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METHODOLOGICAL FOUNDATIONS PROTECTIVE STRUCTURES DEVELOPMENT FOR SHIELDING ELECTROMAGNETIC AND ACOUSTIC FIELDS

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The conceptual principles of designing structures and materials are developed for simultaneous shielding of electromagnetic and acoustic fields of wide frequency ranges. Resonance-type shielding structures consist of two panels, one of which is perforated. A model to calculate main designing performances of the protective structures is presented depending on the predominant amplitudes and frequencies of the fields. Young's modulus, shear modulus, and Poisson's ratio are determined for metal-polymer materials, and the shielding efficiency of protective structures is given depending on composition of the materials in use.
Keywords: electromagnetic field, acoustic field, low-frequency sound, shielding, elastic modules.

1. Introduction

The electromagnetic and acoustic environment inside modern industrial and educational premises is determined by the influence of numerous sources of electromagnetic and noise radiation. Both factors are characterized by wide and diverse spectra with complex amplitude-frequency characteristics.At the same time, the existing measures and means of protection (for example, electromagnetic and acoustic screens) are mainly designed to reduce the levels of electromagnetic fields of single frequency range or band, acousticfields–for sound frequencies to which the human hearing organs are mostly sensitive, and the normative protection limits are the strictest (6–8 kHz).But the electromagnetic environment consists mainly of ultra-low frequency electromagnetic fields of 50 Hz. and fields of ultra-high and higher frequencies -

1.8-5.1 GHz –the frequencies of wireless communication of all types. The principles of creating protective screens for low and high frequencies are different. The same approach is applied to sound waves of low and high frequencies.Therefore, there are no sufficiently effective protective materials for shielding fields of wide frequency ranges. There are practically no materials that can be used for simultaneous shielding of electric and acoustic fields. Availableinformational sources do not provide mechanical properties of the existing protective materials creating the problems regarding their practical correct application. There are many production conditions require theurgent use of simultaneous shielding of both fields in single location. For example, these are medical and educational institutions, dispatch centers of the transport and energy industries, etc. This determines the need for research on the development of the principles of designing the shielding structures for protection against electromagnetic and acoustic fields of a wide frequency range.

2. An overview of literary sources

The greatest attention in the field of protection against physical fieldsinenvironment of anthropogenic origin is paid to the development of materials and structures for shielding electromagnetic fields. References [1, 2] show that traditional metal screens and screens made of amorphous alloys provide high reflection coefficients of the electromagnetic waves, which is undesirable condition in many practical cases.

In recent years, most of the research concerns the development of composite protective materials. They are mainly aimed at shielding electromagnetic fields of ultra-high and higher frequencies [3–5]. Due to their good shielding properties, these materials have a high cost, which is unacceptable for wide application.In addition, their elastic moduli were not investigated. Besides, such materials are practically ineffective in the low-frequency range of the electromagnetic spectrum. The study [6] shows the possibility of shielding the industrial frequency magnetic field and the ultra-high frequency electromagnetic field by use of nanoalloys. But the cost of such material (based on magnetic fluid) is very high.The results of shielding of high-frequency electromagnetic and low-frequency magnetic fields by regular metal structures are presented in studies [7, 8]. Due to them, under certain conditions, metal structures can be used with the provision of the necessary parameters.

Almost no attention is paid to the design of acoustic screens and materials for protection against noise. Part of the research concerns noise reduction with the use of plants [9]. But such protection is unacceptable for industrial enterprises, in particular for shielding of the equipment and premises. Existing noise-absorbing structures have arbitrary, unsubstantiated dimensions and surface perforations, although these parameters can be calculated depending on the acoustic environment.A calculation algorithm is given in [10] regarding the connection of the shielding coefficients of magnetic and electromagnetic fields with the sizes of the holes on the metal surface. It is advisable to determine the possibilities of using such surfaces for noise protection. The analysis of the results presented in [10] on the development of materials for simultaneous protection against electromagnetic and acoustic measurements shows that with acceptable indicators in most frequency ranges of both fields, the noise reduction indices in the low-frequency band are unsatisfactory. Therefore, creating shielding structures effective in wide frequency ranges is an urgent task.

