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DEVELOPMENT OF A METHOD FOR OPTIMIZATION CALCULATION OF A GROUP OF SOUND-INSULATING PANELS FOR AIRBORN NOISE PROTECTION

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Розглядаються різні конструкції і методики розрахунку звукоізоляційних огорож приміщень від повітряного шуму. Дані методики дозволяють розраховувати одношарові, двошарові і тришарові огорожі. Одношарові огорожі можуть складатися з однорідних масивних і тонких матеріалів. Двошарові огорожі можуть складатися з двох тонких шарів різної товщини і повітряним проміжком. Тришарові огорожі можуть бути виконані з двох тонких шарів різної товщини і звукопоглинальним матеріалом в проміжку. Дані методики дозволяють розраховувати і оптимізувати окремі конструкції звукоізоляційних огороджень незалежно один від одного. Розглядається проблема одночасного проникнення шуму з одного джерела в кілька суміжних приміщень. При використанні розглянутих методик не досягається максимальний ефект. У зв'язку з цим запропонований метод оптимізаційного розрахунку групи звукоізоляційних огороджень, спрямований на досягнення найвигіднішого значення цільової функції.

Метод заснований на випадковому пошуку, в основу якого покладено випадковий розподіл типових конструкцій і заготовлених матеріалів по огорожах. Вибір найкращого результату здійснюється в результаті перевірки виконання обмежуючих умов.

Запропоновано наступні варіанти цільової функції: надлишкове шумове навантаження, сумарний індекс зниження шуму в приміщеннях, сумарна вартість звукоізоляційних огорож, кількість виготовлених огорож. Даються рекомендації по вибору цільової функції з урахуванням конкретних умов виробництва.

Результатом оптимізації є вибір конструкції огорожі для кожного приміщення і розподіл по ним наявних матеріалів. Розглядається постановка оптимізаційної задачі з різними варіантами цільової функції та обмежень. Наводиться опис алгоритму та статистичні дані, що свідчать про ефективність запропонованого методу оптимізації. Ефективність підтверджена зниженням вартості огорож при використанні даного методу в порівнянні з роздільним проектуванням огорож традиційними методами приблизно на 24 %

Ключові слова: шум, багатошарові огорожі, звукоізоляція, оптимізаційний розрахунок, алгоритм розрахунку, цільова функція

1. Introduction

Noise belongs to the most common harmful factors adversely affecting people's health and reducing labor productivity. According to the World Health Organization for the years 2017–2018, diseases associated with hearing impairment are the third largest and make 12.5 % [1].

Heightened noise often causes reduced productivity because of increased fatigue of employees. With increased noise due to the sound masking effect, recognizability of sound signals including danger signals is reduced. Because of this, the risk of accidents and occupational diseases grows dramatically. In real production conditions, there is often a problem of increased noise in several adjacent rooms produced by a single source. Existing methods and means of dealing with increased noise make it possible to calculate and optimize individual sound-insulating panels. This approach does not provide maximum reduction of noise effect on people in different rooms. Sound insulation materials and funds are not used with maximum benefit. This study relevance is explained by the need to reduce risks from influence of noise on people as well as the need for rational use of materials and financial resources.

2. Literature review and problem statement

Multilayer structures (sandwich panels) consisting of various materials are the most promising soundproofing means for today. Study [2] is devoted to the characteristic of acoustic insulation of composite sandwich panels consisting of a polyurethane core and laminated composite shells. More effective noise reduction per unit mass of material compared to common plasterboard panels was achieved. However, the study did not consider the possibility of achieving maximum sound insulation using existing materials and technologies. As a result, the maximum possible noise reduction effect was not attained. The characteristics of sound transmission loss in sandwich panels with a lattice core were studied and the results obtained were presented in [3]. It was shown that better sound loss characteristics compared to common sandwich panels were achieved in this structure even without optimization. Thus, the problem of optimizing the design of sandwich panels was not solved. Maximum noise reduction is unattainable having limited material choice and financial resources.

