Sound & Vibration 2025, 59(1), 1680.
https://doi.org/10.59400/sv1680

Article

Renovation of the reverberation room at Ocean University of China based on ODEON simulation

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CITATION

Shi L, Lin J. Renovation of the reverberation room at Ocean University of China based on ODEON simulation. Sound & Vibration. 2025; 59(1): 1680. https://doi.org/10.59400/sv1680

ARTICLE INFO

Received: 3 September 2024
Accepted: 18 September 2024
Available online: 15 November 2024

Abstract: The reverberation room is a crucial laboratory for determining the sound absorption properties of materials. The reverberation room at the Laoshan Campus of Ocean University of China lacks complete acoustic design. Using computer-aided simulations, defects in the sound field can be clearly revealed and the design proposals' effectiveness can be pre-validated. This study focuses on renovating the reverberation room by conducting acoustic performance tests and constructing a three-dimensional model. Leveraging the advantages of ODEON for simulating sound fields, it analyzes the uniformity of sound field diffusion, considering not only reverberation time distribution but also linear decay curves and deviations in sound pressure level distribution. Subsequently, the room undergoes simulated renovation in accordance with national standards of China and international standards, and diffusion body design schemes, including semi-cylindrical and semi-conical hard wall diffusers and suspended plexiglass diffusers, are compared through simulations to arrive at the final optimized renovation plan. The simulations show that the deviation in sound field uniformity can be reduced to less than 1.5 dB after renovation, and the reverberation time is also significantly extended. These findings can inform the actual renovation of the Laoshan Campus reverberation room and serve as a reference for other reverberation room renovations and indoor acoustic simulations.

Keywords: reverberation room; ODEON; simulation; diffuser; reverberation time

1. Introduction

Reverberation rooms, essential for acoustic measurements, are characterized by a long reverberation period and maximum sound field diffusion [1]. Reverberation rooms are commonly used in engineering to measure noise source sound power levels, material absorption coefficients, and related parameters.

In the design and theoretical research of reverberation rooms, several academics have conducted studies and produced valuable cases for consultation. For instance, Xiang et al. [2] focused on the design of sound diffusion in reverberation rooms and came to the conclusion that one of the best ways to create a diffused sound field in the reverberation room is to employ fixed reinforced concrete spherical diffusers along with unevenly shaped and inclined walls. Qiu et al. [3] analyzed the sound field characteristics of the reverberation room at the University of Technology Sydney through spectral analysis of background noise, normal mode analysis, spatial distribution of the reverberant field, and the decay curves of the sound pressure level versus time.

The application of computer acoustic simulation technologies, such as ODEON, in interior sound field research is increasingly common. During acoustic construction, computer sound field simulations can significantly reduce costs and improve flaw detection in sound field design. For example, Masih et al. [4] used computer-based acoustic simulation (ODEON software) to analyze speech intelligibility and acoustical characteristics of two modern mosques in Erbil. By evaluating sound pressure level, reverberation time, and speech transmission index, it revealed cost-effective defect detection in acoustic design, identifying subpar sound quality during prayer sessions without loudspeaker assistance, emphasizing the potential of computer simulation to enhance design and reduce costs. Through field measurements using DIRAC software and ODEON simulation, Fu et al. [5] compared and analyzed the reverberation times of two gymnasiums with similar structures but noticeably different sound quality. They found that the mid-frequency band bulge of the reverberation time curve is the key to determining the two gymnasiums' sound quality. Recognizing the importance of validating indoor acoustic simulation models to minimize errors, Artur et al. [6] combined ray tracing and virtual source methods to validate the ODEON-simulated reverberation room model, comparing error values with validation uncertainty. The results demonstrated that this validation method is effective and applicable to more complex room models.

The goal of this paper is to measure, simulate, and transform the reverberation room at the Laoshan Campus of Ocean University of China, while also forming a case that can be used as a reference for other reverberation room renovation studies and ODEON simulation applications. First, acoustic measurements and modeling were used to identify defects in the existing building infrastructure, while simultaneously obtaining sound field simulation results in ODEON. Subsequently, simulation studies were conducted to evaluate the indoor sound field performance of the reverberation room under different diffuser schemes. Finally, based on the simulation results, an optimized renovation plan for the reverberation room was obtained that not only meets the design requirements but also offers economic rationality.

Based on the findings, the research can be applied to the actual transformation of the reverberation room. It can also be used as a teaching tool in acoustics and related majors. Additionally, it will support acoustic research applications, including environmental noise control and electroacoustic product development.

2. Principles of indoor sound field in reverberation room

2.1. Sound field diffusion

Standard reverberation rooms should uniformly diffuse sound energy throughout rooms via their boundaries, leading to completely random indoor sound propagation and evenly distributed average sound energy density [7]. This ensures the achievement of a diffuse sound field standard in statistical acoustics.

Reverberation decay curves from room sound field recordings are often irregular due to the varying decay periods of standing waves, leading to uneven sound field attenuation. From the perspective of fluctuation acoustics, the room should be as irregular as possible to bring the room's sound field as close to the diffuse sound field. Additionally, various types of diffusers should be placed in the room to smooth out the reverberation curve. [1,3,8]

2.2. Indoor reverberation

The phenomenon of the sound wave energy emitted from the sound source in the room being continuously reflected back and forth by the wall surface and gradually decaying during the propagation process is called indoor reverberation. It is a significant acoustic indicator of bounded space [9].

Reverberation time T_{60} is an acoustic measure used to assess indoor sound attenuation [2,10,11]. It is defined as the time required for the sound pressure level in a diffuse sound field to decrease by 60 dB after the sound source stops emitting, corresponding to a reduction in average acoustic energy density to $1/10^6$ of the original [1,12,13]. Because environmental factors often interfere with direct measurement of the full 60 dB decay, linear extrapolation is typically used to obtain the predicted reverberation time T_{30}, through the decay process of −5 dB to −35 dB. Similarly, the frequently used reverberation time T_{20}, is determined by the decay from −5 dB to −25 dB [14].

Using the room's average free path, the Sabine formula for estimating reverberation time can be derived:

$$T_{60} \approx 0.161 \frac{V}{S\overline{\alpha}} \tag{1}$$

where $\overline{\alpha}$ represents the room's average sound absorption coefficient and S denotes the total sound absorption area of the room [1]. Sabine's formula assumes complete diffusion of the sound field in the room. However, extensive experimental results confirm that the formula provides high accuracy when the room's average sound absorption coefficient is below 0.25 [10].

