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INNOVATIVE APPROACHES TO DESIGNING SOUND INSULATION IN HISTORIC BUILDINGS DURING RECONSTRUCTION

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Abstract

The modern reconstruction and restoration of historic buildings constructed according to individual projects requires individual approaches to the design of sound insulation in a wide range. Therefore, all means of protection against acoustic impacts should be designed individually for each building. A methodology for designing materials and structures to reduce the acoustic load on the environment of historic buildings has been developed. To effectively shield infrasound and low-frequency sound, a mathematical tool for designing resonant-type protective structures has been developed. For absorption of medium and high frequency noise, an easy-to-use mathematical tool for designing porous materials of small thickness is proposed. The main advantages of such materials are manufacturability and the ability to cover large areas of complex configuration without distorting the appearance of the interior and exterior of buildings. This makes it possible to ensure that the noise level in buildings is within the standard range during their reconstruction and restoration. The calculation results have been verified. Acceptable convergence of theoretical and experimental data over the entire sound range is shown. The possibility of expanding the functionality of porous noise-absorbing materials is substantiated.

Keywords*: Noise; Low-frequency sound; Infrasound; Noise reduction; Sound insulation*

Introduction

Historic heritage sites were built in the absence of building codes, using different building materials, technologies, weight and size parameters of structures etc. At the time of construction and operation of such facilities, there was no external impact of man-made factors on the internal environment of the buildings. One of these factors is noise. Over the past decade, there has been a steady increase in the levels of low-frequency sound and infrasound in the environment. This is due to an increase in the intensity of traffic flows of all types of vehicles. Low-frequency vibrations are practically not shielded by building structures made of any materials of large thickness. At the same time, infrasound and audible noise levels are strictly regulated by international and national standards and sanitary norms. In particular, the European Directive [1] sets out requirements for noise levels.

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Today, a large number of standard noise-absorbing and soundproofing materials have been developed and are being produced, which are used for cladding standard buildings and structures. All historical buildings were built to individual designs, have different noise-absorbing properties and are located in places with different acoustic loads on the environment. It is an urgent task to develop innovative approaches to designing sound reduction and infrasound in historic buildings. This makes it possible to take into account the individual characteristics of the building and the necessary and sufficient level of protection of the internal environment from acoustic impacts. This approach can be implemented through a preliminary assessment of the required sound-absorbing properties of materials using mathematical methods. This will minimise the weight and size parameters of sound insulation to avoid distortion of the appearance and interiors of historical and cultural heritage sites.

The need to reduce the noise load on the indoor environment of buildings is driven by the need to create comfortable conditions for people and prevent harm to their health [2]. It is also important in terms of synergistic impact on people [3]. A lot of attention is paid to the substantiation and development of noise protection materials. These are mainly synthetic and natural porous materials [4, 5]. This area is being developed through experimental and theoretical studies [6]. However, these studies are mainly concerned with medium and high frequency noise. In recent years, a number of papers have been published on low-frequency noise and infrasound [7, 8], but most of them focus on monitoring the levels of these factors. The design of protective equipment against low-frequency noise and infrasound is discussed in [9]. It is shown that the only effective means of reducing the levels of low-frequency noise and infrasound is the use of resonant panels. The design methodology presented in this paper is correct, but it is difficult to apply in practice due to the presence of parameters that are not reference, such as panel tension, bending stiffness etc. The calculation apparatus needs to be improved in the direction of operating with the elastic moduli of materials – Young's modulus, Poisson's ratio etc. This approach will make it possible to calculate the efficiency of resonant panels made of standard materials.