A series of papers are devoted to optimization of these structures. In [4], a multi-purpose optimization of a sandwich

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panel with a corrugated core was performed. Minimum weight and deflection was achieved but not minimization of noise and cost of the structure. A similar choice of a compromise solution was made in [5] between design and acoustic characteristics of a car body panel. In addition to the above disadvantage, the design features of car soundproofing hamper its use in building structures. The problem of worsening sound insulation of a sandwich panel with an increase in its rigidity was considered in [6]. However, the task of noise minimization was not solved there when attempting to comply with regulatory requirements and restrictions on the materials and costs. A similar approach was applied in [7] where the design of sandwich panels with a balance of acoustic and mechanical properties at a minimum weight was optimized. The problem of minimizing noise while observing sanitary norms for noise and economic limitations was not solved there as well.

Mechanical, electromagnetic and acoustic properties of sandwich structures with a hybrid honeycomb core were analyzed in [8]. Optimization of the honeycomb core shape improves sound insulation properties in certain frequency bands compared to conventional honeycomb panels. However, this leads to non-uniform mechanical characteristics which limit their use in real building structures.

Possibility of optimizing a sound-absorbing coating in a room by selecting materials and determining the appropriate area was considered in [9]. Minimum cost of applying coating in the room was achieved at a specified limitation of noise level and use of materials. However, the problem of optimizing the group of soundproof structures has not been solved. Mathematical solution of such a problem was presented in [10] where total imbalance of the group of rotors as sources of noise and vibration was minimized. However, the task of determining a set of soundproof panel elements for industrial premises was not solved.

A common drawback of all considered studies consists in the fact that they do not solve the problem of simultaneous optimization of sound insulation for a group of rooms with specified sound insulation characteristics. Such a task often arises in designing or group reconstruction of industrial premises performed by a single contractor. As a rule, different production processes are executed in different rooms. Therefore, noise characteristics and sanitary standards at workplaces in different rooms also differ from each other. The use of existing sandwich panels can ensure observance of sanitary standards but will not result in an optimal reduction of noise or cost. Practice shows that not only multi-layer but even single-layer paneling may be most effective in some cases. Therefore, it is advisable to conduct a study aimed at development of procedure for simultaneous optimization of a group of sound-proofing panels. This technique should enable not only calculation of dimensions and selection of materials but also decide on the basis of design for each panel element. In this case, the applied materials and types of design of various panels may differ from each other.

3. The aim and objectives of the study

The study objective was to optimize a group of sound-proofing panels by selecting optimal structures and optimal distribution of materials.

To achieve the objective, the following tasks were set:

– formulate an optimization problem of determining a group of sound-proofing panels with indication of source data, options of the objective function and recommendations for their use;

– develop a method and an algorithm of optimization calculation.

4. Statement of the optimization problem of calculating a group of sound-proofing panels

Optimization consists in achievement of the best result in terms of the selected quality criterion (objective function) under which limiting conditions are fulfilled. Let us agree that one panel shall be developed for one room. In general, to solve this problem, the following set of initial data was proposed:

– spectra of the required noise reduction in the premises (sound pressure levels in one-third octave frequency bands);

– an objective function depending on the chosen problem formulation;

– a list of restrictions;

– a list of available materials for panels [11];

– the area of partitions, their specific cost with an account of fasteners, thickness and volume density of materials.

The following options of the objective function were proposed:

– excessive noise load;

– total index of noise reduction in the premises;

– total cost of sound insulating panels;

– number of panels made.

The objective function choice is determined by the relevance of the optimization problem in each specific case.