The purpose of the work is to develop general principles and provide a calculation tool for designing the shielding structures for simultaneous protection from electromagnetic and acoustic fields of wide frequency ranges with the possibility of protective structures with the required characteristics.

3. Presentation of the main material

Analysis of approaches to the development of protective structures for shielding from physical fields and providing simultaneous protection from electromagnetic and acoustic impacts in wide frequency ranges showed that the most promising structures are the heterogeneous screens - perforated surfaces with holes of certain sizes and certain distances between them.Such designs may function for different fields according to different principles. Diffraction phenomena are critical for electromagnetic fields, resonance phenomena - for acoustic fields at low frequencies. High-frequency sound absorption is not a problem due to the possibility of using any absorbing porous material in the constructions.

Conductivity and magnetic properties of the material are critical parameters for shielding ultra-low frequency electromagnetic fields. For the shielding of sound waves, the effectiveness depends on the elastic modules and geometric characteristics of the structure. Therefore, the most acceptable is a ferromagnetic sheet material, for example, electrical steel.This material completely shields the electric component of the ultra-low frequency electromagnetic field, and the relative magnetic permeability of up to 200 provides shielding of the magnetic component. The presence of holes reduces the shielding coefficients, but they are necessary for shielding electromagnetic fields of ultrahigh and lower frequencies with small reflection coefficients.

The calculation of the efficiency of a flat screen for shielding stationary and quasi-stationary magnetic fields is based on the comparison of the values of the scalar magnetic potentials U_M in front of the protective surface and behind it. Proceeding from the fundamental relations $H = -gradU_M$ and $\nabla^2 U_M = 0$ and considering a single hole of radius r_0 at a distance r from the source, the solution of the equations with respect to U_{M1} and U_{M2} (potentials in front of and behind the surface) in polar coordinates gives the relation:

$$U_{M1} = H_0 r \sin\theta \sin\varphi + \sin\varphi \sum_{n=1,3}^{\infty} C_n r^{-n-1} P_n(\cos\theta),$$

$$r \geq r_0, \ 0 < \theta < \pi/2,$$

$$U_{M2} = -\sin\varphi \sum_{n=1,3}^{\infty} C_n r^{-n-1} P_n(\cos\theta),$$

$$r \geq r_0 . \pi/2 < \theta < \pi,$$

where $P_n(\cos\theta)$ − the Legendre polynomial; C_n − constants of integration (amplitude values of spatial harmonics of the field).

The solution of these equations can be combined into one for the outer domain. Under the condition of continuity of the tangential and normal components of the magnetic field intensity on the surface of the spherical zone of the hole ($r=r_0$) a system of equations is obtainedfor determining the constants of integration, and from them - a ratio for determining the potentials U_{M1} and U_{M2}.

The shielding coefficient of a flat screen with a round hole can be represented as:

$$K_e \approx \frac{U_{M1}}{U_{M2}} = -\left[\sin\theta + \left(\frac{2}{\pi}\right)\sum_{n=1,3}^{\infty}\frac{(-1)^{0,5(n-1)}}{n(n+2)}\left(\frac{r_0}{r}\right)^n P_n(\cos\theta)\right]\times$$

$$\times\left[\left(\frac{2}{\pi}\right)\sum_{n=1,3}^{\infty}\frac{(-1)^{0,5(n-1)}}{n(n+2)}\left(\frac{r_0}{r}\right)^{n+2} P_n(\cos\theta)\right]^{-1}.$$

The complexity of this expression is imaginary due to the fact that the shielding coefficient at a large distance from the hole ($r>>r_0$) is of practical interest, so all terms of the series except the first can be discardedup to the following case:

$$K_e \approx \left[1-(2/3\pi)(r_0/r)^3\right]\left[(2/3\pi)(r_0/r)^3\right]^{-1}.$$

The shielding factor is a function of the dimensions. Its value in advance is very high even for $r/r_0=10$. At the same time, it should be taken into account that for high-frequency fields the size of the holes should be small compared to the wavelength. Therefore, to evaluate the impact of holes on the shielding coefficients at ultra-low frequency magnetic fields, it is advisable to use simplified ratios.