It is known that the most effective way to reduce medium and high frequency noise levels is to absorb sound wave energy by porous materials. The design of protective materials and structures requires several parameters, such as porosity, pore tortuosity and airflow resistance [10]. Such parameters are not always possible to obtain even experimentally. In particular, this paper considers the parameters of sound-absorbing bedding on the ground surface. However, it is technically difficult to apply these developments in the construction industry. Study [11] compares different models of noise absorption by porous materials. The analysis of the materials in this work allows us to conclude that a promising area of research into the design of noise protection with porous materials is the use of the Delany and Bazley model. Its advantage is the presence of one parameter that requires experimental determination - airflow resistance. However, in its present form, this model is difficult to apply in practice due to the use of complex quantities in the calculations. It is necessary to refine the model in terms of transition to calculations using real values. Thus, the subject of this work is to improve the calculation tools for designing protective panels to reduce the levels of low-frequency noise and infrasound, as well as porous materials for absorbing medium and high-frequency sound and to verify the research results. This will make it possible to minimise the weight and dimensions of the enclosing structures and avoid distortion of the appearance of buildings and the interior of historical and cultural heritage sites.

Materials and methods

The main research method is the calculation method for predicting the sound absorption coefficients of materials and structures. The airflow resistance was measured in accordance with ISO 9053 [12]. The results of theoretical studies were verified using stationary calibrated measuring equipment by Brühl & Kier in accordance with ISO 10534 [13]. The material for verifying the research results was basalt fibre products.

Results and Discussions

Around the world, a large number of historic buildings and historical heritage sites are in need of restoration and repair work. In particular, in Ukraine, as a result of hostilities and terrorist attacks, a large number of such buildings need full or partial restoration. Figure 1a, b, c and d shows that historic buildings have damaged external structures and interior cladding. In the process of restoration, it is advisable to ensure modern acoustic characteristics of the entire structure, taking into account the acoustic load of the urban environment. All historical buildings are non-standard, so a methodology for designing noise protection structures and materials of the required efficiency needs to be developed.

a) b)

c) d)

Fig. 1. The first Ukrainian gymnasium named after Mykola Arkas, Mykolaiv, founded in 1863

Protection against the effects of low-frequency sound and infrasound is the most challenging task of ensuring the acoustic performance of buildings and premises. This is due to the low attenuation of low-frequency vibrations in the air and building structures. Therefore, the most effective way to reduce the levels of such sound is to use protective panels that provide resonant absorption of sound wave energy. This absorption is provided by the bending vibrations of the panel, which reaches a maximum at the critical frequency.

From the theory of sound interaction with surfaces, it is known that the critical vibration frequency of a panel at which the propagation speed of bending waves in the panel coincides with the propagation speed of sound waves in air, f_k is defined as:

$$f_k = \frac{\upsilon_0}{2\pi}\sqrt{\frac{m}{D}}, \tag{1}$$

where: υ_0 – speed of sound in air, m – panel running weight and D – cylindrical rigidity of the panel.

In this case, $m = \rho_m h$, where ρ_m – density of the panel material, h – thickness of the panel.

It is of practical importance to determine the natural frequency density of a panel of finite dimensions, which determines the maximum sound absorption efficiency *n(f)*:

$$n(f) = \frac{l_x l_y}{4\pi}\sqrt{\frac{m}{D}}, \tag{2}$$

where: $l_x l_y$ – linear panel dimensions.

The availability of quantitative data obtained from formulas (1) and (2) allows us to determine the panel parameters that ensure maximum absorption of sound waves due to energy losses due to the excitation of vibrations in the panel.

To reduce sound levels, it is possible to use porous sound-absorbing structures, which are widely used in practice. However, for infrasound vibrations and low-frequency sound with long wavelengths, the reduction of their levels is possible only through resonant wave absorption [9].

All panels for reducing infrasound and low-frequency sound levels are types of Bekeshi panels. Their effectiveness is maximised at resonant frequencies, which are selected as the frequencies of maximum amplitude determined experimentally.

$$f_r = \frac{k}{2l}\sqrt{\frac{F}{\rho bh}}, \tag{3}$$

where: F – material tension force, ρ – density of material, *l*, *b and h* – length, width and thickness of the material and k – order of resonant frequency.

