DOI 10.34185/1562-9945-5-160-2025-02
UDC 004.043

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ANALYSIS OF SCIENTIFIC AND PRACTICAL ACHIEVEMENTS IN THE SPHERE OF REVERBERATION EFFECTS GENERATION

Anotation. The study addresses the problem of creating realistic reverberation sound effects in computer games. The primary features of existing reverberation generation methods are outlined, including the complexity of manual sound parameter adjustments, the static nature of models, and limited adaptability to the geometry of the game environment. It was determined that the problem of creating realistic reverberation effects for computer games is achievable only when using modern approaches that reduce manual tuning and increase the adaptability of sound parameters. Based on the analysis, it was determined that there are significant obstacles that reduce the realism of acoustic accompaniment using available methods.
Keywords: reverberation, acoustic characteristics, procedural generation, machine learning, computer games.

Statement of the problem. Interactive media, particularly computer games, are becoming integral to modern digital culture. Every year, the gaming industry demonstrates rapid growth in terms of the number of users and the complexity and realism of the products presented. One of the key elements of the success of modern games is the creation of a deep immersion of the user in the virtual environment, which is achieved through the complex integration of visual, audio, and interactive components.

Sound in computer games performs several important functions: it not only enhances the emotional impact on the player but also serves as a tool for communication with the game world, providing essential clues about events and actions of characters. One of the most important components of the audio system is the effects of reverberation - the phenomenon of multiple reflections of sound waves from surrounding objects. Reverberation creates a sense of volume and depth in the space in which the player is located and makes the sound environment more realistic and immersive.

In most modern games, the reverb effect is implemented using static algorithms based on predefined sound settings or templates. This approach, although it allows you to achieve high-quality sound, has a number of significant limitations. In particular, static reverb effects cannot adequately adapt to changes in the game space in real-time, which can reduce the realism of interaction with dynamic game environments. In large open worlds or complex architectural structures, this becomes especially noticeable when the player moves between different rooms or open spaces, where the acoustic properties of the environment change.

In this regard, there is a need to develop new approaches to generating sound effects that would allow for automatic and dynamic change of reverberation characteristics in accordance with the parameters of the environment.

History of the development of approaches to creating reverberation effects. Reverberation as an acoustic phenomenon has attracted the attention of scientists and engineers since long before the advent of digital technologies. Initially, reverberation was studied in the context of architectural acoustics for the design of concert halls, theaters, and churches. It affects how sound reflects off walls, ceilings, floors, and other surfaces and how this echo is perceived by the human ear. Important moments in the history of the development of approaches to reverberation are the emergence of both theoretical research and technological innovations that led to its integration into the digital audio industry.

Early studies of reverberation. The first systematic studies of reverberation in the framework of architectural acoustics were carried out as early as the 19th century. The pioneer in this field was the American physicist Wallace Clement Sabine [1], who in 1898 first formulated the basic principles of reverberation in architectural spaces. Sabine discovered the connection between the volume of the room, its surface, and how quickly the sound decays in the room after the source is turned off. His research became the basis for developing many architectural norms and approaches to the acoustic design of spaces. In the 20th century, with the advent of sound systems for cinemas, reverberation began to be actively used to improve sound perception in films and music. During this period, engineers began to experiment with electromechanical methods of reproducing reverberation, using large rooms or special reverberation chambers to provide natural echo for audio recordings [2].

The beginning of the digital era: algorithmic reverberation methods. With the advent of digital computers and audio technology in the 1960s and 1970s, there was a shift from physical models to digital ones. The first important step in this field was the development of digital algorithms for reverberation simulation. One of the first significant algorithms was proposed by M.R. Schroeder in 1961 [3]. Schroeder developed a digital reverberator based on a combination of finite impulse response (FIR) and infinite impulse response (IIR) filters, which allowed the creation of the first synthetic reverberation models suitable for use in audio systems.

