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Quantitative assessment of sound absorption material configuration and sound field uniformity for indoor acoustic environmental art design

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Abstract Modern architectural space is increasingly demanding for acoustic quality, and a good acoustic environment not only relates to the comfort of users, but also directly affects the effect of spatial function. In this paper, to address the issue of the influence of sound-absorbing material configuration on the sound field uniformity in the indoor acoustic environment, using the quadratic residual diffuser (QRD) material, through the establishment of the reverberation laboratory model, the design of seven different material arrangement combinations of the program, the use of VA-Lab6 acoustic test system to measure and analyze the sound pressure level, reverberation time and other key acoustic parameters. The results of the study showed that in the horizontal alternating arrangement scheme of the side walls, combination mode 3 achieved a total score of 38 in the loudspeaker source condition and 34 in the normal male voice condition, both of which were the highest scores; When the rear wall was arranged vertically and alternately, combination mode 4 scored 37 points in the loudspeaker condition, the best performance; The modal density analysis shows that the modal density is 37 in the 500Hz band and reaches 75 in the 1000Hz band, which meets the sound field diffusion requirements. The quantitative assessment of sound field uniformity reveals that the reasonable configuration of sound-absorbing materials can significantly improve the uniformity of indoor sound field distribution, which provides a scientific basis and practical method for the artistic design of indoor acoustic environment.

Index Terms Indoor acoustics, sound-absorbing materials, sound field uniformity, QRD diffuser, reverberant room, sound pressure level

I. Introduction

With the rapid development of economic construction and the rapid increase of urban population, the corresponding noise pollution has become increasingly serious, seriously affecting the normal life of residents [1], [2]. Generally speaking, indoor noise consists of two categories: external noise and internal noise. External noise mainly comes from traffic noise, urban construction noise and industrial noise, while internal noise comes from the interference between floors, noise from indoor equipment, and noise from water supply and drainage pipes [3]-[5]. At present, building interior noise has become a major public nuisance of environmental pollution, which has a great impact on the human body, and it is of great significance to study the methods of interior noise control [6], [7].

Technically speaking, noise control can start from four aspects, i.e., reducing the intensity of occurrence of noise sources, sound insulation, sound absorption, and personal protection [8]. Among them, sound-absorbing materials, as common materials that can significantly regulate the room sound field uniformity, their distribution position in the room affects the regulation effect of the room sound field uniformity [9], [10]. Uneven diffusion of the room sound field is one of the main reasons for the error in the determination of absorption coefficient by the reverberation chamber method, and effective diffusion measures in reverberation chambers to achieve sufficient diffusion of their decaying sound fields is a prerequisite for more accurate absorption coefficient measurements [11]-[14]. However, the traditional method to improve the room sound field uniformity is generally to hang diffusion panels in the room and optimize the sound field uniformity by adjusting the angle and position of the diffusion panels, but this method is time-consuming and laborious [15]-[17]. Therefore, quantitatively evaluating the influence of the configuration of sound-absorbing materials on the sound field uniformity can provide a basis for the design and development of diffuse sound-absorbing structures in rooms.

With the optimization of indoor acoustic environment as the goal, this study thoroughly explores the influence law of sound-absorbing material configuration on sound field uniformity by combining theoretical analysis and experimental verification. The study adopts the quadratic cosine diffuser as the core research object, designs a variety of material arrangement schemes, constructs a reverberation laboratory test platform, and utilizes modern acoustic testing techniques to quantitatively evaluate the acoustic effects of different configuration schemes. By establishing the evaluation index system of sound field uniformity, the influence mechanism of material type, arrangement position, combination mode and other factors on sound field distribution is systematically analyzed, which provides scientific basis for the artistic design of indoor acoustic environment.

