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ANALYSIS OF THE STAGES OF CONDUCTING AN ACOUSTIC EXAMINATION OF CLOSED ROOMS

Relevance. *The work considers the process of conducting acoustic expertise of closed premises for various purposes, taking into account the features of sound content, creating technical and design recommendations for obtaining optimal properties of the sound field. It is shown that for different types of premises (concert halls, conference halls, press centers, office premises, meeting rooms, etc.), there are specific requirements for the necessary properties of the so und field, sequences of stages of expertise, and features of each stage. Therefore, the current task is to develop recommendations for conducting acoustic expertise depending on the type of premises in order to formalize and further automate this process.* ***The subject of the study*** *is methods for determining the acoustic characteristics of closed premises and their optimization.* ***The purpose*** *of the work is to develop recommendations for creating optimal acoustic properties depending on the purpose of the premises and the features of sound content by analyzing the features of conducting acoustic expertise for different types of premises and adapting the stages of expertise for each type of premises.* ***Research objectives:*** *to analyze the stages of conducting acoustic expertise and the tasks that are solved at each stage; consider mathematical methods for determining acoustic characteristics, their areas of application and limitations; analyze the features of conducting an acoustic examination for different types of premises and adapt the stages of conducting the examination depending on the purpose of the premises and the characteristics of the sound content.* ***Research methods.*** *The paper uses statistical theory methods to calculate the reverberation time. Geometric theory considers sound as a set of rays and is used to analyze the structure of reflections from surfaces and detect acoustic defects in rooms with complex shapes. Wave theory is used to analyze the natural modes (resonances) of the premises.* ***The following results*** *were obtained. The stages of conducting an acoustic examination, the characteristics of the sound field that are investigated at each stage, mathematical methods for determining acoustic characteristics, and recommendations for their optimization were considered. The features of conducting each stage depending on the type of premises were noted.* ***Conclusions.*** *The analysis of the features of performing an acoustic examination for different types of premises will allow formalizing this process, reducing the subjective component and increasing the reliability of the results. The results obtained indicate the prospects for further research in the direction of further formalization and construction of a computer decision support system for conducting acoustic expertise.*

Keywords: *acoustic expertise; stages; sound content; acoustic properties; optimization; technical and design recommendations.*

1. Introduction

Statement of the problem

The task of creating optimal acoustic conditions in a room as a whole, depending on its purpose, involves implementing recommendations aimed at creating and optimizing the sound field in the room.

The acoustic properties of a room are determined by the following factors: the volume and shape of the room; the number and presence of furniture; the size, shape, and construction of the enclosing surfaces; the materials used to finish the surfaces of the room and their distribution on the surfaces.

All of the above acoustic properties are interrelated with objective and subjective criteria for assessing room acoustics, such as: loudness-liveliness; spaciousness; intelligibility and clarity; loudness; warmth; absence of echo.

Thus, the tasks of acoustic expertise can be divided into stages:

1) verification of existing architectural and construction solutions for the interior surfaces of the room (geometry, finishing materials);

2) development of recommendations for increasing the diffusivity of the sound field and ensuring the optimal structure of the reverberation process (stage of creating technical specifications for the development of enclosing surface structures);

3) modeling of room acoustics with recommended finishing materials and enclosing surfaces recommended in the technical specifications;

4) measurement of the objective characteristics of the sound field synthesized after the implementation of the recommended measures to ensure optimal acoustic conditions.

The sequence and scope of the above stages may vary depending on the purpose of the room and the

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characteristics of the sound content: rooms in which the characteristics of the sound field formation are taken into account; special-purpose rooms; rooms with special requirements for the objective and/or subjective characteristics of the sound field; rooms with special requirements for the type and quality of content transmission.