Schroeder's algorithm was designed to create artificial reverberation using simple digital circuits that mimicked the process of sound decay in a room. This approach became the basis for the development of many future reverberators used in music and film. One of the key advantages of Schroeder's algorithms was that they required relatively few computational resources, which allowed for real-time reverberation on the computing devices available at the time.

Physically based models. Researchers have since developed more accurate, physically based models of reverberation. A significant advance in this direction has been using ray tracing and numerical methods to simulate the propagation of sound waves in environments with different acoustic properties. This approach has been particularly useful for modeling complex acoustic environments, such as theaters or open-air venues [4]. Some of the most influen-

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

tial works in this field include the work of Allen and Berkeley [5], who proposed the "mirror source" acoustic model method for calculating sound reflections in enclosed spaces. This method became the basis for further developments in the field of convolution reverberation, which allowed the use of real impulse responses of rooms to create the most realistic effects [6].

Algorithmic reverberation and its role in the industry. From the late 1980s to the present, digital reverb algorithms have become the standard in the audio industry. An important step was the emergence of software and hardware reverb solutions, such as the Lexicon and Eventide reverbs, which allowed musicians and sound engineers to create high-quality effects on studio equipment. Reverberators such as the Lexicon 480L, which entered the market in 1986, pioneered the application of digital reverb in practice. Using advanced Schroeder algorithms and other techniques, these devices allowed the creation of detailed and multi-layered reverb effects that are still used in the music industry today. These algorithms were especially useful for processing vocals, and instruments, and creating sound effects in film.

Procedural reverberation and dynamic algorithms in games. The recent development of computer games and interactive media has prompted researchers to search for new, more dynamic approaches to generating reverberation effects that could adapt to changes in the environment in real-time. In the 2000s, researchers such as Tsingos et al. (2007) proposed new dynamic reverberation methods that used ray tracing algorithms and voxel-based methods to accurately model sound reflections in complex environments.

Another important advance in procedural reverberation generation has been the use of path tracing methods, which allow for real-time simulation of sound reflections in interaction with the geometry of the environment. For example, [7] showed how voxel models can be used to simulate sound propagation in complex rooms, taking into account multiple reflections and attenuation.

Modern systems such as AudioKinetic Wwise and FMOD actively use these methods to provide realistic reverberation in games. However, the problems of computational resources and adaptation to real-time changes remain relevant, which encourages further development of procedural approaches.

Classical reverberation methods. Classical reverberation methods used before the advent of modern algorithms can be divided into several main categories, including mechanical, electronic, and digital approaches [8]. These methods have played an important role in creating realistic sound reproductions in music, film, and other audiovisual media. However, despite their importance, classical methods have their limitations, which has led to the need to develop new approaches.

Mechanical Reverb. Plate Reverb. One of the first methods of artificial reverberation to be widely used in studio recording was the plate reverberator. This method originated in the 1950s and involved the use of a thin metal plate on which transducers were placed. The plate was driven by an audio signal, creating complex vibrations that simulated the effect of reverberation. The signal was recorded by a microphone located at the other end of the plate.

Advantages:

– Plate reverberators provided rich, warm sound effects that were particularly valued in the music industry for vocals and instruments.

– Their design allowed for adjustable reverberation time, making them flexible for a variety of applications.

Disadvantages:

– High cost and bulkiness: such systems took up a lot of space in the studio and required special care.

– Unrealistic: Plate reverberation did not fully reproduce natural acoustic spaces, as its sound was too flat and did not contain enough high-frequency detail characteristic of real rooms.

Spring Reverb. Another classic mechanical method was the spring reverberator, often used in guitar amplifiers and portable sound systems. The sound signal was transmitted through a spring that vibrated, creating a reverberation effect.

Advantages:

– Compactness: Compared to plate reverberators, spring reverberators were significantly smaller and cheaper to manufacture.

– Relatively affordable for use on stage and in the studio.

Disadvantages:

– Poor sound quality: spring reverbs gave the reverb a characteristic "ringing" sound that didn't always sound natural.

– Limited control over reverberation parameters: Compared to other methods, spring reverbs had less controllable parameters, which limited their flexibility.