II. Configuration of sound-absorbing materials for room acoustics and quantification of sound field uniformity

II. A. Calculation of indoor sound field

II. A. 1) Simple positive theory of indoor sound fields

Let there be a point source at S in a rectangular room with source intensity $Qe^{-i\omega t}$, which can be expressed, by the theory of simple positives, as:

$$\nabla^2 p(T)+k^2 p(T)=-i\rho\omega Q\sum_n \frac{1}{V\Lambda_n}\phi_n(S)\phi_n(T) \tag{1}$$

where ϕ_n is the simplex function corresponding to the simplex angular frequency ω_n and Λ_n is the mean square value of ϕ_n^2 in a rectangular room. The simplex function is determined by the dimensions and boundary conditions of the rectangular room. The sound pressure at T is solved as:

$$p(T)=\rho c^2 Q\sum_n \frac{1}{V\Lambda_n}\frac{\omega\phi_n(S)\phi_n(T)}{2\omega k_n+i(\omega^2-\omega_n^2)} \tag{2}$$

The sound pressure in a rectangular room is a superposition of sub-simplex modes and is mainly determined by the simplex modes corresponding to similar eigenfrequencies. When the frequency is low, the overlap of multiple simplex frequencies will lead to acoustic coloring in the frequency domain, and the frequency response curve of the sound pressure level at one point in the room will show a series of sharp peaks and deep valleys. The sound pressure will also be very uneven in spatial distribution due to specular reflection and standing waves. In order to improve the listening conditions in a room, structures with different acoustic properties need to be used in the room.

II. A. 2) Acoustic boundary conditions

In order to solve the Helmholtz equation [18] for indoor acoustic fields, the boundary conditions of the acoustic field need to be determined. The model in this paper mainly uses impedance boundary and conductivity boundary. For a point in the medium, the acoustic impedance rate is defined as:

$$z=\frac{p}{v} \tag{3}$$

where v is the particle velocity. Usually p and v have different phases, so the acoustic impedance rate is a complex quantity. For a plane acoustic wave in air, the characteristic impedance is $z=\rho c$. From this the specific acoustic impedance rate of the medium can be defined as:

$$z_0=\frac{z}{\rho c} \tag{4}$$

Assuming that the surface of the boundary is locally reactive, the outer normal derivative of the sound pressure at the boundary $q=\frac{\partial p}{\partial n}$ with respect to the sound pressure p can be expressed as:

$$i\rho\omega p-zq=0 \tag{5}$$

Or:

$$ikp-z_0 q=0 \tag{6}$$

The acoustic admittance at a point in the medium is the derivative of the acoustic impedance rate, i.e.:

$$y=\frac{v}{p}=\frac{1}{z} \tag{7}$$

Similarly, the specific acoustic conductivity can be defined as:

$$y_0 = \rho c y = \frac{1}{z_0} \tag{8}$$

Under the assumption of a locally reactive boundary surface, the relationship between the outer normal derivative q of the sound pressure at the boundary and the sound pressure p can be expressed as:

$$i\rho\omega y p - q = 0 \tag{9}$$

Or:

$$iky_0 p - q = 0 \tag{10}$$

II. A. 3) Configuration of sound-absorbing materials

When a sound wave is incident on the surface of a material from the air, part of the sound energy is reflected and the other part is absorbed by transmission into the material. A material with this sound absorption property becomes an acoustic material [19]. Acoustic materials are usually used to absorb excess sound energy and reduce environmental noise. Indoors, sound-absorbing materials are mainly used to control the reverberation time of a room and to eliminate echoes.

According to the physical properties and the way of sound absorption, sound-absorbing materials can be divided into two categories: porous materials and resonance materials. Among them, porous materials have a large number of connected micropores inside, such as fiber materials and plaster materials. Sound waves incident on the porous material, caused by air vibration in the microporous due to friction and air viscous resistance, part of the acoustic energy into thermal energy, play a role in sound absorption. Practical application of porous acoustic materials, such as fiberboard, is usually rigid, that is, the material structure itself does not vibrate. The flow resistance of a porous material is the ratio of the pressure gradient in the porous material to the air velocity under steady airflow. According to the flow resistivity σ, the acoustic impedance of a porous material is given by the empirical formula of Delany and Bazley [20]:

$$z_p = \rho c(r + \mathrm{i}x) \tag{11}$$

The propagation constant is:

$$\gamma = \alpha + \mathrm{i}\beta \tag{12}$$

When the porous material is mounted on a rigid wall, the acoustic impedance at the surface of the porous material is from the multilayer transmission matrix equation:

$$z = z_p \coth \gamma t \tag{13}$$

where t is the thickness of the porous material.