In summary, before conducting research on reverberation rooms, the acoustic principles of the sound field in reverberation rooms should be clarified first, and attention should be paid to the application of relevant theoretical formulas. Additionally, it is necessary to define and explain related physical quantities.

3. Acoustic measurement and modeling

3.1. Basic information of the reverberation room

Figure 1. The photo of the reverberation room.

The air acoustics laboratory at the Laoshan Campus of Ocean University of China contains a reverberation room, which is connected to a soundproofed room.

The reverberation room (see **Figure 1**), however, had only basic construction work done without considering any acoustic requirements. As a result, the reverberation room has an irrational architectural structure and inadequate diffusion of the indoor acoustic field, among other issues.

The reverberation room has geometric dimensions of L × W × H = 7.55 m × 6.00 m × 7.80 m, while the acoustic isolation room measures L × W × H = 5.60 m × 6.00 m × 4.00 m. A passageway measuring L × W × H = 1.10 m × 2.30 m × 4.00 m connects the two rooms. This passageway is designated for installing sliding acoustic isolation doors, providing variable space for reverberation and supporting sound insulation measurements, as shown in **Figures 2** and **3**.

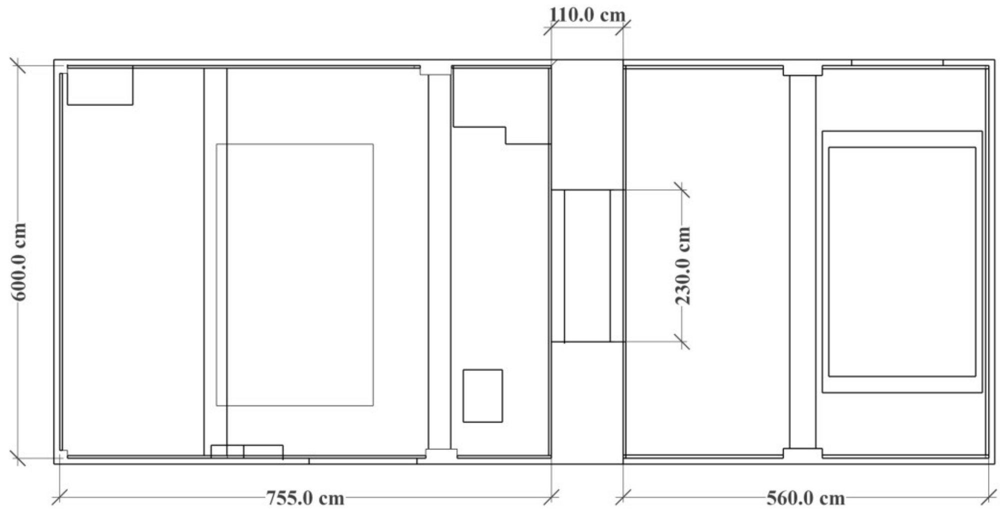


Figure 2. The plan of the air acoustics laboratory.

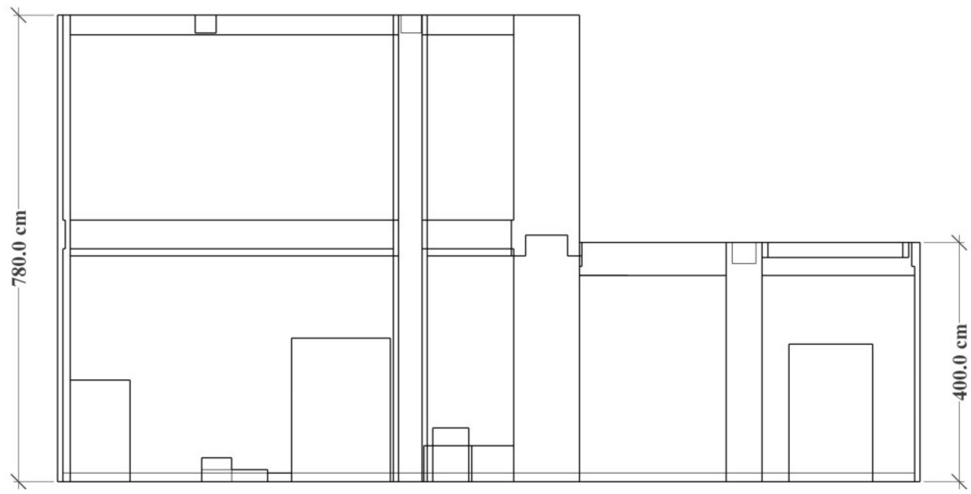


Figure 3. The front view of the air acoustic laboratory.

3.2. Measured lower cut-off frequency

Based on the provided dimensional data, the headroom volume of the reverberation room before remodeling can be calculated to be 353.34 m^3. The headroom volume influences the lower cutoff frequency of the measurement, which is determined by Equation (2):

$$f = 125\left(\frac{200}{V}\right)^{1/3} \quad (2)$$

After calculating the clearance volume, the lower limit frequency is determined to be 103.4 Hz. The center frequency of the nearest 1/3 octave band, 100 Hz, is selected as the lower limit frequency [15]. In the subsequent studies regarding the room's acoustic measurements and reverberation design, attention can be primarily focused on frequencies exceeding 100 Hz.

3.3. Measurement of background noise

In accordance with Calibration Specification for Acoustic Performance of Reverberation Rooms (the technical measurement specification of China, JJF 1143-2006), eight measuring points (marked as blue dots 1 to 8 in **Figure 4**) that comply with the specified distance from the measuring point were selected. Specifically, the distance between each measurement point exceeds half the wavelength of the lowest central frequency (100 Hz in this study) of the measured frequency band, which is approximately 1.7 meters. Additionally, each measurement point should be situated far away from the sound source, the tested specimen, and the boundary surfaces, with the minimum distances being 2 m, 1 m, and 1 m, respectively.

Background noise was measured using an Aihua AWA6292 multi-function sound level meter (calibrated to meet IEC Class 1), with the results displayed in **Figure 5**.

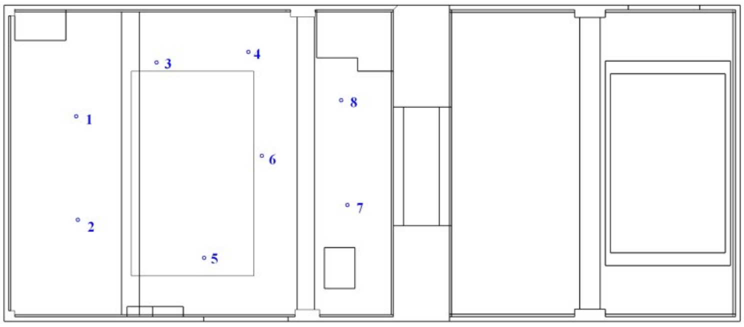


Figure 4. Schematic diagram of measurement points for background noise.