For a single hole

$$K_{S1} = 0,25(S_e/S_o)^{1,5},$$

where S_e - the area of the screen, S_o - the area of the hole.

In the presence of n holes

$$K_S = \left(\sum_{i=1}^{n} 1/K_{e1}\right)^{-1}.$$

For high-frequency electromagnetic fields, it is advisable to determine the parameters of the holes based on the theory of waveguides. Despite the complexity of the mathematical apparatus, the final relations are very simple and acceptable for practical use. Any hole in a solid plane can be considered as a waveguide, the length of which is the thickness of the wall. All waveguides are characterized by a so-called cutoff frequency, i.e. the minimum frequency of the field propagated by the waveguide:

$$f_c = (1,75\cdot 10^8)/d \text{ (Hz)},$$

where d - hole diameter.

The screen thickness the can be chosen based on the needs of protection against high-frequency electromagnetic fields, and protection against ultra-low-frequency fields (at least for the fields of common sources) is practically independent of this parameter, but depends on the magnetic properties of the material. The screen thickness is actually the length of the waveguide.

The field energy loss does not depend entirely on the cutoff frequency. The field with frequencies lower than the cut-off frequency partially penetrates beyond the opening. In this case, the opening is a so-called extra-boundary waveguide. The energy absorption coefficient of such waveguides is determined by the ratio:

$$K_n = 32\, a/d \text{ (dB)},$$

where a - the thickness of the screen, d - the diameter of the hole.

The above holds true for a single round hole, provided the rest of the screen area is solid. For a large number of holes, it is necessary to enter correction factors that take into account the large number of holes. The correction factor K_1 is defined as:

$$K_1 = 10\lg(S_1 n) \text{ (dB)},$$

where S_1 - the area of one hole, n - the number of holes per unit area of the screen.

The product $S_1 n$ corresponds to the fraction in relative units of the area of the holes per unit area of the screen. This reflects its physical meaning, namely, a decrease in shielding efficiency with an increase in the total area of the holes, since $S_1 n$<1. That is, the total absorption coefficient K_c is determined by:

$$K_c = K_n - K_1 .$$

It should be noted that all of the above applies only to the far zone of the electromagnetic field.

The next step is to determine the predicted degree of protection of the structure against the influence of noise.

Calculations regarding the parameters of the external panel are aimed at determining its parameters, based on the frequency of low-frequency sound or infrasound of the predominant amplitude.

They are based on the Bekeshi panel calculation method. The maximum absorption is achieved at the resonant frequency, which is the frequency of the predominant amplitude:

$$f_r = \frac{K}{2l}\sqrt{\frac{F}{\rho b a}} \text{ (Hz)},$$

where K - the order of the resonance frequency (K=1, 2, 3...), F - the tension force of the panel, ρ - the density of the panel material, l, b, a - the length, width and thickness of the panel.

For K=1, the resonance frequency is minimal, and the panel is effective for all frequency's multiples of the minimum.

The internal, perforated panel is also calculated as resonant, but the presence of holes significantly reduces the *Q*-factor of the oscillating system (panel), i.e. makes it effective in a wide band of low-frequency oscillations:

$$f_r = \frac{\upsilon}{2\pi}\sqrt{\frac{S}{a_{ef}c^2h}} \text{ (Hz)},$$

where υ - the speed of sound in air, S - the area of the holes, a_{ef} - the effective thickness of the panel, $a_{ef} = a + 0,5\sqrt{\pi S}$, a - the thickness of the sheet, h - the distance of the panels from the mounting surface, c - the distance between the centers of the holes.