II. A. 4) Diffusers

A quadratic cosine diffuser is a one-dimensional diffuser that uniformly scatters incident sound waves in a certain frequency range over a semicircular circumference. A quadratic cosine diffuser consists of a series of wells of the same width and different depths, separated from each other by thin fins. The depth of the wells is determined by a sequence of quadratic cosine numbers with period prime N. For a given design frequency f_r, the depth of a well of one period can be expressed as:

$$d_n = \frac{c(n^2 \% N)}{N(2f_r)}, n = 0,1,\cdots,N-1 \tag{14}$$

Due to the different depths, the reflected acoustic waves at the bottom of the wells undergo different phase transformations, which results in the diffusion of the acoustic waves. The frequency of action of the quadratic cosine diffuser is affected by the width w and the maximum depth $d_{\max}$ of the well.

In a well with a rigid boundary, the propagation number k_t and the effective density of air ρ_e are:

$$k_t \approx k + \frac{k}{2w}(1-\mathrm{i})[d_v + (\gamma - 1)d_h] \tag{15}$$

$$\rho_e = \rho\left[1+(1-\mathrm{i})\frac{d_v}{w}\right] \tag{16}$$

Under the assumption of a localized response surface, the acoustic impedance of the well at the inlet is:

$$z = -\mathrm{i}\rho_e c\frac{k}{k_t}\cot k_t d_n \tag{17}$$

II. A. 5) Evaluation of the uniformity of the indoor sound field

The range of variation of sound pressure varies by large orders of magnitude, so its logarithmic value is often used as a measure. Taking $p_{\inf} = 20\ \mu Pa$ as the reference sound pressure, the sound pressure level can be expressed as:

$$SPL = 20\ln\left|\frac{p}{p_{\inf}}\right| \tag{18}$$

A large number of reception points are selected in the room, and the sound pressure level at the reception point is set to SPL_i. The diffusion coefficient in the room is then:

$$DC = \sqrt{\frac{1}{n}\sum_{i=1}^{n}SPL_i^2 - \frac{1}{n^2}\left(\sum_{i=1}^{n}SPL_i\right)^2} \tag{19}$$

where n is the total number of reception points. The smaller the diffusion coefficient, the more diffuse the sound field is. In particular, the diffusion coefficient is zero when the sound field in the room is fully diffused and the sound pressure level is uniformly distributed at each receiving point. In practice, the sound field in a room cannot be completely diffused, and the diffusion coefficient varies considerably numerically for rooms with different surfaces. For comparison, this paper calculates the diffusion gain of other models on the basis of the reference model:

$$DG = 1 - \frac{DC}{DC_{\inf}} \tag{20}$$

where $DC_{\inf}$ is the diffusion coefficient of the reference model. For sound fields with better diffusion than the reference model, the diffusion gain is a positive number less than 1. In particular, a fully diffused sound field has a diffusion gain of 1. For sound fields with less diffusion than the reference model, the diffusion gain is a negative number.

II. B.Reverberation Room Acoustic Design Indicators

According to the requirements of GB/T6881.1-2002 and GB/T20247-2006, the volume of the reverberation room should be able to meet the test requirements, the body noise can not be too high, the room in the frequency range of interest in the sound absorption is sufficiently low, the room should be sufficiently diffuse the gradual decay of the acoustic field, the test of the required frequency range are able to provide the appropriate reverberation sound field.