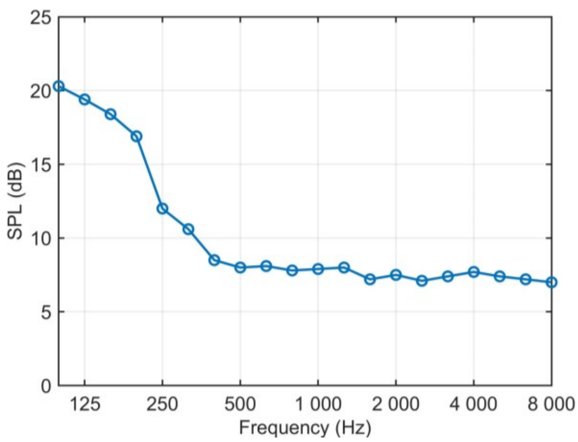


Figure 5. Average result of background noise.

3.4. Measurement of reverberation time

For the measurement of reverberation time in reverberation rooms, one of the commonly used methods is the impulse response integration method [16]. Referring to GB/T 20247-2006 (the Chinese National Standard) and ISO 354:2003, the excitation source can use a balloon burst, a pulse-like sound source, which can provide a very high sound pressure peak and a considerable usable dynamic range, ensuring the maximum usability in the calculation process of reverberation time [11,17]. Therefore, when measuring the reverberation time in this reverberation room, a 12-inch inflated latex material balloon was used as the material for generating the burst sound, and the balloon was punctured and burst at the selected sound source point to produce a burst sound impulse.

Moreover, experimental measurements have shown that the sound of a balloon explosion is a broadband signal. As shown in **Figure 6**, within the frequency band considered in the experiment, the sound pressure level of the sound is 60 dB or higher, and the difference in sound pressure level between adjacent one-third octave bands is less than 6 dB, which complies with the specifications in ISO 354:2003. Additionally, when compared to the background noise levels presented in Section 3.3 (which are generally below 20 dB and even lower than 10 dB in the mid-to-high frequency range), the sound pressure level of the aforementioned balloon sound source is significantly higher. Consequently, the use of these balloons as sound sources can provide accurate reverberation time measurements.

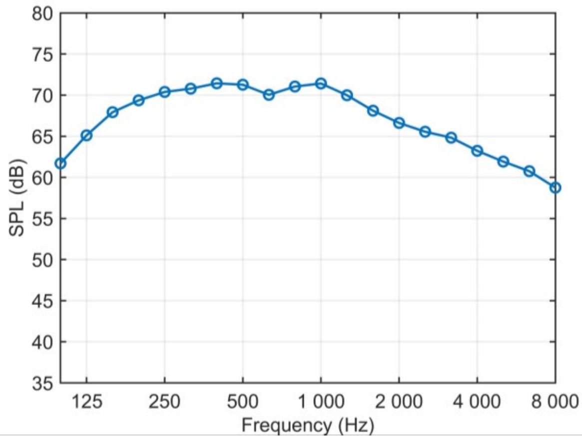


Figure 6. Frequency response curve of balloon burst sound.

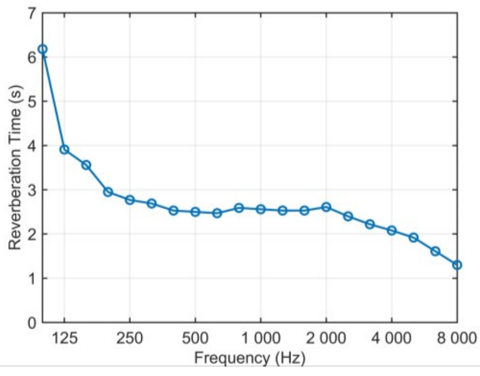


Figure 7. Average results of reverberation time at each measuring point.

During the measurement, the sound level meter's "impulse response" reverse integration calculation function was utilized to obtain the reverberation time T_{30} measurement results, as depicted in **Figure 7**.

It is evident that the present reverberation time within the reverberation room is comparatively low, particularly at mid-to-high frequency ranges, not exceeding 3 s. This is in sharp contrast to the acoustic characteristics of the ideal reverberation room, which exhibits a longer reverberation time. The short reverberation time highlights the excessive overall sound absorption level in the room. From an architectural standpoint, the primary factors contributing to this phenomenon are twofold: First, the interior surface materials possess an unduly high sound absorption coefficient, leading to rapid attenuation of sound waves before undergoing multiple reflections. Second, the room's large size and its connection to the sound insulation room enhance overall airborne sound absorption, especially at high frequencies, which contributes to the reduced reverberation time at mid-to-high frequencies. This also highlights the issue of non-uniform sound field diffusion. Therefore, it is crucial to refine the room's sound diffusion design and use materials with low sound absorption and high reflectivity to remodel the interior surfaces.

3.5. Modeling and verification of the reverberation room

The entire laboratory model was built in the SketchUp modeling program after acquiring the pertinent room parameters (see Section 3.1). Specifically, a rectangular section of the reverberation room's floor was designated for placing the material whose sound absorption coefficient needed to be measured. In **Figure 8**, the reverberation room is shown on the left and the acoustic isolation room on the right, along with the structural framework of the overall model. Due to the rooms' present interconnection, there will be issues with uniform sound field diffusion and increased air absorption.

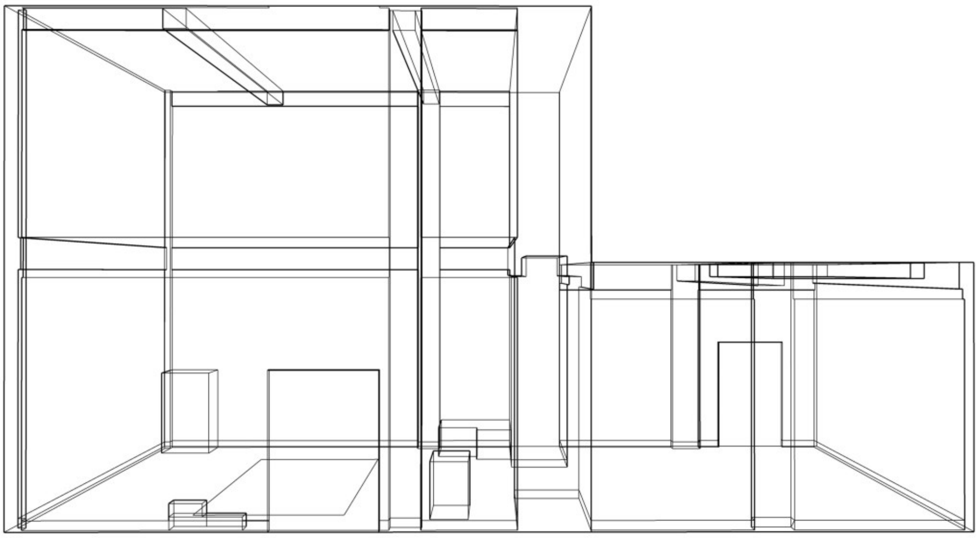


Figure 8. Structural framework diagram of the model.