The technical parameters of the panel are determined on this basis. However, the practical use of ratio (3) is inconvenient. The tension force of the panel depends on its linear size and the densities of materials made in the form of sheets or rolls are not reference values. Usually, the documentation contains surface or linear values – the mass of a unit surface area. That is, this is the value of $m = \rho_m h$, which is measured in kg/m^2.

Instead of the indefinite parameter F, it is advisable to use such an indicator as the cylindrical stiffness of the panel D, measured in N*m, i.e. the load per unit length of the panel.

In this case:

$$f_r = \frac{k}{2l}\sqrt{\frac{D}{mbh}}. \tag{4}$$

The advantage of this calculation is that the D value can be calculated for any material based on the relationships of continuum mechanics:

$$D = \frac{Eh^3}{12(1-\mu^2)}, \tag{5}$$

where: E – Jung's module and μ – Poisson's ratio.

Thus:

$$f_r = \frac{k}{2l}\sqrt{\frac{Eh^2}{12mb(1-\mu^2)}}. \tag{6}$$

The values of μ and m are reference values for the standard material, so to adjust the panel to the required frequency f_r, you need to change the parameters l, b and h. If, for example, a panel with dimensions $l \times b$ is required, then the material of the required thickness is selected from the product range. If a satisfactory result is not achieved, another material with different values of elastic moduli is selected.

Similarly, it is advisable to use the relations (1), (2) in the form:

$$f_k = \frac{\upsilon_0}{2\pi}\sqrt{\frac{12m(1-\mu^2)}{Eh^3}}, \tag{7}$$

$$n(f) = \frac{l_x l_y}{4\pi}\sqrt{\frac{12m(1-\mu^2)}{Eh^3}}. \tag{8}$$

The unification of design parameters makes it possible to develop protective panels of acceptable efficiency for sound and infrasound frequencies. The acoustic characteristics of any source are very different both in terms of the predominant frequencies (frequency bands) of sound and infrasound levels. Therefore, in practice, the most critical frequency bands are determined by measuring the spectral characteristics in terms of the need to reduce the amplitudes of sound and infrasound values. That is, the design of the protective panel is based on the principle of priority. The design solutions, including the choice of panel material, are based on the maximum reduction of vibrations of the largest amplitudes.

If acceptable sound and infrasound reduction is not possible, it is advisable to make a two-layer panel. One of them is designed to screen the sound of the predominant frequencies and frequency bands and the second one is designed to reduce infrasound levels.

Adjusting the panel to screen infrasound and low-frequency sound to the resonant frequency has disadvantages. The high quality factor of the oscillating system makes the panel narrowband. If you need to obtain a wide absorption band of low-frequency vibrations, you need to reduce the quality factor of the vibration system, which is the panel. For this purpose, holes are made in the panel. The central frequency of the preferred absorption is calculated from the ratio:

$$f = \frac{\upsilon_0}{2\pi}\sqrt{\frac{S}{h_{eff}c^2 d}}, \tag{9}$$

where: S – area of the holes, h_{eff} – effective thickness of the panel $\left(h_{eff} = h + 0,5\sqrt{\pi S}\right)$, h – thickness of the panel, c – distance between the centres of the holes and d – distance from the panel to the panel mounting surface.

For a two-layer panel, the distance “d” is the distance between the panels. This design achieves a simultaneous reduction in the sound range and infrasound levels. It should be borne in mind that the shielding efficiency decreases with the frequency moving away from the resonant and critical frequencies. It is not possible to obtain generalised curves that characterise the quality factor of all panels. They are different for each individual case and are determined by both the characteristics of the panel material and its geometric parameters.

The effectiveness of shielding low-frequency sound by resonant panels was compared. Both panels were tuned to a resonant frequency of 125Hz.

As can be seen from Figure 2, the perforated panel is broadband. Noise reduction indices of 4 dB and above for the low-frequency region can be considered satisfactory due to the high permeability of low-frequency vibrations. It is advisable to use solid panels for screening low-frequency noise with a large amplitude at a certain frequency or in a narrow frequency band.