II. B. 1) Reverberation Room Volume and Shape Design Requirements

GB/T20247-2006 suggests that the volume of the newly built reverberation room is recommended to be more than $200\mathrm{m}^3$. According to the relationship between the reverberation room volume V and the lower frequency limit of the test f:

$$f = 125\left(\frac{200}{V}\right)^{\frac{1}{3}} \tag{21}$$

When the volume of the reverberation chamber is less than $200\mathrm{m}^3$, the measurement frequency requirement cannot be met. When the volume of reverberation chamber is more than $500\mathrm{m}^3$, it may not be able to accurately measure the sound absorption in the high frequency band due to air absorption. When doing sound insulation testing, the volume of the reverberation chamber should not be designed too small to meet the lower frequency requirement of the test.

II. B. 2) Background noise control

In order to minimize the influence of vibration noise on the test from the external environment of the reverberation room, the building structure of the reverberation room adopts the double-layered enclosure structure of "room within a room", where the outer room is a solid brick wall structure, and a layer of reinforced concrete is firstly poured at the bottom; a vibration isolator is placed on the ground of the outer room, and then the whole inner room (the reverberation room body), which is built by reinforced concrete, is isolated from the outer room by means of the vibration isolator. The whole inner room (the body of the reverberation room) is built on the vibration isolator and isolated from the outer room, so as to better isolate the vibration noise of the external environment and prevent it from interfering with the experimental tests inside the reverberation room. At the same time, in order to improve the sealing of the reverberation room and the sound insulation of the doors, the reverberation room adopts two large soundproof doors of 10mm thickness, which are filled with sound-absorbing materials inside. The two soundproof doors are 2000mm apart, which increases the additional sound insulation performance of the air layer. In addition, rubber seals are installed between the doors and the overlapping areas between the doors and the walls of the reverberation room. The "room within a room" structure and the design of the two large acoustic doors in the reverberation room satisfy the low background noise requirement. The background noise in this reverberation room was measured to be approximately 20 dB.

II. B. 3) Design of sound absorption in the room

The sound absorption inside the reverberation room includes air absorption and wall absorption. In order to ensure a suitable reverberation sound field, the absorption coefficient of the surface of the reverberation room should be small enough. In order to reduce the wall absorption, the inner surface of the reverberation room should be hard and smooth, and at the same time, there should be no hollow drum. The floor of this reverberation room is made of ceramic tiles, the wall surfaces are coated with smooth putty, and the door and acoustic window areas are baked enamel-treated steel plates. The sound absorption A_t (unit: m^2) of the empty-field reverberation room is calculated by the formula:

$$A_t = \frac{55.3V}{C_1 T_1} - 4Vm_1 \tag{22}$$

where, V - volume inside the empty-field reverberation chamber, m^3, C_1 - speed of sound inside the empty-field reverberation chamber, m/s, T_1 - reverberation time in the empty-field reverberation chamber, s, m_1 - sound intensity attenuation coefficient of the empty-field reverberation chamber, m^{-1}; m_1 is related to the temperature and relative humidity of the empty-field reverberation chamber during the testing process, which can be calculated according to the m_1 value formula $m_1 = \frac{\alpha}{10\lg(e)}$. is calculated, where α is the attenuation coefficient.

II. B. 4) Design of sound field diffusion inside the reverberation room

In the process of reverberation room design, the internal shape of the reverberation room is designed as an irregular rectangular shape, and the walls are designed as multiple semi-cylindrical undulating shapes or hanging diffusion panels in the room, all of which are designed to make the reverberation room achieve as much uniformity and sufficient sound field diffusion as possible. Semi-cylindrical shape wall is easy to achieve good effect of low frequency sound reflection, but due to the design shape is difficult to improve and optimize, so the design does not consider this option. This reverberation room adopts the suspended diffusion plate program, which is not convenient enough to install, but can be flexibly disassembled and arranged according to the need for diffusion plate position and angle, in order to achieve the design of the required sound field diffusion effect. In the top of the reverberation room random and non-overlapping suspension of a number of curved diffusion plate, the total area of the board is close to the ground area, the diffusion plate for the smooth acrylic plate, its own sound absorption is very low, the sound wave through the diffusion of the plate at all angles of the reflection, so as to obtain a uniform sound field effect.