Excessive noise load is a conventional quantity representing the total energy equivalent of excess noise in all rooms as an integral indicator of harmful effect on people. It is recommended as an objective function in designing or reconstruction of industrial buildings with a high class and degree of harmfulness of noise in the workplace [12]. This indicator is calculated from formula:

$$F_1 = \mathrm{ENL} = \sum_{j=1}^{m}\sum_{i=1}^{n} \Delta I_{ji} \cdot 10^{0.1A_i} \cdot t_j \to \min, \qquad (1)$$

where ENL is the excessive noise load, W·h/ m^2; Δ_{Iji} is the value of the excess sound intensity without correction «A», W/m^2; j is the number of the panel; m is the number of panels; i is the number of the one-third octave band; n is the number of one-third octave bands in which the sound pressure level exceeds the norm; A_i is correction of sound impact in accordance with the «A» characteristic [2], W/m^2; t_j is duration of the noise impact on people, h.

The total noise reduction index in rooms is the sum of corresponding R_{Wj} indices calculated for individual rooms [12]. It is recommended as an objective function for designing and reconstruction of external and internal panels in residential, public and general service buildings of industrial enterprises. Value of this indicator is calculated from formula:

$$F_2 = \sum_{j=1}^{m} R_{Wj} \to \max. \qquad (2)$$

The total cost of sound-proofing panels is a cost estimate that includes the cost of materials, fasteners and work. This objective function is recommended in conditions of financial shortage:

$$F_3 = Z = \sum_{j=1}^{m}(C_{1j}+C_{2j}+C_{3j})S_j \rightarrow \min, \qquad (3)$$

where C_{1j}, C_{2j}, C_{3j} is the unit cost of materials of the 1st, 2nd and 3rd layers taking into account fasteners and work, respectively, conv.un./m^2; S_j is the panel area, m^2.

The number of panels obtainable from available materials. This objective function is recommended in the conditions of shortage of insulation materials:

$$F_4 \rightarrow \max. \qquad (4)$$

The following is offered as limiting conditions:

– permissible sound pressure levels in one-third octave frequency bands, dB. If the total noise reduction index in rooms is used as *a* objective function, then the normalized airborne noise reduction index, dB, should be the limiting condition;

– maximum allowable total cost of sound-proofing panels Z_{MAX}, conv.un.;

– minimum allowable number of panels made.

Permissible sound pressure levels of 9 frequencies are estimated using this inequality:

$$L_{Pi} \le L_{Pi.NORM}, \qquad (5)$$

where L_{PI} and $L_{PI\ NORM}$ are the actual and normalized sound pressure levels in the one-third octave band, dB, respectively.

The airborne noise reduction index is estimated using this inequality:

$$R_{Wj} \ge R_{W.NORM}, \qquad (6)$$

where R_{Wj} and $R_{W.NORN}$ are the actual and normalized indices of airborne noise reduction in the room, dB, respectively.

The cost of a group of coatings is estimated by comparing with the maximum allowable quantity Q_{MAX}:

$$\sum_{j=1}^{m}(C_{1j}+C_{2j}+C_{3j})S_j \le Q_{MAX}, \text{ y. e.} \qquad (7)$$

Solution of the optimization problem results in a table (matrix) including:

– type of structure for each panel;

– distribution of sound-proofing materials according to numbers and layers of panels;

– value of the objective function, a decrease in sound pressure levels in one-third octave bands and the total cost of panels.

5. The method and algorithm for calculating a group of panels based on a random search

The problem relates to structural optimization. Given nonlinearity of the objective function and limitations, solution can be achieved by means of methods of non-linear discrete programming. It was proposed to solve this problem on the basis of a random search using the Monte-Carlo method [10, 13]. The algorithm diagram is shown in Fig. 1.

The method is based on a random distribution of standard structures and procured materials among panels with subsequent verification of fulfillment of limiting conditions and selection of the best result.