2. Analysis of recent studies and publications

The acoustic examination process is carried out in accordance with regulatory documents [1–3]. The peculiarities of sound content perception by listeners are analyzed in [4–6]. In [6–8], the general theory of sound field formation, boundary conditions, and methods for calculating objective sound field indicators, such as reverberation time (RT60), content clarity indicators (C7, C50, C80), and speech content intelligibility indicators (%ALcons, STI, RASTI) [9, 10]. An analysis of the features of each stage of acoustic expertise is given in [11–13]. At the same time, the specifics of conducting the stages of expertise for the following types of premises are noted: concert halls, conference rooms, press centers, and meeting rooms. Despite the sufficient volume of regulatory documents and publications on the subject of acoustic expertise, today there is an influence of subjective factors, experience, and qualifications of experts on the results of acoustic expertise, and there is no single formalized approach that takes into account the specific requirements for sound field parameters for each type of room when conducting acoustic expertise. Thus, the urgent task is to develop recommendations for conducting acoustic expertise depending on the type of premises in order to formalize all stages of acoustic expertise of premises and further automate this process.

The scientific novelty of the work is the improvement of the acoustic examination process by adapting the sequence and content of each stage to the functional purpose of the premises, the nature of the content, and the design and architectural constraints, which will formalize this process, reduce the subjective component, and increase the reliability of the results.

3. Purpose and objectives of the study

The purpose of the study is to develop recommendations for creating optimal acoustic properties depending on the purpose of the room and the characteristics of the sound content by analyzing the features of conducting acoustic expertise for different types of rooms and adapting the stages of conducting expertise for each type of room. To achieve this goal, the following tasks must be solved:

– analyze the stages of acoustic expertise and the tasks that are solved at each stage;

– to consider the mathematical methods used to determine acoustic characteristics, their range of definition, and limitations;

– to analyze the features of acoustic expertise for different types of rooms and adapt the stages of expertise depending on the purpose of the room and the characteristics of the sound content.

4. Analysis of the acoustic examination stages

4.1. First stage

The first stage of acoustic expertise involves checking architectural and construction solutions for the configuration of enclosing surfaces of walls and ceilings in rooms using geometric theory of sound propagation in rooms [14–16]. The main purpose of the check is to identify surfaces that focus sound rays, which can lead to a significant reduction in the unevenness (diffuseness) of the sound field, as well as to check for the presence of parallel surfaces that create conditions for the formation of stable interference patterns (standing waves) for a number of resonant frequencies and, as a result, echoes, reverberation, and excessive spaciousness. There will be multiple reflections of sound.

The first stage of acoustic expertise also includes determining the frequency dependence of the reverberation time T60 when treating enclosing surfaces with materials proposed by architects.

4.2. Second stage

At this stage, measures are developed to correct the acoustic deficiencies of the room that were identified in the first stage. The following are developed: recommendations on the geometry of enclosing surfaces to increase the diffusivity of the sound field; recommendations on the selection of sound-reflecting and sound-absorbing materials for finishing surfaces in the room in order to optimize the frequency dependence of the reverberation time and the structures of the reverberation process [11–13].

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4.3. Third stage

Provides the opportunity to: verify the design solutions for the geometry of wall and ceiling panels proposed in the first and second stages of acoustic expertise; analyze the frequency dependence of reverberation time using the interior finishing materials proposed at the second stage; analyze the structures of reverberation processes at control points [11–13].

4.4. Fourth stage

The results of the final stage of acoustic testing are the characteristics of the sound field measured at control points in the room after completion of all construction and finishing works. To perform measurements, a hardware and software complex based on Easera 1.1.3 is usually used [11, 13, 15].

5. Mathematical methods for determining acoustic characteristics

When conducting acoustic testing of enclosed spaces, three fundamental mathematical theories are used, each of which is applied depending on the frequency range and size of the space.

5.1. Statistical theory (Sabine's theory)

It is used to analyze diffuse sound fields where sound is considered to be evenly distributed. Based on statistical theory, the reverberation time T60 is calculated – the main indicator of the acoustic quality of a room. The statistical formulas of Sabine and Eiring are typically used for this purpose.