Electronic Reverb. With the development of electronics in the 1960s, external electronic reverberators such as the Lexicon 224 pioneered the field of artificial reverberation. These devices used digital processors to create a variety of reverberation effects, simulating the echoes of sound waves in different rooms.

Advantages:

– The ability to precisely adjust reverb parameters such as delay time, echo density, and brightness.

– Compact compared to mechanical systems.

– Rich functionality: electronic reverberators offered the ability to create a wide range of reverb effects.

Disadvantages:

– High cost of equipment in the early stages of development.

– Technological limitations: Early electronic reverbs had limited sound quality, especially compared to modern algorithms.

Digital Reverb. Algorithmic Reverb. In the 1970s and 1980s, digital reverberation became dominant due to the development of algorithms such as the Schroeder algorithm. These algorithms are based on digital signal processing, using mathematical models to simulate the behavior of sound in enclosed spaces. The main types of algorithms included convolution-based methods and infinite impulse response filters (IIR) [9].

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

Advantages:

– Flexibility: Digital algorithms allowed any type of room, from small rooms to large cathedrals, to be simulated by changing parameters using software.

– Real-time implementation: Digital processors allowed reverberation to be applied without significant delay, which was important for live performances and interactive applications such as computer games.

– Ability to integrate with other effects: Reverb algorithms could be easily combined with other digital effects, allowing the creation of multi-layered soundscapes.

Disadvantages:

– Early sound quality: Early digital reverbs did not always reproduce the natural behavior of sound. Their algorithms sometimes generated unrealistic or overly "metallic" echoes.

– High computational complexity: While modern processors are capable of handling complex algorithms, early versions required a lot of computational resources, which limited their use in real-time or on low-cost hardware.

Convolution Reverb. With the advent of more powerful computing systems, the convolutional reverberation method emerged, which allowed the use of real impulse responses to simulate the reverberation characteristics of specific rooms. This method consists of superimposing the recorded impulse response of the room onto the audio signal, which allows for a very accurate reproduction of the sound of a specific room.

Advantages:

– High realism: Convolutional reverberation allows for extremely accurate and natural results.

– Flexibility in room selection: Users can record impulse responses in any real space and use them to create the desired reverb effect.

Disadvantages:

– High computational complexity: Convolutional reverberation requires significant computational resources, especially for large impulse responses.

– Limited dynamics: Compared to algorithmic methods, convolutional reverberation is less flexible in adapting to real-time changes, making it less suitable for interactive applications such as computer games.

Classical reverberation methods, despite their importance, had a number of limitations that necessitated their improvement or replacement with new technologies.

Procedural generation of reverberation effects: modern scientific developments. Procedural generation of reverberation effects has become an important research area in the field of sound processing with the advent of modern algorithms and increasing demands for sound quality and realism in interactive environments such as computer games, virtual reality (VR), and augmented reality (AR) [10]. Compared to classical methods with limited capabilities in reproducing realistic spaces, procedural generation offers more flexible and adaptive approaches that allow for the dynamic generation of reverberation effects in real-time.

Algorithmic approaches and physically based models. One of the key directions in procedural reverberation generation is the development of algorithmic approaches based on physical models of acoustic spaces. Current scientific developments in this area focus on simulating sound waves' complex interactions with spatial boundaries, such as walls, floors, and ceilings, using accurate mathematical models [11].

Ray Tracing. One of the most common methods for modeling acoustic spaces is the ray tracing method [12]. This approach allows you to track the paths of sound waves as they reflect from different surfaces in a room. In computer games and VR environments, this method can be used to create realistic reverberation effects that change depending on the location of the object or the user.

Advantages:

– Realism: The method allows for accurate reproduction of the behavior of sound waves in complex spaces, especially in large architectural structures such as cathedrals, concert halls, or tunnels.

– Dynamics: Ray tracing can be applied in real-time, allowing the reverberation to adapt to changes in the scene, such as the movement of objects or changes in the configuration of the room.

