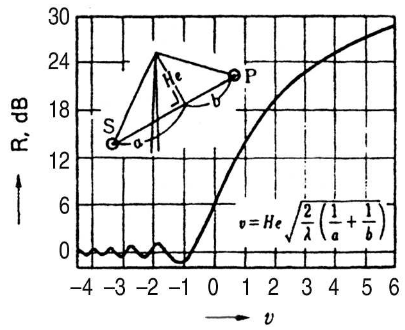

Fig. 4. Sound reduction of semi-infinite screens calculated according to the Kirchhoff's theory of diffraction

4. Complicated screens

The efficiency of noise reduction of complicated screens depends on the characteristics of the sound insulation and sound absorption, as well as on the above-mentioned characteristics. Based on the theory presented in [20], [21], one determined that after application of a cylindrical and semi-cylindrical element in acoustic screens it was possible to increase the insulation characteristics of the screens. The work [20] presents the theory of External Sound Insulation of Cylindrical Shells.

5. Theory of sound insulation of cylindrical elements

Wave propagation in closed cylindrical shells ($|\bar{u}| << h << \lambda, h << R_r$) described here on the basis of known equations [22]

$$\left.\begin{aligned} L_{11}U_1 + L_{12}U_2 + L_{13}U_3 &= \frac{1}{c^2}\frac{\partial^2 U_1}{\partial t^2} \\ L_{21}U_1 + L_{22}U_2 + L_{23}U_3 &= \frac{1}{c^2}\frac{\partial^2 U_2}{\partial t^2} \\ L_{31}U_1 + L_{32}U_2 + L_{33}U_3 &= \frac{1}{c^2}\frac{\partial^2 U_3}{\partial t^2} \end{aligned}\right\} \tag{9}$$

$$\left.\begin{aligned}
&L_{11} = \left(\frac{\partial^2}{\partial t^2} + \frac{1-\sigma}{2R_r^2}\frac{\partial^2}{\partial\varphi^2}\right), \quad L_{12} = \frac{1+\sigma}{2R_r}\frac{\partial^2}{\partial z\partial\varphi}, \quad L_{13} = -\frac{\sigma}{R_r}\frac{\partial}{\partial t},\\
&L_{21} = \frac{1+\sigma}{2R_r}\frac{\partial^2}{\partial t\partial\varphi}, \quad L_{22} = \left(\frac{1-\sigma}{2}\frac{\partial^2}{\partial t^2} + \frac{1}{R_r}\frac{\partial^2}{\partial\varphi^2}\right),\\
&L_{23} = -\frac{1}{R_r^2}\frac{\partial}{\partial\varphi}, \quad L_{31} = \frac{\sigma}{R_r}\frac{\partial}{\partial t}, \quad L_{32} = \frac{1}{R_r^2}\frac{\partial}{\partial\varphi},\\
&L_{33} = \left(-\frac{1}{R_r^2} - \frac{h^2}{12}\left[\frac{\partial^2}{\partial t^2} + \frac{1}{R_r^2}\frac{\partial^2}{\partial\varphi^2}\right]^2\right).
\end{aligned}\right\} \tag{10}$$

where U_1, U_2, U_3 are the components of the vector of displacement (see Fig. 4), h, R_r, c, σ are the parameters of the shell: thickness, radius, sound propagation speed in the shell material, Poisson's coefficient, accordingly.

For mathematical solution of the problem, it is also necessary to apply excitation in the form of sources of sound situated at a sufficiently high distance from the shell. Finally, it is important to define the concept of sound insulation in such a way that this concept would reflect the essence of the phenomenon. The coefficient of sound insulation is understood as the sound pressure level in dB in the presence of the shell to the corresponding sound pressure level in dB when the sound-insulating device /shell/ is absent. This definition can be illustrated by the examples from works [23] and [24]. For the case when the radiator represents a cylindrical dipole located on the axis of the shell, sound insulation for points situated outside the shell, expressed in dB scale, will be:

$$\begin{aligned}
R = 20\lg\frac{\pi\rho c^2 h}{2\rho_0 c_0^2 R_r} + 10\lg\Bigg\{&\left(\frac{1}{\Omega^2\alpha - 1} - \Omega^2\alpha + \frac{d^2}{12} + 1\right)\dot{I}_1^4(\Omega) + \\
+ &\left[\frac{1}{\Omega^2\alpha - 1} - \Omega^2\alpha + \frac{d^2}{12} + 1\right]\dot{I}_1(\Omega)\dot{N}_1(\Omega) + \frac{2\rho_0 c_0^2 R_r}{\pi\rho c^2 h}\Bigg\}.
\end{aligned} \tag{11}$$

where $\Omega = \dfrac{\omega R_r}{c_0}$; $\alpha = c_0^2/c^2$; $d = h/R_r$; $I_n(x)$ $N_n(x)$ are Bessel and Neumann functions, accordingly; R – sound insulation.

For the case of the multipole of n-th order, sound insulation will be

$$R = 20\lg \frac{\pi\rho c^2 h}{2\rho_0 c_0^2 R_r} + 10\lg\left\{\left(\frac{1}{\Omega^2\alpha - h^2} - \Omega^2\alpha + \frac{h^2 d^2}{12} + 1\right)\right.$$
$$\left.\dot{I}_n(\Omega) + \left(\frac{n^2}{\Omega^2\alpha - n^2} - \Omega^2\alpha + 1\right)\cdot \dot{I}_n(\Omega)\,\dot{N}_n(\Omega)\right\}. \tag{12}$$

The corresponding graphs are presented in Figs 6a and 6b.

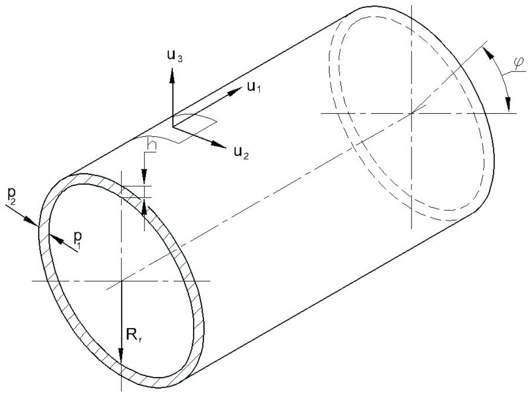

Fig. 5. Sketch to the choice of designations

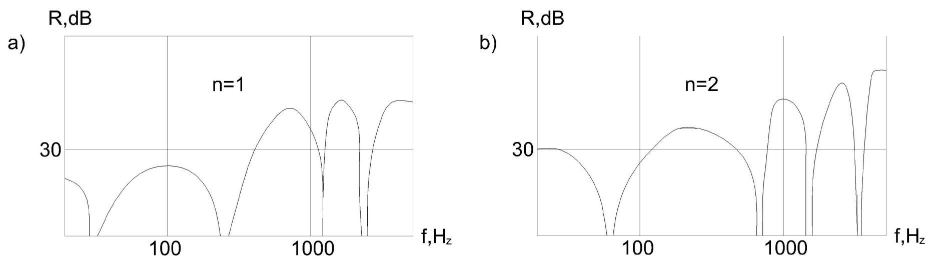

Fig. 6. Sound insulation of the cylindrical shell (h = 2 mm, R_r = 300 mm) in the air at the multipole (n = 1 and n = 2) sources of sound, located on the axis

6. Analysis of theory and practical implementation

Analyzing the obtained results, one can state that after using cylindrical elements for the structures of acoustic screens the values of parameters characterizing screen sound insulation would increase especially in the low-frequencies region [25].

The results shown in this article indicate that acoustic properties of screens are also determined by sound absorption properties.

Sound reflected from the screen evokes vibrations of the screen wall, which also radiates the sound at the corresponding frequencies. Therefore, the vibrations evoked by the screen wall should be either at very low frequencies or very high frequencies, namely, in the range of not audible sound frequencies.