1. Sabine's formula is used for "boomy" rooms with low absorption (when the average sound absorption coefficient $\alpha_{cp} < 0.2$

$$T_{60} = \frac{0{,}161V}{A} = \frac{0{,}161V}{\sum_i S_i \alpha_i}, \qquad (1)$$

where V – room volume (m^3); A – equivalent absorption area (m^2 or "Sabines"), which is equal to the sum of the products of surface areas and their absorption coefficients.

2. The Eiring formula is considered more accurate for rooms with high absorption levels (studios, cinemas), as it takes into account the attenuation of sound with each reflection.

$$T_{60} = \frac{0{,}161V}{-S\ln\left(1-\alpha_{cp}\right)}, \qquad (2)$$

where S – total area of interior surfaces of the premises (m^2); α_{cp} – average sound absorption coefficient, calculated as $\alpha_{cp} = A/S$; Ln – natural logarithm.

Sabine's formula (1) gives an error in rooms with a lot of soft materials, while Eiring's formula (2) better models the situation when sound is almost completely absorbed (at $\alpha = 1$, the reverberation time according to Eiring is zero, which is physically correct).

For very large rooms (with a volume of more than 1000–2000 m^3), the term $4\mu V$ is added to the formula, where μ is the sound attenuation coefficient in the air itself.

5.2. Geometric (radial) theory

It considers sound as a set of rays that propagate in a straight line inside a room and are reflected from surfaces according to the laws of geometric optics. The mathematical basis of geometric theory is the laws of reflection (the angle of incidence equals the angle of reflection) and the methods of mirror sources or ray tracing. Geometric theory is used to analyze the structure of early reflections and detect acoustic defects (echoes, sound focusing) in complex rooms.

5.3. Wave theory

It is based on solving differential equations of the sound field and takes into account the wave nature of sound (diffraction, interference). The mathematical basis is the wave equation (Helmholtz equation) and the analysis of the room's eigenmodes (resonances).

The propagation of sound in space is described by the classical **wave equation** for sound pressure

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} - 0, \qquad (3)$$

where ∇^2 – Laplace operator; p – sound pressure; c – speed of sound; t – time.

For stationary processes (when the source emits a pure tone with frequency f), the wave equation (3) transforms into Helmholtz's equation:

$$\nabla^2 p + k^2 p = 0,$$

where $k = 2\pi f/c$ – wave number.

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Solving this equation, taking into account the boundary conditions (room walls), allows us to find the natural frequencies at which resonance occurs.

Analysis of the premises' own modes

Natural modes are standing waves that arise between parallel or angular surfaces. For a rectangular room, natural frequencies are calculated using Rayleigh's formula:

$$f_{n_x,n_y,n_z} = \frac{c}{2}\sqrt{\left(n_x/L\right)^2 + \left(n_y/W\right)^2 + \left(n_z/H\right)^2}, \qquad (4)$$

where L, W, H – length, width, and height of the room; n_x, n_y, n_z – integers (0, 1, 2...), which indicate the order of the mode.

Classification of waves (modes)

1) **Axial:** the wave is reflected between two parallel walls (for example, $n_x = 1$, $n_y = 0$, $n_z = 0$). They carry the most energy and have the greatest impact on the "color" of the sound.

2) **Tangential:** formed after reflections from two pairs of parallel surfaces (for example, $n_x = 1$, $n_y = 1$, $n_z = 0$). The energy of such waves is approximately 2 times less than that of axial waves.

3) **Oblique:** formed after reflections from three pairs of parallel surfaces. They have the lowest energy (at least 4 times less than axial ones).

Wave theory is used to analyze the acoustic field in small rooms at low frequencies, where standing waves occur (room "hum").

It should be noted that the application of wave analysis is critical only up to a certain frequency, above which the modes become so dense that the field can be considered diffuse. This limit is called the *Schreder frequency* (f_s):

$$f_s = 2000\sqrt{T_{60}/V}\ .$$

At frequencies below f_s, wave theory must be used. Bass traps and geometry correction are needed to combat "booming".

At frequencies above f_s, statistical theory (Sabine and Eiring formulas) is used.