Disadvantages:

– High computational cost: This method requires significant computational resources to track the trajectories of numerous sound beams accurately. Although modern computing systems are capable of handling this task, optimization of the algorithms is required for interactive applications.

Diffusion-based Models. Another popular method is diffusion-based models, which simulate reverberation in enclosed spaces with complex, uneven surfaces. These models simulate the scattering of sound waves after multiple reflections, allowing for more realistic effects for sound scenes [13].

Advantages:

– Ability to model complex environments, including rooms with soft or uneven surfaces.

– Ability to precisely control sound propagation and energy dissipation in a room.

Disadvantages:

– Difficulty in real-time implementation due to computational costs.

Procedural approaches to generating sound environments. Current research also aims to develop procedural methods that allow for the automatic generation of reverberation parameters based on room geometry. Such methods are particularly relevant for interactive environments where space structure can change in real-time (for example, in computer games).

Voxel-based Sound Propagation is an innovative approach to the procedural generation of reverberation effects, where space is divided into voxels (three-dimensional pixels), each of which is responsible for a particular part of the space. Sound waves are modeled as propagat-

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

ing through these voxels, which allows for the creation of detailed and realistic sound environments that adapt to changes in space.

Advantages:

– Ability to realistically simulate sound environments with various obstacles and objects.

– Adaptation to dynamic changes in space in real-time, making this approach ideal for computer games and VR.

Disadvantages:

– High computational resource requirements for accurate simulation of large spaces.

– The need for accurate voxel mesh definition for efficient simulation.

Modern scientific achievements. Today, the development of the procedural generation of reverberation effects is intensive and multifaceted. Many companies and research institutes focus on combining physical models, algorithmic approaches, and machine learning to create realistic, interactive, and high-quality reverberation effects [14].

Machine learning and neural networks. Recently, the scientific community has been working on the application of neural networks to simulate reverberation effects. Such models are able to learn from large data sets and generate reverberation that corresponds to real acoustic conditions. One direction is the use of convolutional neural networks to process impulse responses and create realistic reverberation.

Real-time impulse reverberation. While convolutional reverberation has long been used to create realistic acoustic environments, new research is focusing on optimizing it for real-time use. The introduction of optimization techniques allows impulse reverberation to be used even in interactive applications with high frame rates.

Despite significant progress in the development of procedural generation of reverberation effects, current approaches have a number of challenges that require further research. For example, the main problem remains in optimizing computational processes to implement high-quality reverberation in real-time. Other challenges include the need to adapt models to specific environments and usage scenarios, such as computer games with high performance and graphics requirements. Machine learning and hybrid approaches may become key tools to overcome these limitations in the future.

Comparison of global and domestic achievements in the field of audio technologies. Audio technologies, particularly reverberation effects, occupy an essential place in the modern entertainment industry, and developments in this area are carried out globally and domestically. Comparison of achievements allows us to assess the place of domestic innovations in the global context and determine their potential for further development [15].

Western companies and scientific institutes are actively developing innovative technologies for the simulation of reverberation and sound environments. In particular, corporations such as Waves Audio, iZotope, and Avid are leaders in creating professional audio tools for the music industry, cinema, and computer games. The main areas of their research are the development of algorithms to improve the realism of sound effects and the integration of machine learning to improve the quality of sound simulation [16].

One of the most significant world achievements is the development of convolution reverb, which allows you to create virtual acoustic environments based on the impulse characteristics of real rooms. This technology has become an integral part of audio production in various industries due to its ability to convey spatial sound effects realistically. In addition, in the field of interactive applications, such as virtual reality (VR) and augmented reality (AR), procedural acoustic modeling methods are actively used, allowing you to adapt reverberation effects to dynamic changes in the scene.

Realistic reverberation technologies for games are also being actively developed around the world. Companies such as Epic Games and Unity Technologies [17] are integrating advanced audio solutions, such as ray tracing techniques for acoustic environments, into their game engines, allowing for effects that are as close to real-world conditions as possible.