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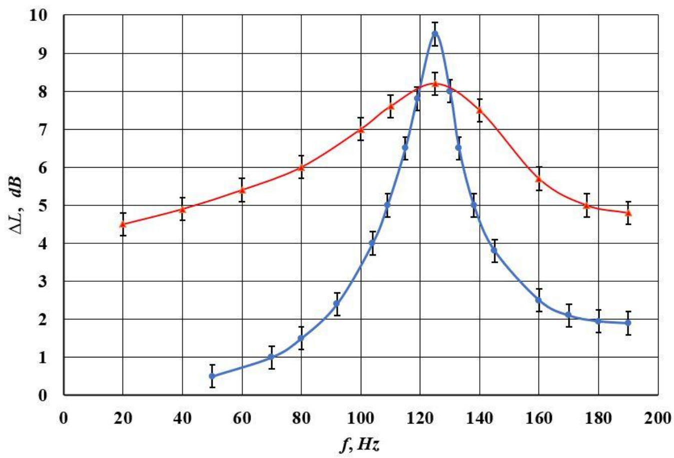

Fig. 2. Indices of low frequency sound reduction by resonant panels:
solid panel; perforated panel

Measurements of noise reduction by panels for screening the sound of medium frequencies were carried out. The panel designs are designed for the critical frequencies of 1800 and 2500Hz.

As can be seen from Figure 3, the nature of the noise reduction index curves is the same. At the same time, the efficiency of the panels is significantly higher for frequencies above the critical frequency. Therefore, in the process of designing noise protection, it is necessary to take into account the limits of panel efficiency for frequencies below the critical frequency. That is, in the process of calculating panels, the frequency of the highest amplitude should be selected as the critical frequency, taking into account the amplitudes of frequencies below the critical frequency. This can be achieved by varying both the dimensions of the panel and by selecting a material with acceptable elastic moduli and surface density.

A common disadvantage of panels of all types and designs is their acceptable noise reduction performance when installed on flat surfaces. Therefore, it is advisable to use them for cladding the surfaces of large halls, specialised rooms, as well as rooms with high levels of infrasound and low-frequency sound. In addition, at medium and high frequencies, the efficiency of the panels may be unsatisfactory. It is known that the most effective materials for reducing noise levels are porous sound-absorbing materials. There is a problem of designing sound-absorbing and soundproofing coatings for a particular acoustic environment.

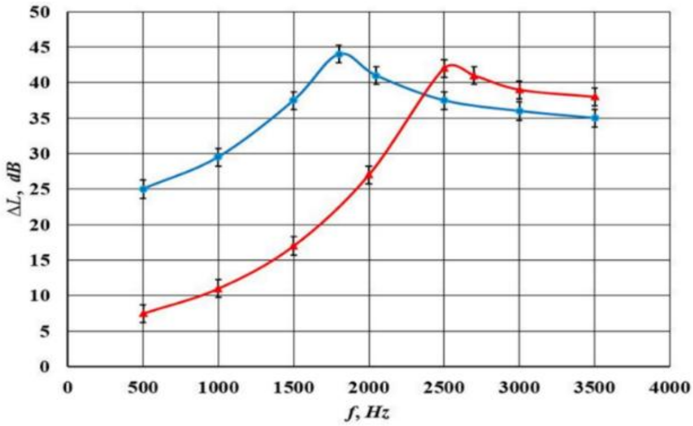

Fig. 3. Midrange sound reduction indices of protective panels; critical frequency of 1800 Hz; critical frequency of 2500 Hz

Therefore, it is advisable to develop an acceptable mathematical apparatus for designing protective coatings with the required sound absorption coefficients. The absorption coefficient can, in particular, be calculated using the Delany-Bazley model, the parameter of which is the specific resistance to air flow:

$$\sigma = \frac{\Delta P}{V \times d}, \qquad (10)$$

where: ΔP – pressure difference on both sides of the material, V – air flow velocity outside the sample and d – thickness of porous layer.