After importing the model, the surface materials are adjusted to match those of the actual reverberation room using ODEON software. **Table 1** shows some of the parameter settings.

Table 1. Surface parameter settings for the reverberation and soundproof room model.

Surface	Material number in ODEON	Sound absorption coefficient at each center frequency (Hz)					
		125	250	500	1000	2000	4000
Floor	2001	0.01	0.01	0.01	0.01	0.02	0.02
Glassdoor	10006	0.35	0.25	0.18	0.12	0.07	0.04
Wall	4002	0.02	0.02	0.02	0.02	0.02	0.02

Reverberation time simulations were initially conducted, and the results are presented in **Table 2**. Moreover, the *t*-test was used to test the difference between the simulation value and the measured value, and the *t*-value and *P*-value results were obtained. The results showed that there was no significant difference at 125 Hz, a very significant difference at 250 Hz and 500 Hz, and a slightly significant difference in the high-frequency band. By comparing the background noise results in **Figure 5** and the balloon frequency response curve in **Figure 6**, it can be seen that at the medium and low frequencies, the background noise level is relatively high, and the sound pressure level of the balloon sound source is slightly lower, which has a significant impact on the reverberation time results measured in this frequency band, resulting in a significant difference from the simulated value. In addition, since room interconnections can increase sound absorption, the measured reverberation time should theoretically be lower than the simulated value. Therefore, within the frequency range investigated in this study, the overall trend of the measurement results is consistent with the simulation results. These results suggest that the constructed model accurately mirrors the actual reverberation room conditions, rendering it a viable tool for subsequent renovation and design endeavors.

Table 2. Comparison between simulation and measurement results of T_{30} and *t*-test results between them.

Frequency (Hz)	125	250	500	1000	2000	4000	8000
Measured T_{30} (s)	3.91	2.77	2.50	2.56	2.61	2.08	1.30
Simulated T_{30} (s)	3.95	3.36	3.10	2.81	2.72	2.16	1.17
t-value	0.560	6.091	7.383	2.124	2.062	1.567	1.874
P-value	> 0.05	< 0.01	< 0.01	< 0.05	< 0.05	< 0.05	< 0.05

The sound pressure homogeneity in the space was analyzed using ODEON simulation, with results shown in **Figure 9** (e.g., at 500 Hz). The statistical percentile sound level (X90–X10) is analogous to the "range" of sound pressure levels, where X10 and X90 signify the sound pressure level values at the 10% and 90%, respectively, after sorting the sound field in the reverberation chamber from the lowest to the highest. When employing the statistical percentile sound level to evaluate the uniformity of the sound field, it can serve as an indicator of spatial distribution deviations. Compared to a typical reverberant room, where the standard deviation is usually below 3 dB, the (X90–X10) value from the simulation at 1000 Hz is 4.6 dB. This indicates a substantial difference. The current design lacks sufficient reflective surfaces, contributing to the uneven sound field. Additionally, the room's inadequate diffusion structure contributes to this issue.

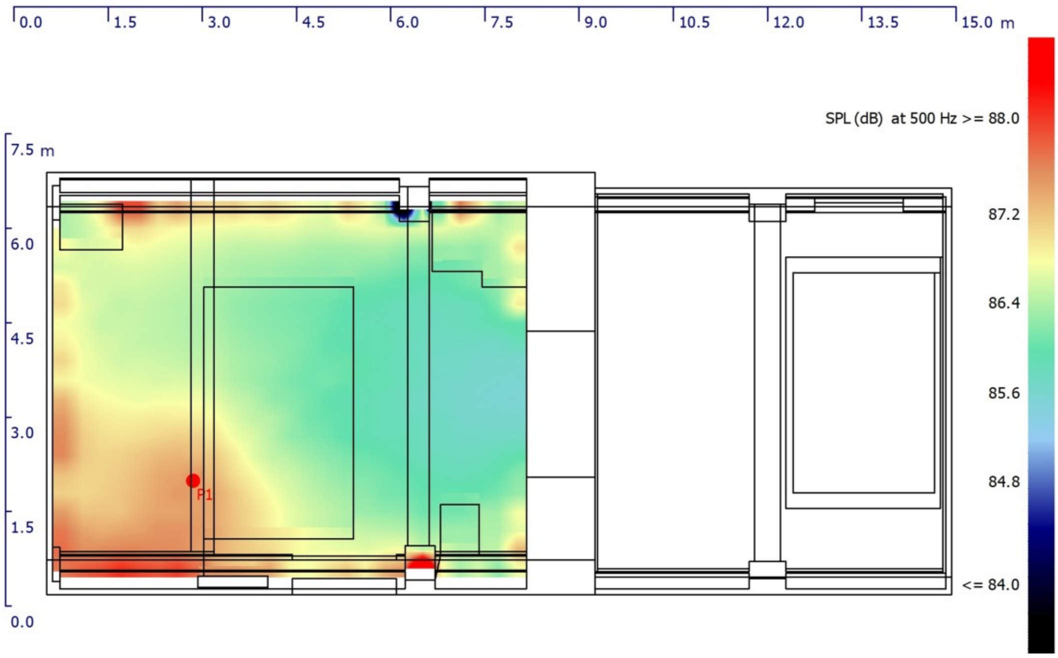


Figure 9. Sound pressure level distribution plan (500 Hz).

In this chapter, the acoustic measurement of the reverberation room can not only help understand the current acoustic defects of the chambers but also lay a foundation for subsequent design. More importantly, the measurement results of reverberation time provide data support for verifying the reliability of modeling. By comparing the reverberation time results from simulation and actual measurement, we can judge whether the built model is similar to the real room. Furthermore, with the aid of computer acoustic field simulation, it can further reflect the deficiencies of the sound field in the existing reverberation room (such as the sound pressure level distribution diagram), which is difficult to obtain through on-site equipment measurement.