In Ukraine, the development of audio technologies, especially in reverberation, also has its achievements, although the domestic industry is smaller in scale compared to world leaders. However, several domestic research centers and universities are actively working on new approaches to sound processing. For example, the institutes of Taras Shevchenko National University of Kyiv and the National Technical University of Ukraine "Kyiv Polytechnic Institute" are researching methods of sound synthesis and processing for interactive environments and multimedia systems. It is especially worth noting the contribution of Ukrainian developers in the field of audio technologies for music applications. For example, the Ukrainian company Warm Audio, which is engaged in creating high-quality analog audio devices, has received international recognition. Although domestic companies mainly focus on hardware, there are also innovative attempts to create software solutions, in particular in the gaming industry, where Ukrainian studios often work on integrating audio technologies into modern game engines.

The global audio industry is characterized by a greater diversity of research and innovation due to access to greater financial resources and an advanced technical base. Companies in Europe, the USA, and Japan can invest in the development of algorithms and use high-performance computing systems to simulate sound effects in real-time. At the same time, domestic developments have potential, especially in integrating audio processing with low computational costs, which is relevant for small game studios and startups.

However, Ukraine still has to overcome a number of challenges to reach the world level. These include insufficient research funding, limited opportunities for implementing complex algorithms in the industry, and the lack of wide access to modern hardware for simulating reverberation effects.

Analysis of similar solutions on the market. The market for audio processing, particularly reverberation effects, is actively developing and offers a variety of software and hardware solutions for professionals in the music industry, film, computer games, and other areas where a realistic sound stage is a key component. Analysis of existing products on the market allows us to identify the advantages and disadvantages of modern technologies, determine their competitiveness and opportunities for improvement [18].

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

Software solutions. Among the software for creating and processing reverberation, several key products can be distinguished that occupy leading positions in the market.

1) Waves Audio – Abbey Road Reverb Plates

This plugin emulates the classic reverb plates used in the legendary Abbey Road studios. The plugin allows users to adjust reverb parameters, creating warm and deep effects for vocals and instrumental recordings.

Advantages:

– Realistic reproduction of vintage sound, ideal for the music industry.

– Numerous settings allow you to precisely select reverb parameters for different genres of music.

Disadvantages:

– Limited use in interactive environments such as games or VR due to the specificity of reverberation effects.

2) iZotope – Neoverb

Neoverb from iZotope is one of the most innovative solutions on the market, using artificial intelligence to automatically adjust reverb parameters based on audio content. This tool allows you to quickly obtain high-quality reverb effects, focusing on the characteristics of the input sound.

Advantages:

– Use of artificial intelligence to optimize parameters, which greatly simplifies the sound processing process.

– High-quality reverberation with minimal settings, which saves time.

Disadvantages:

– High license cost for small studios or individual users.

3) Valhalla DSP – ValhallaRoom

ValhallaRoom is one of the most popular reverb plugins due to its ease of use and efficiency. It allows you to create reverb that can be customized for different types of rooms - from small studios to large concert halls.

Advantages:

– High performance with low system resource requirements.

– Extensive customization options and affordable prices make it popular among indie developers and small studios.

Disadvantages:

– Lack of advanced capabilities such as artificial intelligence or realistic modeling of complex spaces, which limits use in high-budget projects.

Hardware solutions. In addition to software tools, there are also hardware solutions on the market that allow you to implement reverb effects.

1) Lexicon PCM92

Lexicon is a legendary manufacturer of hardware reverbs, providing exceptional sound quality used in the music and film industries. The PCM92 is one of the leading solutions for

creating realistic reverb effects thanks to advanced algorithms and high-quality sound processing.

Advantages:

– High sound quality and the ability to adjust reverberation for large acoustic spaces.

– Reliability and stability of operation, which is important for large studios and concert venues.

Disadvantages:

– High cost makes this device inaccessible to individual users or small studios.

2) Bricasti M7

Another well-known hardware reverb is the Bricasti M7. It is used in many leading studios to create high-quality reverb effects, including in the film industry and for music recording.

Advantages:

– Advanced sound processing technology with the ability to simulate various types of reverberation.