The sound absorption coefficient α is determined by the expression:

$$\alpha = 1 - |R|^2, \qquad (11)$$

where: R – reflection coefficient:

$$R = \frac{Z_s - \rho_0 c_0}{Z_s + \rho_0 c_0}, \qquad (12)$$

where: ρ_0 – air density, c_0 – is the speed of sound in the air, Z_s – surface impedance:

$$Z_s = -iZ_c \cot(k_c d). \qquad (13)$$

i – imaginary unit, Z_c – characteristic impedance, k_c – propagation constant and d – thickness of the porous layer;

$$Z_c = \rho_0 c_0 \left[1 + 0{,}0571 \left(\frac{\rho_0 f}{\sigma} \right)^{-0{,}754} - i0{,}087 \left(\frac{\rho_0 f}{\sigma} \right)^{-0{,}732} \right], \qquad (14)$$

$$k_c = \frac{2\pi f}{c_0} \left[1 + 0{,}0978 \left(\frac{\rho_0 f}{\sigma} \right)^{-0{,}7} - i0{,}189 \left(\frac{\rho_0 f}{\sigma} \right)^{-0{,}595} \right], \qquad (15)$$

where: f – frequency of the sound wave.

In order to obtain the ratios that are of practical importance for the design of protective surfaces of the required efficiency, it is necessary to obtain the design functions in real form. As a result of standard mathematical transformations, we obtain:

$$\alpha = \frac{4\rho_0 c_0 \left(\cosh(\varepsilon) - \cos(\theta)\right)\left(\beta \sinh(\varepsilon) - \gamma \sin(\theta)\right)}{\left(\beta \sin(\theta) + \gamma \sinh(\varepsilon)\right)^2 + \left(\beta \sinh(\varepsilon) - \gamma \sin(\theta) + \rho_0 c_0 (\cosh(\varepsilon) - \cos(\theta))\right)^2}, \quad (16)$$

where:

$$\beta = \rho_0 c_0 \left(1 + 0,0571\left(\frac{\rho_0 f}{\sigma}\right)^{-0,754}\right), \quad (17)$$

$$\gamma = 0,087\rho_0 c_0 \left(\frac{\rho_0 f}{\sigma}\right)^{-0,732}, \quad (18)$$

$$\varepsilon = 0,756\frac{\pi f d}{c_0}\left(\frac{\rho_0 f}{\sigma}\right)^{-0,595}, \quad (19)$$

$$\theta = \frac{4\pi f d}{c_0}\left(1 + 0,0978\left(\frac{\rho_0 f}{\sigma}\right)^{-0,700}\right). \quad (20)$$

These relationships, presented in real terms, make it possible to unambiguously determine the necessary parameters of the protective layer to obtain the desired sound wave energy absorption coefficient. Despite the large amount of input data, in real life the amount of data is limited by airflow resistance. In real conditions, the thickness of the porous layer is limited by the possibility of applying it to wall surfaces, especially those with complex relief, which is typical for historical and cultural buildings.

Based on the developed mathematical apparatus, a noise-absorbing material based on basalt fibres was designed and its noise absorption coefficients were determined. The study was carried out in an impedance tube. The thickness of the basalt fibres was 3–5μm. The density of the material was 300–310kg/m^3. The resistance to blowing was 6–8·10^4(Pa·s)/m^2. The samples were tested with thicknesses of 20 and 50mm. The test results are shown in figure 4.