In addition, in modern expertise of rooms with complex configurations, methods of random process theory for noise diagnostics and mathematical modeling are actively being introduced, in particular using the finite element method (FEM), which allows you to visualize nodes and pressure points at each point in the room.

6. Features of conducting acoustic expertise for different types of premises

A) ***Concert halls.*** To conduct the first stage of the examination in the auditorium, software modules [4, 11, 12] are used to construct ray patterns on plans and sections of the auditorium, which makes it possible to check the geometry of wall structures on all floors, the geometry of the ceiling, balcony railings, etc.

The main reason for using different wall panel geometry options is to try to eliminate the parallelism of surfaces, which will reduce the likelihood of standing waves forming and eliminate excessively high amplitude reflections in the reverberation process.

B) ***Conference rooms.*** For small premises (meeting rooms, conference rooms, meeting halls, press centers), the first stage of acoustic expertise is conducted differently than for auditoriums [14]. A distinctive feature of these premises is that they are usually rectangular in shape and all surfaces are parallel to each other. In such conditions, the reflection of waves from parallel surfaces and the formation of standing waves leads to the appearance of echoes and an increase in reverberation time [4, 15]. In addition, with small room sizes, it is practically impossible to change the geometry of the surfaces in order to reduce the number of parallel surfaces. With large glass surfaces, there is a problem of developing effective measures to reduce reflection amplitudes due to the low sound absorption coefficient of such surfaces.

Since the rooms are small in volume, it is not always possible to change the geometry of the enclosing surfaces for a number of reasons:

– the surfaces are made of glass and cannot be changed in shape;

– since the volume of the room is small, the dimensions of the enclosing surfaces are significantly smaller than the wavelength, especially in the low-frequency range.

These features of the rooms impose corresponding restrictions on the correction of sound field parameters, namely, we can only make corrections in a limited frequency range where the wavelength is commensurate with the size of the room. However, this limitation is not critical because the main sound material in the rooms

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under study is speech content, for which the frequency range corresponds to the size of the room.

To optimize the frequency dependence of the reverberation time, finishing materials that work in the speech frequency range are used [7, 16]. In the presence of glass wall surfaces, it is practically impossible to change the acoustic properties by replacing the material on them, and then one of the options for increasing the sound absorption of glass surfaces is the use of curtains. Curtains are made from special "acoustic" fabrics with different sound absorption properties, or from fabrics used to make stage costumes.

Another option used to correct the acoustic properties of the rooms in question is the use of additional suspended ceiling structures such as "frameless sound-absorbing ceiling islands" and vertical sound-absorbing "Baffle" panels.

7. Adaptation of the acoustic examination process to the functional purpose of the premises

Based on the above, it should be noted that acoustic expertise is implemented as a sequence of stages that is sensitive to the functional purpose of the room, the nature of the content, and the structural and architectural limitations, which significantly affects both the content of individual stages and the possibility of changing the sequence of stages in order to adapt the acoustic expertise process to a specific type of room.

Thus, it is possible to generalize such adaptation for the four most representative types of rooms:

1. For auditoriums, acoustic expertise is structured as a sequence of stages [11, 12]: first, the existing architectural and construction solutions are checked (to find surfaces that focus sound and impair diffusivity), while at the same time the frequency dependence of the reverberation time and its compliance with the optimal values are assessed. Next, if any inconsistencies are found, recommendations are formulated – requirements for the geometry of the enclosing surfaces are formulated and reflective and absorbent materials are selected or placed to obtain the desired reverberation structure. After that, acoustic modeling of the hall is performed taking into account the proposed solutions, and as a final step, measurements of the objective characteristics of the sound field can be carried out after the completion of construction and finishing works.