– High accuracy and realism of reverb effects.

Disadvantages:

– Like the Lexicon PCM92, the device is expensive and more suitable for large studios than for individual use.

The global market offers a wide range of solutions for creating reverb effects, from software products aimed at various audio industries to professional hardware. Software plugins such as ValhallaRoom are affordable and offer a sufficient level of flexibility for small projects, while more advanced solutions from iZotope or Lexicon provide the highest quality but require a significant financial investment.

There is also interest in creating software solutions for reverberation in the Ukrainian market, but these products are often focused on budget options or narrowly specialized tasks, such as music production, with less attention to interactive environments, such as game engines.

Conclusions. Despite significant progress in the development of audio technologies and the creation of reverberation effects, there are a number of unresolved problems that require further research and improvement. They are concerned with both optimizing technologies for interactive environments and improving sound quality under conditions of limited computing resources [19].

1) Computational complexity of reverberation algorithms

One of the main problems remains the high computational complexity of current reverberation algorithms, especially when simulating realistic acoustic environments in real-time. Procedural methods such as ray tracing for acoustic effects or convolutional reverberation require significant CPU and memory resources, which is problematic for interactive applications such as computer games or virtual reality (VR).

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

Research area: further improvement of procedural algorithms for reverberation, in particular by implementing machine learning methods to reduce computational requirements and improve real-time efficiency.

2) Reverb quality in dynamic environments

Another essential problem is to provide realistic reverberation in dynamic environments, where the acoustics change depending on the position of objects, changes in the room, or the movement of sound sources. Although modern reverberation plugins allow for accurate simulation of reverberation for static rooms, the technology still needs improvement for dynamic scenarios such as virtual environments or games.

Research area: development of adaptive reverberation methods that automatically adjust to changes in the acoustic environment in real-time, taking into account the movement of objects and changes in spatial parameters.

3) Integration with game engines and VR environments

Although many software solutions for reverberation exist in the music and film industries, integrating these technologies with game engines such as Unity or Unreal Engine is still challenging. Creating realistic reverberation in games requires accurate sound modeling and optimization to work on a wide range of devices, including mobile platforms.

Research area: Research on optimized reverberation algorithms for integration into game engines, with a particular focus on efficiency for mobile platforms and systems with limited resources.

4) Reverb for immersive technologies

With the development of immersive technologies such as augmented reality (AR) and virtual reality (VR), there is a need for even more realistic reproduction of acoustic effects that change according to the user's or objects' movement in the virtual environment. Traditional reverberation algorithms do not always provide the necessary level of realism for such scenarios [20].

Research area: development of new reverberation methods for AR and VR that will take into account the position and movement of the user in the virtual space to create a full immersion effect.

5) Reverberation effect on sound perception

Reverberation is an essential factor in the perception of soundstage and spatial sensation, but its impact on the audiopsychological perception of listeners has not yet been thoroughly studied. Different types of reverberation can affect the perception of space, time, and sound timbre in various ways, especially in interactive media.

Research area: conducting experimental studies on the impact of different types of reverberation on the psychoacoustic perception of the sound environment and integrating the results into the creation of new algorithms.

6) Acoustic ecology

Another challenge is the application of reverberation technologies to improve acoustic conditions in public spaces, such as concert halls, offices, or shopping malls. Modeling the acoustics of such environments requires special attention to detailing the reverberation effects to ensure comfortable sound perception.

Research area: studying reverberation methods to improve the acoustic characteristics of large spaces, in particular public spaces, to create acoustically pleasant environments.