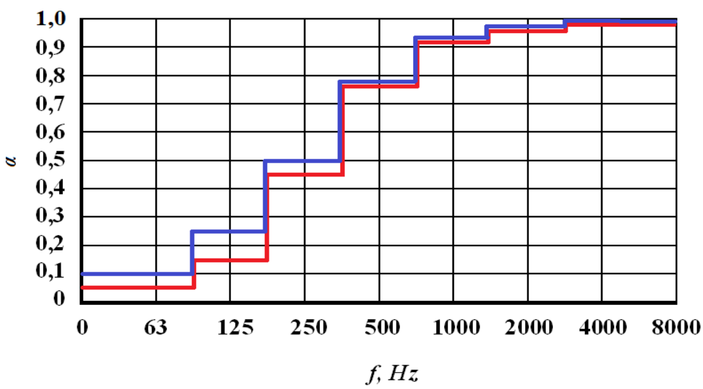

Fig. 4. Dependence of the noise absorption coefficients α on the sound wave frequency of the basalt material: thickness of the sample 20mm thickness of the sample 50mm

The results shown in figure 4 indicate that the noise absorption coefficients have an acceptable agreement with those calculated at frequencies above 250Hz. For frequencies of 125–250Hz, the discrepancy reaches 20–25%, which should be taken into account when designing protective materials and structures. In general, the proposed calculation apparatus can be used in engineering practice. Material design - determination of noise absorption coefficients in a wide frequency range requires large amounts of calculations with the definition of hyperbolic functions. Therefore, in order to speed up the design process and optimise the protective properties of the material by searching, it is advisable to automate this process. This is possible, for example, using the approach proposed in [14]. This approach made it possible to obtain adequate results on the propagation of electromagnetic fields and low-frequency noise [15]. It is also possible to rationalise the process of selecting the required parameters by their large number [16]. This would improve the accuracy of the calculations presented in this paper. Using more factors than the chosen model, for example, using the Johnson-Champoux-Allard Model (JCA). This model, in addition to airflow resistance, takes into account the tortuosity of air channels in porous material, the overall porosity of materials and thermal and viscous characteristic lengths.

In some cases, it is necessary to provide sound insulation against external and internal noise sources with different amplitude and frequency characteristics. Therefore, the developed design mechanism allows the use of two thin soundproofing materials with different properties.

The use of basalt fibre as a raw material for the manufacture of noise-absorbing materials opens up opportunities to expand their functionality. Preliminary studies show that composite paints for shielding electromagnetic radiation have good adhesion to the surface of basalt. Therefore, the addition of such paints to the raw material provides, in addition to noise-absorbing properties, shielding of electromagnetic radiation by the final material.

Conclusions

The reconstruction and restoration of historic buildings requires the use of materials that meet modern regulatory requirements for quantitative noise values in a wide frequency range inside the building. The main requirements for such materials are manufacturability, the ability to cover large areas of complex configuration without distorting the appearance of the interior and exterior of buildings.

All historical buildings were constructed according to individual designs. Therefore, all means of protection against acoustic impacts must be designed separately for each building. We have developed a mathematical tool for designing resonant-type protective structures that effectively shield infrasound and low-frequency sound. It has been shown theoretically and experimentally that applying perforations of certain sizes to resonant panels makes the protective panel broadband. In particular, at frequencies from 20 to 200Hz, noise reduction indices of 4–8dB are achieved, which can be considered satisfactory for this frequency range. At frequencies of 500–1000Hz, the noise reduction indices are 7–37dB when the panel is tuned to the resonant frequency of 2500Hz. When the panel is set to a resonant frequency of 1800Hz, noise reduction indices of 25–35dB are achieved. The resonant frequency is the frequency of maximum amplitude, which is determined on the basis of acoustic monitoring of the environment.

An easy-to-use mathematical tool for designing porous materials of small thickness for absorbing medium and high frequency noise has been developed. It was found that high absorption coefficients of 0.8 and higher are achieved at frequencies above 300Hz. At the same time, the increase in the absorption coefficient when the material thickness increases from 20mm to 50 mm for frequencies above 300Hz is insignificant. This makes it possible to minimize the thickness of noise protective materials for absorbing medium and high frequencies.

The possibility of expanding the functionality of porous noise-absorbing materials is substantiated. Coating basalt fibres with paint to shield electromagnetic radiation will provide simultaneous protection against noise and electromagnetic fields of man-made origin.

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