II. B. 5) Determination of sound sources

The sound in the reverberation room should be emitted by an omnidirectional radiating sound source. In order to ensure that the test can obtain a sufficiently large sound pressure level and uniform reverberation field, the reverberation room using the sound frequency of 200Hz-10000Hz ball sound source, sound sources were placed in the four corners of the reverberation room, more than 2 meters away from the wall, while the location of the asymmetric.

II. C.Experimental materials and sound field uniformity

II. C. 1) Experimental materials

The QRD material, which is the object of study in this experiment, is a pseudo-randomly distributed diffusion structure generated based on the sequence of quadratic residues. QRD includes one-dimensional QRD diffusers and two-dimensional QRD diffusers.

The two-dimensional QRD material has a beautiful appearance, and the installation construction in the room is simple and convenient. A grooved track is usually installed for wall-mounted connection. Specifically, the material is connected to the wall through the rail and rivets, and the rail has grooves to facilitate the replacement of the QRD material.

Combined with the above material performance advantages, the diffuser selected in this experiment is a two-dimensional QRD diffuser. In the experiment, four identical diffusers are arranged in different ways to investigate the effect of positional changes on the sound field uniformity.

II. C. 2) Sound field uniformity

Reverberation laboratories are commonly used to measure material absorption coefficients, component sound insulation, etc. In order to obtain accurate acoustic measurements, the reverberation chamber sound field needs to be sufficiently diffuse. The ideal diffuse sound field can be described as a superposition of plane waves with random phase and equal amplitude in the propagation direction, and uniformly distributed in the propagation direction. The degree of diffusion of the sound field is currently assessed in terms of the spatial homogeneity of the sound pressure, the homogeneity of the decay rate and the linearity of the decay curve. The most commonly used descriptions are the spatial uniformity of the sound pressure level and the correlation between the sound pressures at neighboring locations.

From the point of view of statistical acoustics, the non-uniformity of room sound field attenuation is a sign of insufficient diffusion of the indoor sound field. To make the indoor sound field diffusion is good, should try to make the room is irregular shape, diffusion treatment in the room, so that the indoor sound field in the attenuation process tends to be uniform. From the statistical point of view diffusion sound field can be considered sound waves through any position of the same chance, and through the direction of the same chance, in the same position of the sound line meets the phase is not regular, which leads to the indoor sound field of the average energy density distribution is uniform. The transmission process of sound waves is essentially the propagation process of acoustic vibration energy, the average acoustic energy density per unit volume is:

$$\bar{\varepsilon} = \frac{\overline{\Delta E}}{V_0} = \frac{p_a^2}{2\rho_0 c_0} = \frac{p_e^2}{\rho_0 c_0^2} \tag{23}$$

where $p_e = \frac{p_a}{\sqrt{2}}$ is the effective sound pressure, ρ_0 is the density, and c_0 is the sound velocity constant. Therefore, the average acoustic energy density is proportional to the square of the effective sound pressure.

From the point of view of fluctuation acoustics, the simple positive frequency is the intrinsic frequency of the room to do free vibration, when the excitation frequency of the sound source in the room and a certain intrinsic frequency in the room, the room resonates. And the simple positive frequency distribution is dense and uniform means that the transmission frequency characteristics of the room is uniform, otherwise it means that the frequency characteristics of the inhomogeneity. Differentiate the frequency to obtain the number of simple positive frequencies in df :

$$dN = \left(\frac{4\pi f^2 V}{c_0^3} + \frac{\pi f S}{2c_0^2} + \frac{L}{8c_0} \right) df \tag{24}$$