LITERATURE/ REFERENCES

1. P. Doyle, Echo and Reverb: Fabricating Space in Popular Music Recording, 1900–1960. By Peter Doyle., т. 88, Middletown, CT: Wesleyan University Press, 2005, pp. 379-382.
2. L. L. Beranek, Acoustics, New York: Acoustic Society of America, 1954.
3. M. R. Schroeder, «Natural sounding artificial reverberation» Journal of the Audio Engineering Society, vol. 10, № 3, pp. 219-223, 1962.
4. J. D. Polack, «Modifying the Decay Rate of Reverberation in Room Acoustics» The Journal of the Acoustical Society of America, vol. 83, № 3, pp. 1057-1066, 1988.
5. J. B. Allen and D. A. Berkley, «Image method for efficiently simulating small-room acoustics» The Journal of the Acoustical Society of America, vol. 65, № 4, pp. 943-950, 1979.
6. B. Blesser, «Audio rendering: An overview of approaches to physically modeling the acoustics of spaces.,» Journal of the Audio Engineering Society, vol. 49, № 7/8, pp. 534-554, 2001.
7. N. Raghuvanshi, N. Rahul and M. C. Lin, «Efficient and accurate sound propagation using adaptive rectangular decomposition» IEEE Transactions on Visualization and Computer Graphics, vol. 15, № 5, pp. 789-801, 2009.
8. J. A. Moorer, «About this reverberation business» Computer Music Journal, vol. 3, pp. 13-28, 1979.
9. M. &. J. H. Karjalainen, «Reverberation modeling using digital signal processing techniques» in AES Convention, Amsterdam, 2001.
10. N. Tsingos, E. Gallo and G. Drettakis, «Perceptual audio rendering of complex virtual environments» ACM Transactions on Graphics (TOG), vol. 23, № 3, pp. 249-258, 2004.
11. N. Tsingos, E. Gallo and G. Drettakis, «Parametric wave field coding for precomputed sound propagation» ACM Transactions on Graphics (TOG), vol. 33, № 4, pp. 1-11, 2014.
12. L. Savioja and P. U. Svensson, «Overview of geometrical room acoustic modeling techniques» The Journal of the Acoustical Society of America, vol. 138, № 2, pp. 708-730, 2015.
13. J. Reiss and A. McPherson, Audio Effects: Theory, Implementation and Application., Boca Raton: CRC Press, 2014.
14. T. Lentz, «Virtual acoustics based on the wave equation: Echoes, late reverberation, and listening tests.,» AES Journal, vol. 55, № 9, pp. 723-740, 2007.
15. M. Vorländer, Auralization: Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality., Heidelberg: Springer Berlin, 2008.
16. K. &. M. P. Misztal, «Current State of Research in Audio Signal Processing» Journal of Audio Engineering Society, vol. 66, № 5, pp. 401-415, 2018.
17. G. Somberg, Game Audio Programming: Principles and Practices., Boca Raton: CRC Press, 2016.
18. T. Carpentier and O. Warusfel, «A Review of 3D Audio Techniques for Sound Design and Game Audio Applications» in AES Conference: 147th International Audio Engineering Society Convention., Amsterdam, 2020.

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

19. N. Tsingos, T. Funkhouser, A. Ngan and I. Carlbom, «Modeling acoustics in virtual environments using the uniform theory of diffraction» ACM Transactions on Graphics, vol. 20, № 2, pp. 187-194, 2001.
20. B. C. J. Moore, An Introduction to the Psychology of Hearing. 6th ed., Bingley: Emerald Group Publishing, 2012.

Received 02.05.2025.
Accepted 13.05.2025.

Аналіз наукових і практичних досягнень у сфері генерації реверберaційних ефектів

У роботі розглянуто проблему створення реалістичних звукових ефектів реверберації в комп'ютерних іграх. Показано основні особливості існуючих методів генерації реверберації, серед яких складність ручної обробки параметрів звуку, статичність моделей та обмежена адаптивність до геометрії ігрового простору. Визначено, що проблема створення реалістичних реверберaційних ефектів для комп'ютерних ігор є досяжною лише при застосуванні сучасних підходів, що зменшують ручне налаштування та підвищують адаптивність звукових параметрів. На підставі аналізу визначено, що існують значні перешкоди, які знижують реалістичність акустичного супроводу доступними методами.

Ключові слова: реверберація, акустичні характеристики, процедурна генерація, машинне навчання, комп'ютерні ігри.

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