The space between two resonant panels is filled with a noise-absorbing material that is effective for the sound of medium and high frequencies. It is shown in [11] that granulated polystyrene has such necessary properties. And covered with the metal-containing substance it may reduce the level of electromagnetic fields.

As can be seen from the given ratios, the effectiveness of shielding panels depends on the geometric characteristics. This is especially critical for absorbing low-frequency sound. In many cases, large indices of low-frequency sound reduction (or total absorption) are not required. For this case, a composite metal-polymer facing material in the form of tiles was developed, designed for simultaneous shielding of electromagnetic and acoustic fields.

The material was made on the basis of latex (matrix) and finely dispersed magnetite (average size – 12 mm). Latex was produced in the form of pinolatex (with the addition of synthetic oleic acid – 1.1–1.7%). With a magnetite content of 45–60% by weight (11–12% by volume), the shielding coefficients of the industrial frequency magnetic field were 2.8–7.2, of the 2.45 GHz electromagnetic field – 5.8–8.4 sample thickness - 10 mm.

The results of noise reduction measurements are shown in Table 1.

Table 1

Reduction of noise levels in octave frequency bands

Octave frequency bands, Hz	Noise reduction indices, dB									
	31,5	63	125	250	500	1K	2K	4K	8K	16K
Pinolatex 10 mm	8	26	27	28	37	44	41	43	44	32

As can be seen from the obtained data, in the low-frequency range of the sound spectrum, the noise reduction is 8–28 dB, which is satisfactorily compared to known materials.

The main problem in the process of designing structures from composite materials is the lack of reference data on their physical properties. Therefore, tests were performed on the values of the elastic moduli of the developed composite.

It was established that Young modulus (E) is 10–12 GPa, shear modulus (G) is 4.0–4.2 GPa, Poisson ratios are 0.43–0.45, and average densities are 1770–1980 kg/m^3.

Comparing these data with the parameters of polymers used for noise protection in civil aviation, it can be concluded that the coefficients of the protective composite are practically not inferior to the standard ones, and the developed material is sufficiently technological.

But in the process of designing structures for simultaneous shielding of the electromagnetic and acoustic fields, the problem of optimizing the design parameters - panel thicknesses, diameters, and distances between holes - arises. It is obvious that the real optimization of the parameters is a separate difficult task.

Therefore, it is advisable to consider the possibility of certain rationalization of these parameters. It is expedient to do this based on the priority of protection against each factor and predominant frequencies or frequency bands of the electromagnetic field or acoustic noise. This approach is implemented according to a certain algorithm.

At the first stage, measurements of the spectra of electromagnetic and acoustic fields are used to detect the frequencies of the largest amplitudes. At the same time, applying a standard definition of sound levels in octave and third-octave frequency bands is not entirely informative. Accurate determination of dominant frequencies is possible using a microphone connected to the line input of a computer and processing the signals using software *Spectrogram* for acoustic spectrum analysis.

At the second stage, the levels of electromagnetic fields and noise are compared with the normative limits at specified frequencies or frequency bands. Based on the received data, a priority is chosen to reduce the levels of electromagnetic or acoustic fields of the specified parameters.

At the third stage, the required efficiency of protection against the main factor and the efficiency of protection against the influence of the secondary factor are calculated. If some parameter is unsatisfactory, a compromise option should be chosen.

The experience of calculations regarding the effectiveness of heterogeneous screens shows that this process is laborious and requires a lot of time. Therefore, a promising direction of work in this field is the creation of application software for automating this process. In the presence of such a package, there is no urgency to solve the problem of optimizing the parameters of shielding panels. Determining acceptable values is possible by the iterative method with fixation of parameters that are impossible or impractical to change.