where V is the volume of the room, S is the total wall area of the room, L is the total length of the room sidings, and c_0 is the sound velocity constant. The dN number increases more rapidly with higher frequency, and the superposition of a large number of standing wave modes can average out the standing wave effect, thus making the sound field uniform. If the sound source emits not a single frequency but a certain bandwidth of sound waves, and its center frequency is relatively high, the volume of the room is relatively large, or the wavelength of the sound wave corresponding to the center frequency is much smaller than the average linearity of the room, and the number of simple positive waves excited in the room is larger, the diffuse acoustic field in statistical acoustics is in fact a high-frequency approximation of the standing wave acoustic field of a large room in fluctuation acoustics. Therefore, the room tends to have a homogeneous sound field in the high frequency range.The presence of QRD material changes the resonance frequency and modal distribution of the sound field, thus affecting the homogeneity of the room sound field.

II. D.Experimental design

II. D. 1) Experimental environment and test system

The experiments were carried out in the reverberation laboratory of the Institute of Acoustics, A University of Architecture. The geometrical dimensions of the reverberation laboratory are 8m long, 5m wide and 6m high with a cut-off frequency below 200Hz.

The measurement system uses the VA-Lab6 acoustic test system (triangular sound source, dodecahedral sphere sound source, power amplifier, six-channel data collector, computer, transducer, etc.); six transducers for measurement (the microphone conforms to the current national standard "Electroacoustic Sound Level Meter Part 1: Specification (GB/T3785.1-2010)" in the Ⅰ type of the provisions of the national standard), and the experimental instruments are connected to the experimental test system.

II. D. 2) Measurement point layout and test program

The sound pressure levels at measurement points 1, 2, 3 and 4 in the reverberation laboratory are obtained through measurements, and the uniformity of the sound field is judged by comparing different QRD arrangement schemes and analyzing the deviation of the sound pressure levels at each of their measurement points. According to "Acoustic Building and Building Component Sound Insulation Measurement Part III: Laboratory Measurement of Airborne Sound Insulation of Building Components (GB/T19889.3-2005)" laboratory test standard.

According to engineering practice, diffusers are usually installed on the ceiling or around the walls. Since the reverberation laboratory has three walls (top, north and east) with diffusion treatment, in which the ceiling is hung with diffusion panels, the experiment selected other walls and floors without diffusion treatment, and the floor is analogous to the ceiling of the room. According to the centralized and decentralized arrangement, six diffuser arrangements that are more in line with common sense in the experiment are selected to provide reference suggestions for the arrangement of QRD.

Step (1) in the simulation experiment of sound-absorbing materials simulates the effect of side-wall arrangement of sound-absorbing materials on the sound field uniformity. Step (2) simulate the effect of rear wall arrangement of sound-absorbing materials on sound field uniformity. The combination is divided into 1-7, whose frequencies of sound-absorbing materials at the intersection of the two walls are low frequency, high frequency, low frequency, high frequency, low frequency, low frequency, low frequency, high frequency.

III. Analysis of simulation results

III. A. Simulation results of sound-absorbing materials

The results of the influence degree of each parameter in the simulation of steps (1) and (2) are shown in Fig. 1-Fig. 4, and the scoring results are shown in Tables 1 and 2, respectively.

When the same sound-absorbing materials are arranged in the same way on the side walls, the uniformity of SPL, D50 and STI is better when the sound source is a loudspeaker, and the uniformity of EDT is better when the sound source is an ordinary male voice. The arrangement of sound absorbing materials on the side walls has a greater effect on EDT vs. T30 uniformity and a smaller effect on SPL, C80 shot, D50 vs. STI uniformity. The sound source has a greater effect on EDT, SPL, D50 & STI uniformity, while on T30 & C80. The effect of uniformity is small. In the case of the same arrangement of sound-absorbing materials and sound sources, the sound field uniformity is good when the low-frequency sound-absorbing materials are arranged along the intersection of the two walls. Whether it is loudspeaker or common male sound source, when the horizontal alternating arrangement of sound-absorbing materials on the side wall, the total score of low-frequency sound-absorbing materials arranged along the junction of two walls is the highest, among which the total score of combination method 3 is the highest, which is 34 and 38 points respectively.