4. Renovation design and simulation

4.1. Design standards and evaluation methods

4.1.1. Shape of the reverberation room

The interior dimensions of the existing reverberation room at the Laoshan Campus are 7.55 m × 6.00 m × 7.80 m, with a width: length: height ratio of 1:1.26:1.3. The size ratio is not an integer ratio, which can effectively eliminate acoustic degeneracy [18,19].

According to the guidelines of GB/T 20247-2006 and ISO 354:2003, the main diagonal of the room (a rectangular room) must match the requirements of the following Equation (3):

$$l_{\max} < 1.9V^{1/3} \quad (3)$$

The maximum linear dimension, $l_{\max}$=12.4 m, is included in the parameter calculation since the room must be set up with a diffuser volume of (20–30) m^3 to meet national standards.

4.1.2. Operating frequency

It is typically established that the reverberation room's test frequency range for sound-absorbing materials is between 100 Hz and 4000 Hz. Due to significant air absorption at high frequencies and the requirements specified in Section 3.2 of the Chinese standard, the target operating frequency range of 100 Hz to 4000 Hz is adjusted in the reverberation room design. This adjustment is necessary because the reverberation room has a volume of approximately 300 m^3.

4.1.3. Reverberation time

Lengthening the reverberation time in the empty room aids in the sound field diffusion, and reverberation duration and its spatial variation are crucial indicators of the reverberation room's acoustic performance [18]. In addition to having a sufficient reverberation period, a qualified reverberation room must have the lowest feasible absorption coefficient on its surfaces. In conjunction with GB/T 6881-2023, ISO 3741:2010 and the actual laboratory conditions, it is determined that each frequency's reverberation time must reach the standard limit shown in the following **Table 3**. Simultaneously, the maximum sound absorption of the unoccupied reverberation room must not surpass the value indicated in **Table 3**.

Table 3. Standard limits for reverberation time T_{60} and sound absorption.

Frequency (Hz)	125	250	500	1000	2000	4000
Reverberation time T_{60} (s)	5.0	5.0	5.0	4.5	3.5	2.0
Sound absorption (m^2)	9.0	9.0	9.0	9.7	13.1	18.0

4.1.4. Sound field uniformity

The reverberation room's interior sound field needs to be evenly dispersed. The following three approaches to measuring the uniformity of the reverberation room's sound field can be suggested based on the ODEON program, in conjunction with the diffuse sound field characteristics and empirical study. Each of these approaches is investigated in the simulation that follows.

First, the reverberation time spatial variation can be used to determine the reverberation room's acoustic quality by comparing the reverberation times at each location [7]. Better acoustic performance is typically indicated by reverberation times at each location having a deviation of no more than 0.1 s. ODEON simulation can be used as a uniformity test to efficiently collect reverberation time data from each location in the room.

Second, the homogeneity of the sound field can be reflected in the sound field attenuation, and a uniformly diffused sound field should have a good linear attenuation relationship, which can be examined by observing the linear relationship between the attenuation curves of sound pressure levels at each frequency [1,3,8]. Further, based on the definition of reverberation time T_{20} and T_{30}, the sound field uniformity can be identified in ODEON by checking whether T_{20} and T_{30} are numerically consistent.

Third, the homogeneity of the sound field is directly reflected in the numerical closeness of the sound pressure levels at each point in the indoor space after the sound field is stabilized [19]. Therefore, it can be tested by whether the measured sound pressure levels at each point are similar, and can also be identified by the (X90–X10) index of the cumulative distribution function result in the ODEON simulation. In view of the relatively large volume of the reverberation room, reference to national standards, the reverberation room after the renovation of (X90–X10) indicators needs to meet the standards in **Table 4**.

Table 4. The set sound field uniformity index.

Frequency (Hz)	(X90–X10) Index (dB)
100 ~ 315	≤ 3.0
≥ 400	≤ 1.5

4.1.5. Noise control

The background noise measurement results indicate that the reverberation room has a low sound pressure level of background noise. The current reverberation room has already met both the national standard and the requirements for practical use, as the working sound pressure level is often above 70 dB once the room is placed into operation. But in the ensuing refurbishment, the current glass acoustic door will be replaced with a steel acoustic door to improve the acoustic insulation performance and reinforce the acoustic vibration isolation treatment of the reverberation room.

It is worth mentioning that before designing the reverberation room, the target after the renovation should be set according to relevant standard documents. At the same time, it is also necessary to determine what methods should be used to test the results after the renovation. For example, in the verification of sound field uniformity, this study proposes three methods based on ODEON to test the diffusion effect of the sound field (see Section 4.1.4). These three methods complement and verify each other, providing more theoretical support for the practicability of the simulation results.

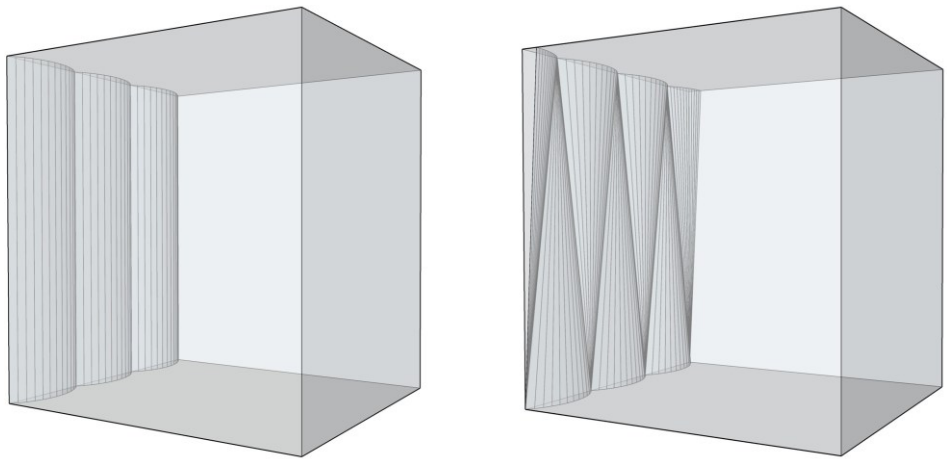
4.2. Selection of diffusers

To ensure uniformity in the sound field diffusion, the diffuser in a reverberation room should not only fulfill the properties of low surface absorption and strong reflection via the selection of suitable surface materials, but also disperse the sound energy through suitable shape design. To enhance the acoustic diffusion performance of a reverberation room, two common techniques are employed in practice: the first involves creating semi-cylindrical, hemispherical, or comparable convex rigid diffusers on one of the two opposing wall surfaces [1]; the second involves positioning movable diffusers, like rotating diffusers, etc.