Therefore, in the proposed acoustic screen made of cylindrical and semi-cylindrical elements, we have foreseen the use of specially designed sound absorbers, which not only absorb the reflected sound, but also improve the characteristics of screen sound insulation.

Fig. 7 presents the model of such a screen.

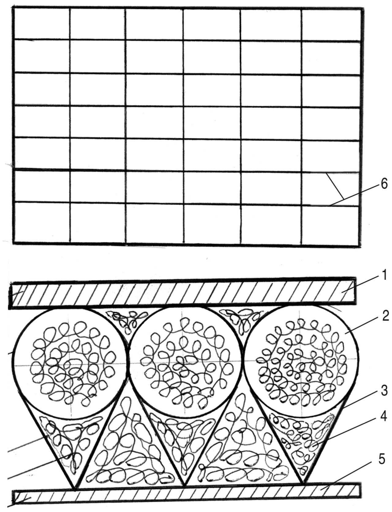

Fig. 7. The screen model with cylindrical elements and sound absorbers in the shape of a cone

Cylindrical elements can be made of various materials. Their efficiency for sound insulation is determined by the rigidity of cylindrical surfaces [25], even though the total weight of the elements adds to the sound insulation in accordance with the law of mass. Sound absorption elements having the shape of a cone do not reflect the sound, but absorb up to 80% of the energy of the incident sound wave depending on the material used for sound absorption.

For field screens, we propose to use the porous material which consists of aluminum powder or aluminum alloy [26]. Aluminum material is a porous body made of aluminum, with high mechanical strength and durability qualities , resistant to weather changes and heat. Owing to its properties, this material can withstand mechanical hazards and climatic stress and heat. As a porous body, it is superior to porous bodies belonging to the group of copper alloys. In addition, such a porous body is noticeable because of its lightness and inexpensiveness.

7. Conclusions

1. It has been demonstrated that for proper evaluation of acoustic screens applied for noise reduction it is required to carry out theoretical and experimental assessment.
2. To assess a screen in a theoretical way, it is necessary to know the characteristics of the noise that we intend to reduce, as well as the requirements for screen to be applied along with the screen's geometrical parameters.
3. For determination of the efficiency of the designed screens, we propose the classical Frenel-Kirchhoff approximation theory.
4. In analyzing the acoustic characteristics of a screen, one needs to insulate and absorb the energy of sound coming in to the screen; acoustic characteristics depend on the materials and dimensions selected for the screen.
5. When considering the qualities of the screen materials and the shapes of the structures, we have demonstrates that screen sound insulation and absorption depend on the acoustical characteristics of individual elements used there, such as rigidity (in changing the shape of the element), porosity, etc.
6. It has been determined that by applying cylindrical and cone-type elements it is possible to significantly improve screen sound insulation characteristics, in particular at low frequencies, while the screen mass (weight) is not increased.
7. A new design of a screen with cylindrical and cone-type elements is proposed. Its advantages have been proved theoretically, and that design has been partly implemented in practice.

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Struktury ekranów akustycznych, ich właściwości dla tłumienia hałasu i wibracji

Streszczenie

W pracy przedstawiono badania nad tłumieniem hałasu i wibracji prowadzone przy wykorzystaniu teorii ekranów akustycznych. Pokazano także wdrożenie tych badań do praktyki. Ekrany akustyczne podzielono zgodnie z ich strukturą i zastosowaniem. Artykuł dotyczy praktycznych zastosowań ekranów, przedstawia teoretyczną ocenę i analizę wpływu struktury i materiałów. Oceniono, które z właściwości ekranów są korzystne bądź niekorzystne pod względem akustycznym. Wnioskiem z badań jest, że właściwości akustyczne ekranu można poprawić wykorzystując przy ich projektowaniu nowe materiały, które pozwalają zwiększyć efektywność tłumienia hałasu. Wykonano obliczenia teoretyczne, a uzyskane wyniki poddano analizie. Stwierdzono, że w strukturze ekranu powinny być stosowane elementy cylindryczne, półcylindryczne i stożkowe.