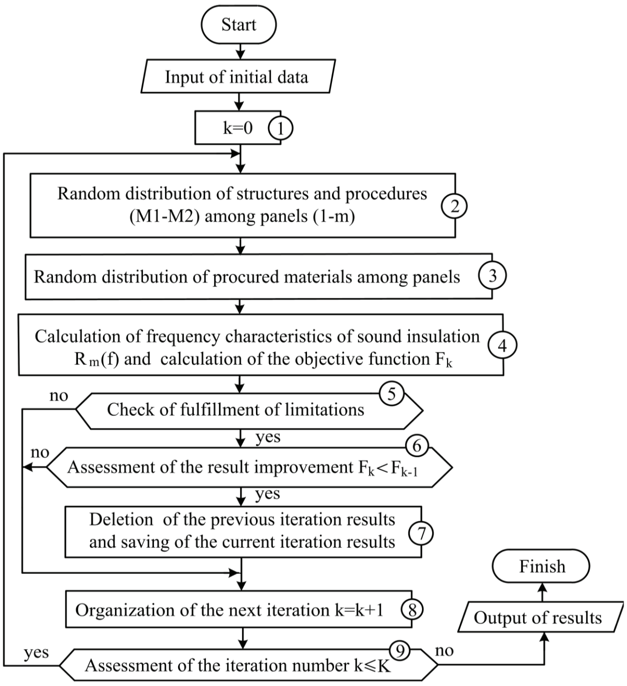


Fig. 1. The algorithm for calculating the group of panels based on a random search (Monte Carlo technic)

Block 1 starts the first iteration. Random distribution of structures among panels is performed in block 2. To this end, random values of the structure number and the corresponding calculation procedure (M1–M5) are generated. Next, a generated structure number is assigned to each panel (1–*m*).

Random distribution of the procured materials among panels is made in block 3 (Fig. 2). For clarity, numbers of materials are presented by broken lines. The material number is equal to the value at the break point. The number of panels and materials in this example is 5 and 10, respectively.

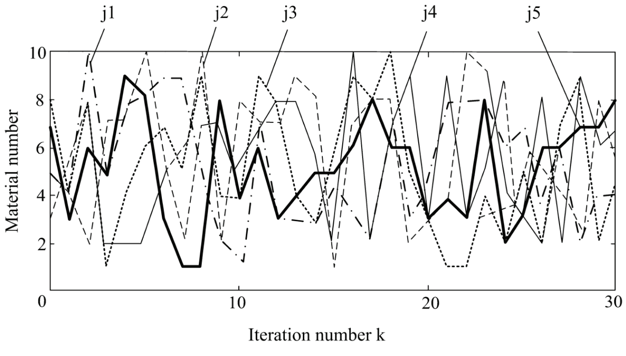


Fig. 2. Examples of graphs of random distribution of materials among panels (Mathcad [14]): *j*1–*j*5 are numbers of panels

Frequency characteristics $R_m(f)$ of sound insulation and the value of the objective function F are calculated in block 4 depending on the chosen option. An example of a graphical dependence of the value of the objective function *Q* on the iteration number *k* is shown in Fig. 3. For clarity, the graph is shown in the form of a broken line similar to Fig. 2. Values of the objective function correspond to the break points.

Fulfillment of limitations (5)–(7) is checked in block 5. If the answer is positive, the result of optimization of this iteration is evaluated in block 6 by comparing value of the objective function with a similar value of the previous iteration. If the answer is positive, result of the previous iteration is deleted in block 7. Block 8 organizes the next iteration. The number of iterations is estimated by block 9. When implementing this technique, the number of iterations *K* is given in the input data.

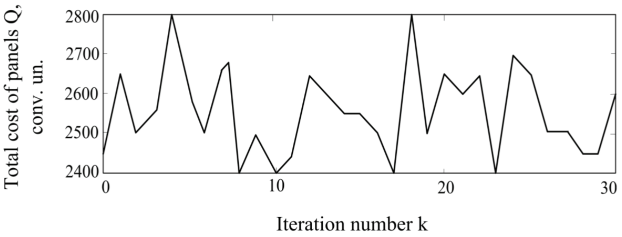


Fig. 3. Values of the objective function *Q* depending on the iteration number *k*