2. For small-volume rooms with predominantly speech content [12, 14], the general sequence of the examination stages does not change compared to concert halls, but the content of the key steps changes. At the first stage, instead of focusing on the geometric verification of enclosing surfaces, the main action is to analyze the structures of the reverberation process at listening points in order to identify deficiencies in the formation of the sound field (for example, insufficient field diffusivity). The second stage focuses on recommendations for improving sound absorption and eliminating multiple reflections between parallel surfaces (in particular through local changes in geometry, suspended structures, curtains, etc.), while the subsequent stages are performed without fundamental changes.

3. For rooms such as press centers, the methodology is described as typically consisting of three stages, but depending on the initial conditions, the "role and place" of the stages may vary, in particular due to the purpose of the room (high requirements for speech clarity/intelligibility) or the inability to significantly change the geometry due to small dimensions. In the examples given [12, 17], the list of tasks was shifted towards the tools of the second and third stages (recommendations/modeling), because it was during the modeling and analysis of reverberation structures that "problematic" parallel surfaces were identified. Because of this, it is noted that the shortcomings, which in the usual sequence would have been found in the first stage, were actually found later, and as a result, the first stage became the final one, while no stage of the examination was excluded.

4. For special rooms [13, 17], where there are special requirements for the quality of speech content and/or a sound amplification system is already in use, a new sequence is proposed: to start with the "final" fourth stage as the first. This approach involves first determining the conditions for research, taking into account the specifics of the premises and content, selecting the hardware and software complex and informative evaluation criteria, and then processing and analyzing the results. The advantage is that it is possible to identify "problematic" areas of sound field formation and possible ways of correction early on, even before the stage of checking architectural and construction solutions and developing technical specifications for enclosing structures.

Thus, the specific sequence and content of the stages of acoustic expertise are determined by a specialist

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individually for each object, taking into account the functional purpose of the room, the type of dominant content, geometric and structural limitations, as well as the possibilities for making changes to planning and finishing solutions. In fact, the choice of methods, priorities, and "control points" is largely based on the professional experience of the expert and accumulated practical experience, which provides flexibility but at the same time increases subjectivity and complicates the reproducibility of results by different performers. In this context, it is advisable to formalize and, if possible, automate the process of forming a sequence of stages and corresponding assessment procedures based on the type of premises, initial conditions, and target quality criteria. Automation (in the form of a decision support system) would allow standardizing the approach to selecting stages, reducing the influence of the human factor, shortening the time required to prepare the assessment, and increasing the comparability of results, while retaining the possibility of expert adjustment in non-standard cases.

In view of the above, a promising direction for further development is to expand the functionality of such a system through intelligent mechanisms for working with data and queries: in particular, the introduction of semantic search in the knowledge/measurement base and typical cases, the individualization of results (for example, by adapting recommendations to a specific type of room and nature of use based on accumulated behavioral data), as well as the use of external NLP modules to improve the accuracy of processing complex text queries and generating more relevant recommendations. This will not only automate the selection of the sequence of examination stages, but also increase the accuracy, convenience, and practical value of the results for the end user.

9. Conclusions and prospects for further research

The paper showed that the main goal of acoustic expertise in enclosed spaces is to create optimal acoustic properties of the sound field. At the same time, acoustic expertise is implemented as a sequence of stages that is sensitive to the functional purpose of the room, design constraints, and the characteristics of the sound content, which has a significant impact on both the content of individual stages and the possibility of changing the sequence of stages. The specific sequence and content of the stages of acoustic expertise for each object are usually determined by a specialist based on their professional experience.

To achieve the set goal, the study analyzed the four stages of acoustic expertise. The tasks to be solved at each stage were formulated, in particular:

– at the first stage, architectural and construction solutions are checked in order to identify surfaces that focus sound rays, which can lead to a significant reduction in the diffusivity of the sound field, as well as checking for the presence of parallel surfaces that create conditions for the formation of standing waves;

– at the second stage, measures are developed to correct the acoustic deficiencies of the room (recommendations on the selection of sound-reflecting and sound-absorbing materials);

– at the third stage, the design solutions proposed at the first and second stages are checked by means of acoustic modeling;

– the results of the fourth stage are the characteristics of the sound field measured at control points in the room.