Considering the high room, to ensure a good longitudinal sound diffusion, the design uses a combination of fixed wall rigid sound diffusers (cast in concrete) and suspended plexiglass (acrylic) sheet diffusers.

4.3. Wall diffuser

Semi-cylindrical and semi-conical wall diffusers are common in reverberation rooms because of their good sound dispersal capabilities. Generally speaking, semi-conical diffusers outperform semi-cylindrical diffusers in terms of diffusion frequency range [20]. Through the simulation of an ideal model, the sound diffusion performance of these two types of wall diffusers is compared (see **Figure 10**). The bottom radius, chord length and height of the two diffusers are 1.358 m, 1.92 m and 7.80 m respectively. The diffusers are intended to be cast through concrete and painted on the surface.



(a) **(b)**

Figure 10. Different wall diffuser models. **(a)** Semi-cylindrical diffuser model; **(b)** semi-conical diffuser model.

In terms of reverberation time, the smaller volume and surface area of the semi-conical diffuser compared to the semi-cylindrical diffuser led to reduced room absorption, especially at low frequencies. This results in a 0.15-second increase in reverberation time compared to the semi-cylindrical diffuser. As frequency increases, the difference between the two schemes diminishes, with the difference reducing to 0.10 s in the mid-frequency range. **Figure 11** shows that, overall, the semi-conical diffuser provides higher reverberation times than the semi-cylindrical design at all center frequencies.

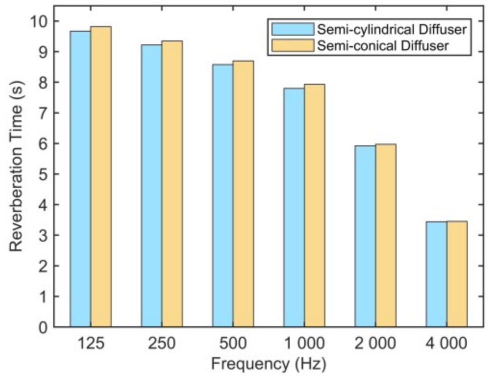


Figure 11. Comparison of reverberation time T_{30} results for two different diffusers.

Based on the sound field uniformity analysis (see **Figure 12**), there is not a significant difference in uniformity between the two diffuser schemes. The semi-cone diffuser's oblique surface allows for more sound wave diffusion, resulting in a more uniform sound field distribution. Overall, this results in a slightly lower (X90–X10) index for the semi-conical diffuser compared to the semi-cylindrical one, with a maximum reduction of 0.1 dB at most frequencies. This indicates that its sound field uniformity is marginally superior to that of the semi-cylindrical program.

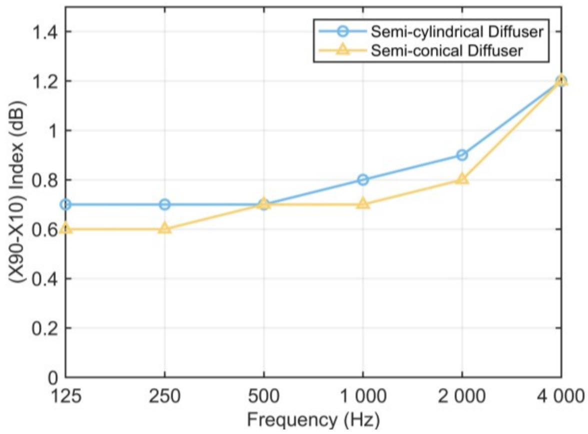


Figure 12. Comparison of (X90–X10) index for two types of diffusers.

Adopting a semi-conical diffuser not only reduces costs by minimizing the amount of poured concrete but also enhances sound field uniformity and extends the reverberation time in the reverberation room. Therefore, the renovation will proceed with the semi-conical diffuser design.

4.4. Suspended diffuser

Even with the wall diffuser installed, the room volume remains over 300 m^3. Therefore, installing vertically hanging thin plexiglass (acrylic) panels will expand the room's sound diffusion area and significantly improve sound diffusion performance, while maintaining a low level of sound absorption due to the panels' low acoustic absorption coefficient.

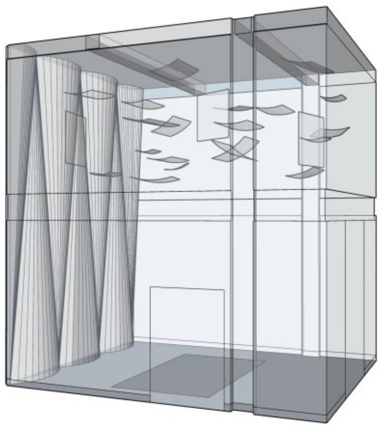


Figure 13. Design scheme of diffuser.

The study used plexiglass panels of three sizes: 80 cm × 120 cm, 120 cm × 120 cm, and 60 cm × 60 cm, each with a thickness of 0.2 cm. The random arrangement of the plexiglass diffusers in the hanging setup statistically enhances the dispersion of acoustic energy in the room.

Combined with the wall half-conical diffuser, the overall design scheme of sound diffusion in the reverberation room is shown in **Figure 13**.

4.5. Simulation of comprehensive renovation scheme

The model is imported into the ODEON building acoustics simulation program for processing. In accordance with the reverberation room's surface design, the necessary surfaces are set in accordance with the actual circumstances using the "Material List" option page in conjunction with the ODEON material package. A portion of the surface setting parameters are displayed in **Table 5**.

Table 5. Surface settings in the renovation scheme.

Surface	Material	Sound absorption coefficient at each center frequency (Hz)					
		125	250	500	1 k	2 k	4 k
Door	Marble or glazed tile	0.01	0.01	0.01	0.01	0.02	0.02
Soundproof door	Steel	0.10	0.07	0.05	0.06	0.06	0.06
Wall	Painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Wall Diffuser	Painted plaster surface	0.02	0.02	0.02	0.02	0.02	0.02
Suspended Diffuser	Plexiglass	0.01	0.01	0.01	0.01	0.01	0.01

Following the provisions of JJF 1143-2006, the simulation setup includes a non-directional sound source point (P2, red), the receiving point (R1~R10, blue) as shown in **Figure 14**.