When calculating frequency characteristics of sound insulation of individual panels (block 4), it is proposed to use known procedure [12]. Procedure 1 (M1) is intended for calculation of sound insulation of acoustically homogeneous partitions (concrete, brickwork, plaster, etc.), Fig. 4. Depending on the surface density, coordinates of the B point are determined by empirical formulas. The corresponding frequency value is rounded to the geometric mean frequency of the octave band. The A point is obtained at a frequency of 100 Hz by drawing a horizontal line segment BA from the A point. The C point is obtained by drawing an inclined line segment BC from 7.5 dB/oct. up to the level of 60 dB. The D point is obtained at a frequency of 3150 Hz by drawing a horizontal line segment CD from the C point. The resulting broken line ABCD is the frequency characteristic of the sound-insulating ability taking into account the noise bypasses that are possible in real structures.

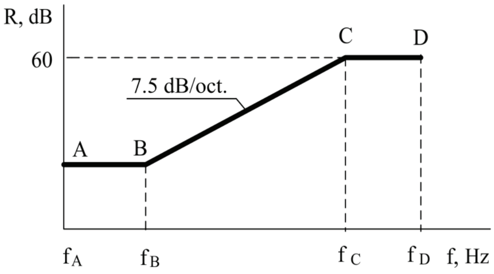


Fig. 4. Frequency characteristic of soundproofing of a uniform panel

The procedure 2 (M2) makes it possible to calculate sound insulation of single-layer thin structures made of sheet materials (metal, glass, asbestos-cement, plasterboards, fiber reinforced gypsum boards, wood-chip boards, wood fiberboard, etc.), Fig. 5.

The procedure 3 (M3) makes it possible to calculate structures of two thin sheets of the same thickness and the same material with air insulation between them, Fig. 6. Sheets can be glass, plasterboards, fiber reinforced gypsum boards, wood-chip boards, metal, etc. Using empirical data, an ABCD broken line is built and corrections are made. After corrections are added, the A1B1C1D1 and A1EFKLMNP broken lines are sequentially built. The last broken line is frequency characteristic of the airborne sound insulation by this enveloping structure.

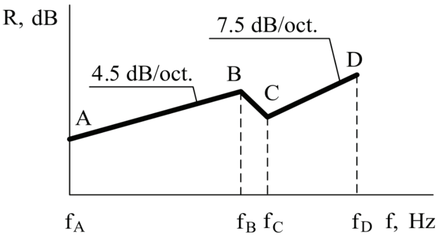


Fig. 5. Frequency characteristic of soundproofing of a uniform panel of a thin sheet material

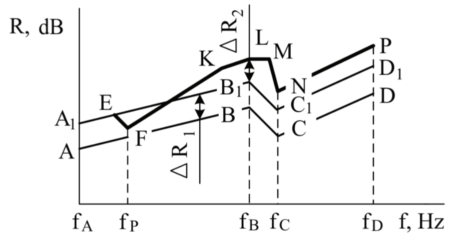


Fig. 6. Frequency characteristic of sound insulation with two identical sheets with an air gap between them

Procedure 4 (M4) is designed to calculate structures of two thin sheets of the same material, different thickness with air insulation between them, Fig. 7.

Procedure 5 (M5) provides calculation of a structure consisting of two thin sheets of different thickness and a sound-absorbing material between them, Fig. 8.

Thus, the proposed calculation method includes the well-known procedures developed for calculation of single panels. This has made it possible to simultaneously optimize a group of sound-proofing panels.