4. Conclusions

1. In many cases, there is a need for simultaneous shielding of electromagnetic and acoustic fields. This cannot be realized with traditional coatings in full due to the difficulties of reducing low-frequency sound levels with sound-absorbing materials and the various requirements for protective

materials that shield ultra-low-frequency electromagnetic fields and ultra-high and higher frequency fields.

2. A two-layer protective structure is proposed and investigated, the outer panel of which is solid and the inner is perforated. All panels work on the resonance principle with respect to acoustic waves and based on the cut-off frequency of the high-frequency electromagnetic field.

3. An easy-to-use calculator is provided, which allows determining the main parameters of the panels, based on the amplitudes of the predominant sound frequencies and electromagnetic fields. Calculations regarding the necessary shielding coefficients are carried out on a priority basis, based on the predominant influence of one or the other physical factor and the predominant frequency or frequency band (octave or third-octave). The need to develop application software to simplify the process of designing protective structures is substantiated.

4. The elastic moduli of the developed composite material for simultaneous shielding of electromagnetic and acoustic fields (Young's modulus, shear modulus, Poisson's ratio) were measured. It was established that in terms of mechanical properties, the material is not inferior to standard polymers, and the presence of a shielding filler and structural inhomogeneities does not reduce the manufacturability of its use.

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МЕТОДОЛОГІЧНІ ЗАСАДИ РОЗРОБЛЕННЯ ЗАХИСНИХ КОНСТРУКЦІЙ ДЛЯ ЕКРАНУВАННЯ ЕЛЕКТРОМАГНІТНИХ ТА АКУСТИЧНИХ ПОЛІВ

У багатьох випадках потрібний одночасний захист від впливу електромагнітних та акустичних полів широких частотних діапазонів. Складність такоїзадачі полягає у неможливості суттєвого зниження рівнів низькочастотного звуку традиційними звукопоглинання матеріалами, а також різними вимогами до матеріалів, які екранують низькочастотні та високочастотні електромагнітні поля. Запропоновано розв'язання цієї задачі за рахунок створення двошарової конструкції, лицьова поверхня якої суцільна, а внутрішня перфорована. Лицьова панель може бути виконана з непровідного матеріалу. Вона є варіантом панелі Бекеші і призначена, в основному, для зниження рівня низькочастотного звуку певної частоти з високою амплітудою. Перфорація внутрішньої (металевої) панелі обирається, виходячи з необхідності забезпечення екранування електромагнітних та акустичних полів певних частот або смуг частот. Надано розрахунковий апарат з розрахунку необхідних параметрів панелей (лінійні розміри, товщина, діаметри отворів, їх кількість на одиницю площі поверхні). Проміжок між панелями доцільно заповнювати звукопоглинальним матеріалом, наприклад, гранульованим пінополістиролом. Він забезпечує поглинання звуку середніх та високих частот і робить конструкцію широкосмуговою. Застосування феромагнітного матеріалу внутрішньої панелі забезпечує захист від магнітної складової електромагнітного поля наднизької частоти (в основному – промислової). Перфорація панелі розраховується, виходячи з теорії хвилеводів електромагнітних хвиль високої частоти. Наведено результати випробувань ефективності облицювального металополімерного матеріалу у вигляді плиток. Ефективність матеріалу є задовільною для більшості виробничих та побутових умов. Визначення механічних властивостей матеріалу (модуля Юнга, модуля зсуву та коефіцієнта Пуассона) показали, що він не поступається відомим матеріалам навіть за великого вмісту екрануючої субстанції. Для раціоналізації проектування конструкції на основі натурних вимірів електромагнітного та акустичного спектрів обирається пріоритетний чинник та частоти (смуги частот). Показано, що розрахунки мають великі обсяги, а розв'язання задач оптимізації по двом чинникам не завжди можливе. Доцільне створення прикладного програмного забезпечення для спрощення процесу проєктування захисних конструкцій та раціоналізації параметрів панелей на принципах розумної достатності.