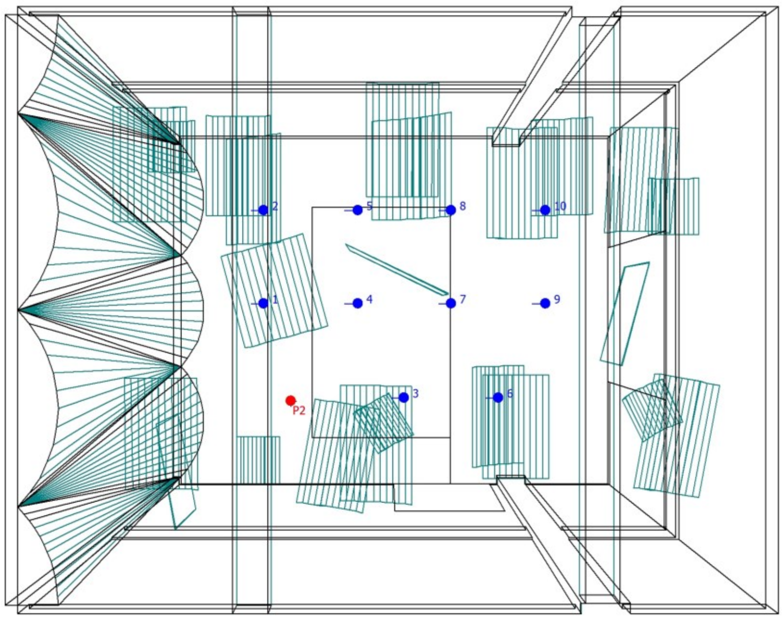


Figure 14. Schematic diagram of sound source and measurement point layout in simulation.

Initially, the reverberation time was examined. **Figures 15** and **16**, and **Table 6** show the global decay curves, reverberation time, and sound absorption computed from the simulation. After modifying the reverberation room, the reverberation time T_{30} increased across the working frequency range. It now exceeds 8.0 s at 500 Hz, a notable improvement from approximately 3.0 s before modification. At 1000 Hz and 2000 Hz, it is significantly above 5.0 s, and at 4000 Hz, it reaches 3.36 s, aligning with the design index in **Table 3**. Additionally, the sound absorption is consistently below the set upper limit at all frequencies. The attenuation curves are nearly linear, as per the method outlined in Section 4.1.4, indicating good sound field uniformity in the reverberation room.

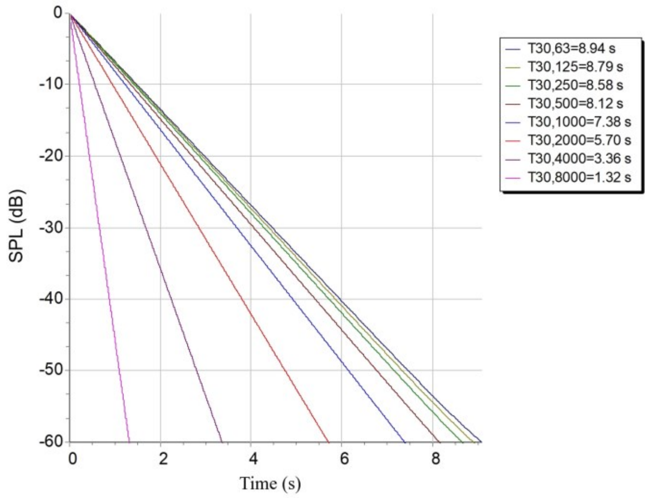


Figure 15. Simulation results of the global attenuation curve.

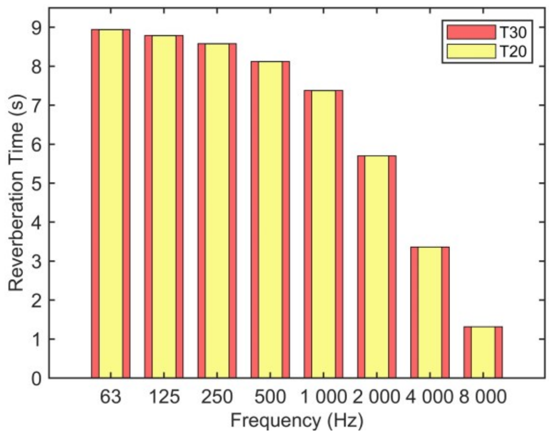


Figure 16. Bar chart of simulation results for reverberation times T_{20} and T_{30}.

Table 6. Simulation results of sound absorption.

Frequency (Hz)	**125**	**250**	**500**	**1000**	**2000**	**4000**
Sound absorption (m2)	6.6	6.8	7.2	8.0	10.3	17.8

The reverberation time results obtained from the two calculation methods are nearly identical, as illustrated by the comparison of T_{20} (yellow) and T_{30} (red) in Fig. 16. Additionally, the test conducted using the method mentioned in Section 4.1.4 can also demonstrate that the decay of sound pressure is linear. Since the linear decay shows that the reverberation times T_{30} and T_{60} are essentially identical, the study adopts the reverberation time T_{30} as the test quantity for T_{60} in national standard documents, aligning with the requirements of acoustic theory.

Regarding the spatial distribution (refer to **Figure 17**), all areas of the room had comparable reverberation times, with no discernible variation in the reverberation time T_{30} measurements at the set 10 measurement locations (R1~R10) at any frequency.

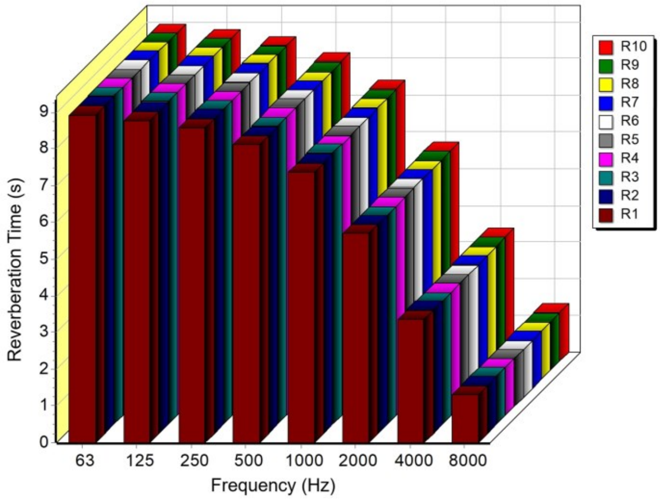


Figure 17. Bar chart of reverberation time T_{30} results at different measurement points after renovation.

In terms of sound pressure distribution, the sound pressure level distribution plan is shown in **Figure 18** (500 Hz for example), and the derived (X90–X10) index is shown in **Table 7**, which is 1.0 dB up to 1000 Hz, and slightly increased at 2000 Hz and 4000 Hz. But the maximum is not more than 1.5 dB, which reflects the uniform distribution of the sound pressure at all places in the reverberation room and the sound diffusion is good, which is in line with the calibration content proposed in Section 4.1.4 and meets the design standard of **Table 4**.