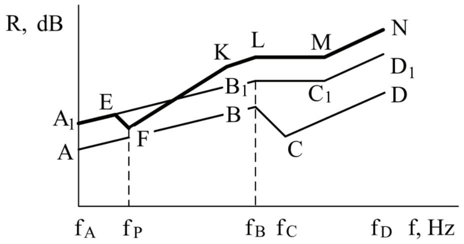


Fig. 7. Frequency characteristic of soundproofing with two thin sheets of different thickness with an air gap between them

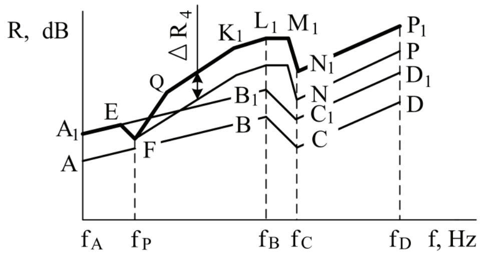


Fig. 8. Frequency characteristic of soundproofing with two thin sheets of different thickness with an air gap between them

6. Assessment of optimization results

As a result of the optimization calculation using the proposed method, various options of a 5-piece group of sound-proofing panels were obtained. Fig. 9 shows polygons of distribution of the total cost of a group of panels with a different number of iterations K. The number of intervals was calculated using the Sturgess formula [15].

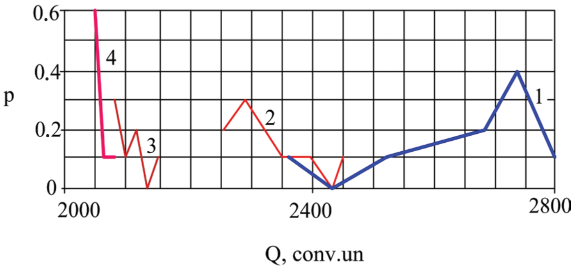


Fig. 9. Polygons of distribution of the total cost of a group of panels: at $K=10^2$ (1); at $K=10^3$ (2); at $K=10^4$ (3); $K=10^5$ (4) (Mathcad)

Mathematical expectation and variance [15] of the cost of a group of panels depending on the number of iterations are presented in Fig. 10, 11, respectively.

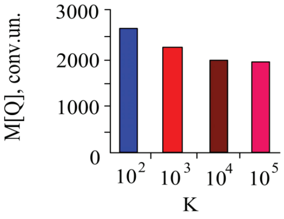


Fig. 10. Mathematical expectation of the cost of a group of single-layer panels

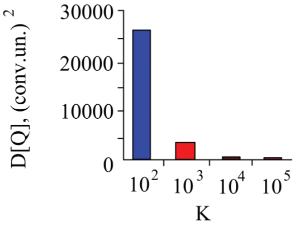


Fig. 11. Variance of the cost of a group of single-layer panels

Analysis of the obtained results indicates a steady improvement in optimization results with an increase in the number of iterations.

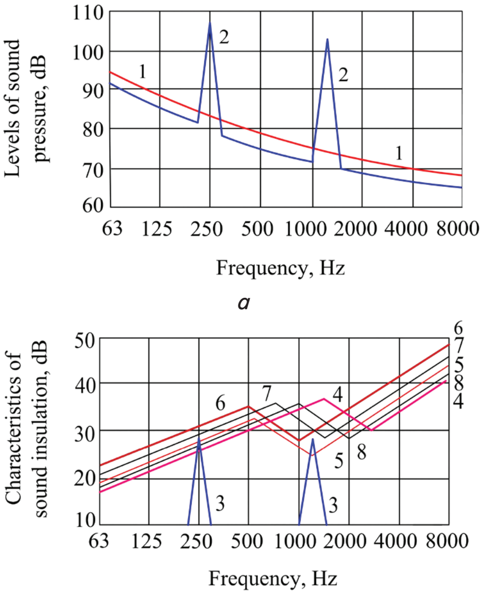
These characteristics clearly demonstrate the algorithm convergence at which an acceptable solution is achieved in a finite number of steps. The number of steps K is considered sufficient if improvement of the result does not exceed specified error ε [13]:

$$\left|F_K - F_{K+1}\right| \le \varepsilon, \quad (8)$$

where F_K and F_{K+1} are the minimum (most advantageous) values of the objective function obtained when performing K and $K+1$ iterations, respectively.