Ключові слова: електромагнітне поле, акустичне поле, низькочастотний звук, екранування, пружні модулі.

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METHODOLOGICAL FOUNDATIONS PROTECTIVE STRUCTURES DEVELOPMENT FOR SHIELDING ELECTROMAGNETIC AND ACOUSTIC FIELDS/

In many cases the simultaneous protection against electromagnetic and acoustic fields of wide frequency ranges is required. The complexity of such a task lies in the impossibility of significantly reducing low-frequency sound levels with traditional sound-absorbing materials, as well as the different requirements for materials that shield low-frequency and high-frequency electromagnetic fields. It is proposed to solve this problem by creating a two-layer structure, the front surface of which is solid, and the inner surface is perforated. The front panel can be made of non-conductive material. It is a variant of the Bekeshi panel and is mainly intended to reduce the level of low-frequency sound of a certain frequency with high amplitude. The perforation of the internal (metal) panel is chosen based on the need to provide shielding of electromagnetic and acoustic fields of certain frequencies or frequency bands. A calculator is provided for calculating the required panel parameters (linear dimensions, thickness, hole diameters, their number per unit of surface area). It is advisable to fill the space between the panels with a sound-absorbing material, for example, granulated polystyrene. It provides sound absorption of medium and high frequencies and makes the design broadband. The use of ferromagnetic material of the inner panel provides protection against the magnetic component of the ultra-low frequency electromagnetic field (mainly industrial). The perforation of the panel is calculated based on the waveguide theory of high-frequency electromagnetic waves. The results of tests of the effectiveness of facing metal-polymer material in the form of tiles are presented. The performance of the material is satisfactory for most industrial and domestic conditions. Determination of the mechanical properties of the material (Young's modulus, shear modulus and Poisson's ratio) showed that it is not inferior to known materials even with a large content of shielding substance. In order to rationalize the design of the structure, a priority factor and frequency (frequency band) is selected on the basis of live measurements of the electromagnetic and acoustic spectra. It is shown that the calculations have large volumes, and the solution of two-factor optimization problems is not always possible. Appropriate creation of application software to simplify the process of designing protective structures and rationalizing panel parameters based on the principles of reasonable sufficiency.

Keywords: electromagnetic field, acoustic field, low-frequency sound, shielding, elastic modules.

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Глива В.А., Запорожець О. І., Левченко Л.О., Бурдейна Н.Б., Назаренко В.І. **Методологічні засади розроблення захисних конструкцій для екранування електромагнітних та акустичних полів**// Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА. 2023. – Вип. 110. – С. 245-255. – Англ.
Розроблено концептуальні засади проектування конструкцій і матеріалів для одночасного екранування електромагнітних та акустичних полів широких частотних діапазонів. Конструкції резонансного типу складаються з двох панелей, одна з яких є перфорованою. Представлено математичний апарат для проектування захисних конструкцій у залежності від переважних амплітуд і частот. Для металополімерних матеріалів визначені модуль Юнга, модуль зсуву та коефіцієнт Пуассона, а також надано ефективності екранування полів у залежності від складу матеріалу.
Табл. 1. Бібліогр. 11 назв.

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Glyva V.A., Zaporozhets O.I., Levchenko L.O., Burdeina N.B., Nazarenko V.I. **Methodological Foundations Protective Structures Development for Shielding Electromagnetic and Acoustic Fields**// Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA. 2023. – Issue 110. – P. 245-255.
The conceptual principles of designing structures and materials are developed for simultaneous shielding of electromagnetic and acoustic fields of wide frequency ranges. Resonance-type shielding structures consist of two panels, one of which is perforated. A model to calculate main designing performances of the protective structures is presented depending on the predominant amplitudes and frequencies of the fields. Young's modulus, shear modulus, and Poisson's ratio are determined for metal-polymer materials, and the shielding efficiency of protective structures is given depending on composition of the materials in use.
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