Three fundamental mathematical theories were considered, namely: statistical theory, geometric (ray) theory, and wave theory, which are used to determine acoustic characteristics, their scope of application, and limitations.

The features of conducting acoustic expertise for different types of rooms were analyzed, and recommendations were formed on adapting the sequence and content of the stages of conducting the expertise depending on the purpose of the room and the characteristics of the sound content. Thus, the goal of the work has been achieved, since the conduct of acoustic expertise for different types of premises has been scientifically and technically substantiated and systematized, and recommendations have been formulated for adapting its stages depending on the purpose of the premises and the characteristics of the sound content, which creates the basis for further formalization and automation of the process.

Prospects for further research include formalization and further automation of the process of forming the sequence and content of stages depending on the type of room. The implementation of a decision support system for acoustic expertise will allow standardizing the approach to the selection of stages, reducing the influence of the human factor, and increasing the effectiveness of expertise, while maintaining the possibility of expert correction in non-standard cases.

Conflict of interest

The authors declare that they have no conflict of interest with respect to this research, including financial, personal, authorship, or other conflicts that could influence the research and its results presented in this article.

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technology in the creation of this work.

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АНАЛІЗ ЕТАПІВ АКУСТИЧНОЇ ЕКСПЕРТИЗИ ЗАМКНЕНИХ ПРИМІЩЕНЬ

Актуальність. *У роботі розглянуто акустичну експертизу замкнених приміщень різного призначення з огляду на особливості звукового контенту, сформовано технічні та проєктні рекомендації для отримання оптимальних властивостей звукового поля. Продемонстровано, що для різних типів приміщень (концертні зали, конференц-зали, прес-центри, офіси, переговорні кімнати тощо) існують специфічні вимоги щодо необхідних властивостей звукового поля, послідовностей етапів експертизи та особливостей проведення кожного етапу. Тому актуальним завданням є розроблення рекомендацій щодо акустичної експертизи залежно від типу приміщення з метою формалізації та подальшої автоматизації цього процесу.* ***Предметом дослідження*** *є методи визначення акустичних властивостей замкнутих приміщень та їх оптимізація.* ***Мета роботи*** *полягає в розробленні рекомендацій щодо створення оптимальних акустичних властивостей з огляду на призначення приміщення та специфіку звукового контенту за допомогою аналізу особливостей акустичної експертизи для різних типів приміщень і на адаптацію етапів експертизи для кожного типу приміщень.* ***Завдання дослідження:*** *проаналізувати етапи акустичної експертизи та завдання, які розв'язуються на кожному етапі; розглянути математичні методи визначення акустичних властивостей, сфери їх застосування й обмеження; визначити особливості акустичної експертизи для різних типів приміщень й адаптувати етап експертизи залежно від призначення приміщення й особливостей звукового контенту.* ***Методи дослідження.*** *У роботі застосовано методи статистичної теорії для розрахунку часу реверберації. Геометрична теорія розглядає звук як сукупність променів і застосовується для аналізу структури відбиттів від поверхонь і виявлення акустичних дефектів у складних за формою приміщеннях. Хвильову теорію впроваджено для аналізу власних мод (резонансів) приміщення.* ***Досягнуті результати****. Розглянуто етапи акустичної експертизи, властивості звукового поля, які досліджено на кожному етапі, математичні методи визначення акустичних властивостей і рекомендації щодо їх оптимізації. Наголошено на особливостях кожного етапу з огляду на тип приміщення.* ***Висновки****. Аналіз акустичної експертизи для різних типів приміщень дасть змогу формалізувати цей процес, зменшити суб'єктивний складник і підвищити достовірність результатів. Досягнуті результати свідчать про перспективність подальших досліджень у напрямі формалізації та побудови комп'ютерної системи підтримки прийняття рішень для проведення акустичної експертизи.*

Ключові слова: *акустична експертиза; етапи; звуковий контент; акустичні властивості; оптимізація; технічні та проєктні рекомендації.*

Бібліографічні описи / Bibliographic descriptions

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