When the number of iterations was 10^5, cost of the group of panels reached 2,055 conv.un. A further increase in the number of iterations did not give the cost reduction exceeding the specified error ε conv.un. Therefore, the number of iterations 10^5 is sufficient for this case.

Fig. 12 shows examples of frequency characteristics of the acting noise and a single-layer sound insulation in an individual virtual room. Curve 1 in Fig. 12, *a* represents marginal noise spectrum (a plurality of permissible sound pressure levels). Curve 2 represents spectral characteristic of noise conditionally acting at a given point prior to the use of panels. This characteristic is considered to be specified (p. 4). Since the indoor noise is created by an external source, noise reduction depends only on the sound-proofing characteristics of the panel. Therefore, dimensions of the room and distance to the source are not taken into account.



a

b

Fig. 12. Frequency characteristics: noise acting with no panels (*a*); noise insulated using single-layer panels (*b*)

The following notation was used in Fig. 12: limitary spectrum No. 75 (1); acting noise (2); required noise reduction (3); soundproofing of a 12.5 mm thick plasterboard (4); soundproofing of a 22 mm thick wood-chip board (OSB) (5); soundproofing of a 16 mm thick asbestos-cement board (6); soundproofing of a 22 mm thick fiberboard (MDF) (7); soundproofing of a 6 mm thick silicate glass sheet (8).

As can be seen in Fig. 12, *a*, the sound pressure levels of noise exceed permissible sound pressure levels in octave bands with average geometric frequencies of 250 Hz and 1,250 Hz. As control examples, various options of simplified single-layer panels were calculated. Curves 4–8 in Fig. 12, *b* present examples of frequency characteristics of sound insulation of a separate room. The figure shows that the required sound insulation in the entire frequency range was provided by panels with materials 6 and 7. Material 7 had the lowest unit cost and belonged to a solution close to the global optimum. Solutions that used materials 4, 5 and 8 in this panel did not pass the test for condition (5) and were deleted.

7. Discussion of results obtained in the study of optimization results

Solutions based on the use of materials 6 and 7 as well as the corresponding spectral characteristics of sound insulation are explained by the action of an optimization algorithm based on the Monte-Carlo method of random search. In the course of calculations, a multitude of options were compiled using generation of random numbers and a choice was made of an option with the minimum cost of panels, 2,000 conv.un. (Fig. 9). According to the calculation, a panel made of material 7 (Fig. 12, *b*) corresponded to the specified room.

Despite the apparent similarity, the problems solved by this method significantly differ from the problems in the references considered. Features of the proposed method consist in the possibility of simultaneous optimization of a group of sound-proofing panels. Optimal solution is sought not only by taking into account the available materials but also various types of panel structures. For example, the number of solutions using this method can include not only multilayer but also single-layer structures. Individual multilayered structures (sandwich panels) were optimized in the considered references which greatly limits search for an optimal solution when designing a group of panels.

As a result of application of this method, a more effective result was achieved compared to the independent calculation of individual panels. To assess effectiveness, the values of mathematical expectation and variance of cost of panels were compared at the number of iterations 10^2 and 10^5 (Fig. 10, 11, respectively). As a rule, in the case of a separate structure using conventional procedure, materials were randomly distributed among panels. Mathematical cost expectation in this case is close to 2,650 conv.un. which corresponds to the minimum number of iterations, the is, 10^2. When using the proposed method with the number of iterations of 10^5, the expected cost value decreased to 2,010 conv. un. The effect was about 24 % of the original cost of panels. Also, algorithmic simplicity inherent in the Monte-Carlo method of random search is the advantage of the proposed method.

Low rate of convergence is disadvantage of this method. This disadvantage determines the limitations inherent in this method. The number of simultaneously designed structures and materials used is limited and amounts to units.