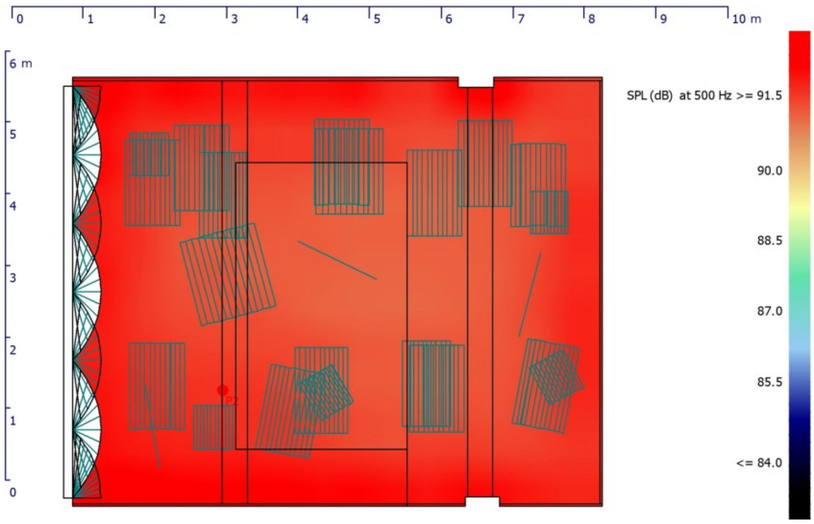


Figure 18. Sound pressure level distribution plan after renovation (500 Hz).

Table 7. Simulation results of sound pressure uniformity index (X90–X10) after renovation.

Frequency (Hz)	125	250	500	1000	2000	4000
(X90-X10) Index (dB)	1.0	1.0	1.0	1.0	1.2	1.4

By combining **Tables 3** and **4** design standards for comparison, **Table 8** is produced. The results demonstrate that the room has good reverberation characteristics and uniform sound pressure, meeting or exceeding the design standards. In fact, most of the parameters are significantly higher than the standards: the reverberation time in the low frequency is more than 3.0 s, the uniformity indicators (X90–X10) in the high and medium frequencies are better than the standard 2.0 dB, and the room overall satisfies the pre-design requirements.

Table 8. Comparison between renovation results and design standards.

Type	Frequency (Hz)	125	250	500	1000	2000	4000
Design standards	T_{60} (s)	5.0	5.0	5.0	4.5	3.5	2.0
	(X90-X10) (dB)	3.0	3.0	1.5	1.5	1.5	1.5
Renovation results	T_{30} (s)	8.79	8.58	8.12	7.38	5.70	3.36
	(X90-X10) (dB)	1.0	1.0	1.0	1.0	1.2	1.4

In addition, the results of background noise (see **Figure 5**) indicate that the current background noise level in the reverberation room is relatively low, primarily in the low-frequency range (up to 10 dB or more). Since the working noise pressure level is generally much higher than this background noise level, it meets the requirement that "the difference between them is greater than 12 dB". Finally, this design can serve as a reference program for the renovation of the reverberation room at the Laoshan Campus.

5. Conclusions

The reverberation time and background noise of the reverberation room were first assessed in this study using a sound level meter. It was discovered that the homogeneity of the sound field was low and that the reverberation duration was essentially less than 3.0 s. Based on this, the existing reverberation room was modeled using SketchUp software, and the inside sound field of the reverberation room was recreated in ODEON to guarantee the correctness and dependability of the simulation results. The simulation evaluates the reverberation time, a key factor commonly considered in the industry. It also uses computer simulation to clearly illustrate the inhomogeneous distribution of the sound field and to reasonably estimate how the sound field will diffuse. Lastly, the simulation's results further elucidate the flaws in the current reverberation room.

By referring to international and national standard documents, the revamping indicators of the reverberation room were determined in the study. Meanwhile, with the aid of indoor sound field theory and ODEON, an identification method for the diffusion uniformity of the sound field in the reverberation room was specifically proposed from three angles: measurement of the spatial distribution of reverberation time, consistency of T_{20} and T_{30} reflecting linear attenuation, and quantification of the deviation in sound pressure level distribution using statistical distribution functions.

In order to achieve cost savings, the semi-conical diffuser can reduce the volume of poured concrete. It can also produce a more uniform sound field and longer reverberation time in the reverberation room. The study compares the two wall diffuser schemes, semi-cylindrical and semi-conical, through simulation.

The final decision to use half-conical diffusers to improve the reverberation room's sound field uniformity and the unique addition of organic glass diffusers hanging to enhance the sound diffusion not only lowers costs, enhances construction, installation, and post-correction of the convenience, but also avoids the complexity of simultaneously modifying the two walls due to the complexity. The program's application allows the reverberation room's reverberation time to reach more than 8.0 s for low frequency, 5.0~7.0 s for medium frequency, and more than 3.0 s for high frequency. It also allows the sound pressure uniformity indexes (X90–X10) to reach levels of 1.0 dB for low and medium frequency, and 1.5 dB for high frequency. Ultimately, this determination shows that the reverberation room can achieve the necessary levels of sound pressure uniformity and reverberation time under the modified program mentioned above. As a result, the reverberation room can complete the program mentioned above with the necessary reverberation time and sound pressure homogeneity.

Following the implementation of the simulation program in real construction, the Laoshan Campus will benefit from some assistance with acoustics education, as well as experimental sites for environmental control applications and research on electroacoustic equipment. In the meantime, it is anticipated that this paper's findings will serve as references and support further ODEON simulation and indoor acoustics studies.

Author contributions: Conceptualization and methodology, JL and LS; measurement experiment, LS; analysis and interpretation of measurement results, JL; simulation and analysis, LS; writing—original draft preparation, LS; writing—review and editing, JL and LS; project administration, JL. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Student Research Developing Program of Ocean University of China (OUC-SRDP, No. 202310423109X).

Acknowledgments: The author sincerely thanks Shi Zhaojun, Qin Binkai, and Pei Jiaxuan for their invaluable contributions during the SRDP phase of this research. The author also thanks Xi Tao, Jiang Kangkang, and Lin Bopeng for their assistance in arranging experimental venues and equipment. The author is also grateful to Qiu Mingshuo for his help in preparing experimental materials. Special thanks to Wang Yilu and Lin Sen for their insightful suggestions during the thesis writing process. Finally, heartfelt appreciation is extended to all individuals who contributed to the successful completion of this research.

Availability of data and materials: The data will be made available by the author upon request.

Conflict of interest: The authors declare no conflict of interest.

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