Further development of this method will include increase in the number of simultaneously designed structures and nomenclature of materials used. Obviously, that will require application of other mathematical methods with a greater rate of convergence. In this case, the problem formulation will not lose its meaning and may remain unchanged. It is also obvious that computer implementation will require professional programming experience. In addition, an experimental confirmation of effectiveness of the sound-proofing panel group will be required.

8. Conclusions

1. The optimization problem was formulated. It included composition of initial data, four options of the objective function and corresponding recommendations for their use in real production conditions. The composition of the source data is determined by the procedure of calculation of frequency characteristics and cost of sound-proofing panels. Choice of the objective function is determined by relevance of the optimization problem in specific production conditions. Formulation of this optimization problem can be used later in further development of this method.

2. Method and algorithm for optimization calculation of a group of sound-proofing barriers against airborne noise were elaborated. Structure and materials were selected for each panel in the course of calculation. The structure type was chosen from among five standard structures including single-layer, two-layer and three-layer panels. Optimization effectiveness was determined by the number of iterations of the computational process, the number of panels and the nomenclature of materials used. The obtained algorithm has convergence. At a small number of panels, materials used (no more than ten) and iterations (100,000), the method makes it possible to obtain a solution close to the global optimum.

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ASSESSMENT AND PREVENTION OF THE PROPAGATION OF CARBON MONOXIDE OVER A WORKING AREA AT ARC WELDING

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Проведено дослідження повітряного середовища у виробничих приміщеннях, де відбуваються зварювальні процеси, особливу увагу звернено на утворення монооксиду вуглецю (СО) в робочому середовищі в процесі ручного електродугового зварювання. Наведено класифікацію основних шкідливих речовин, які утворюютьсяпри зварюванні і споріднених процесах за характером негативного впливу на організм зварювальника. Побудовано математичну модель динаміки зміни концентрації чадного газу в повітрі робочої зони, виходячи зкількості шкідливої речовини (т) в повітрі приміщення у момент часу, інтенсивності виділення її у повітря та кратності повітрообміну. Дана математична модель включає розповсюдження чадного газу в повітрі, враховуючи повітрообмін між загальним об'ємом приміщення і локальними об'ємами робочої зони.

Досліджень щодо утворення монооксиду вуглецю у процесах електрозварювання обмаль, тому необхідність дослідження цього є пріоритетним.

Експериментальними дослідженнями було підтверджене, що концентрація чадного газу за межами локальних об'ємів пристроїв місцевої вентиляції, тобто в повітрі робочих зон, залишається постійною (до 0,01 мг/м^3) і не перевищує ГДК (20 мг/м^3). Відмова або відсутність загально-обмінної вентиляції, призводить до швидкого зростання концентрації газу монооксиду вуглецю (СО) в експоненційній залежності (від 150 до 200 мг/м^3 за 0,5–0,6 години) у малому замкнутому робочому просторі (1 м^3), а далі може розповсюджуватись по усьому приміщенню.

Але відмова загально-обмінної вентиляції, призводить до швидкого зростання концентрації газу монооксиду вуглецю (СО) в експоненційній залежності. Це свідчить про те, що загально-обмінна вентиляція має важливе значення, але вона не є гарантом забезпечення безпеки зварювальників та інших працівників щодо отруєння газом. Тому повинно бути передбачено застосування місцевої вентиляції та захист органів дихання усіх, хто є присутнім при проведенні процесів електрозварювання. Отримані математичні моделі дозволяють виконати оцінку ризиків праці зварювальників, врахувати емісії СО при розрахунках систем вентиляції у робочій зоні, скорегувати систему менеджменту ризиками та охороною праці

Ключові слова: електродугове зварювання, монооксид вуглецю, шкідливі емісії, робочий простір, отруєння газом

1. Introduction

Arc welding processes are widely used in many industries for making non-detachable joints when assembling separate elements of articles and structures [1]. Given the large number of enterprises where these types of processes are common, as well as a possibility to apply them at small workshops and everyday life, there is an issue related to improving their