Table 1: Step 1 must calculate the results

Combination mode	Ordinary men's voices are always divided	The speaker's sound source has to be divided
1	23	24
2	22	22
3	34	38
4	12	20
5	16	18
6	31	24

7	20	21

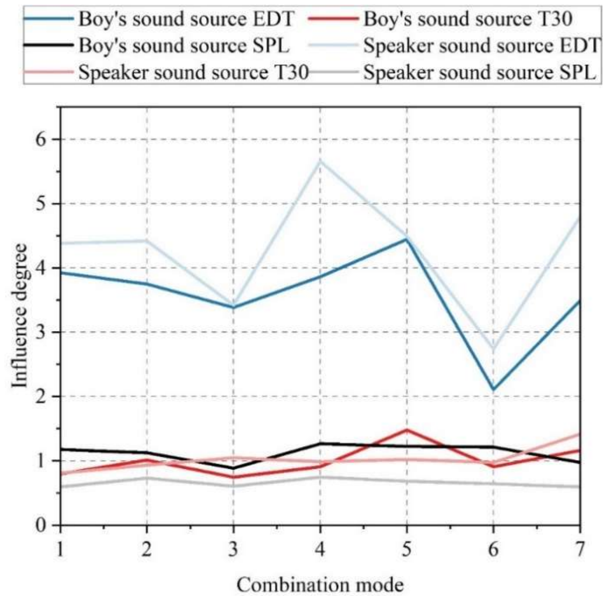

Figure 1: Effect of step (1) combination on EDT, T30, SPL

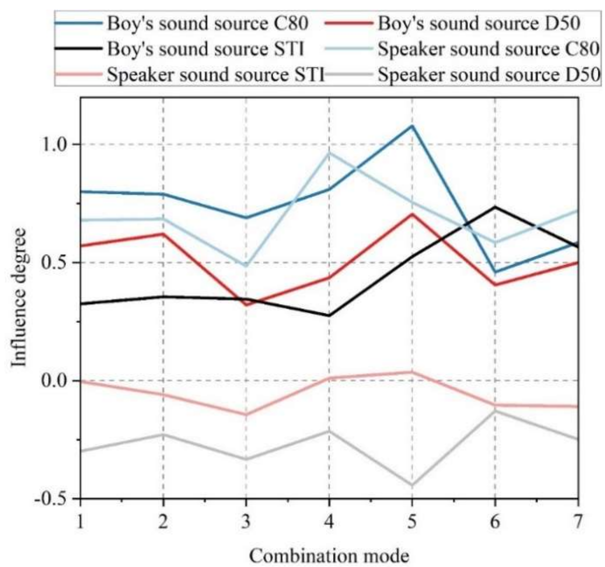

Figure 2: Effect of step (1) combination on C80, D50, STI

When the same sound-absorbing materials were arranged in the same way on the rear wall, the uniformity of SPL, D50, and STI was better when the source was a loudspeaker, and the uniformity of EDT was better when the source was an ordinary male voice. The arrangement of sound absorbing materials in the rear wall has a greater effect on EDT vs. T30, homogeneity, and a smaller effect on SPL, C80, D50. vs. STI homogeneity. The influence of sound source on the uniformity of EDT, SPL, D50, and STI is larger, while the influence on the uniformity of T30 and C80 is smaller. The arrangement of sound-absorbing materials in the rear wall has a smaller effect on the sound field uniformity, while the sound source has a larger effect on the sound field uniformity. When the sound source is an ordinary male voice and the rear wall is arranged with vertical alternating sound-absorbing materials, the arrangement of low-frequency sound-absorbing materials along the junction of the two walls has the highest total score, and it has the highest score of 32 points under combination mode 3. When the sound source is a loudspeaker and the sound-absorbing materials are arranged vertically alternately on the rear wall, the total score of the high-frequency sound-absorbing materials along the junction of the two walls is the highest, and the highest score is 37 under the combination mode 4.

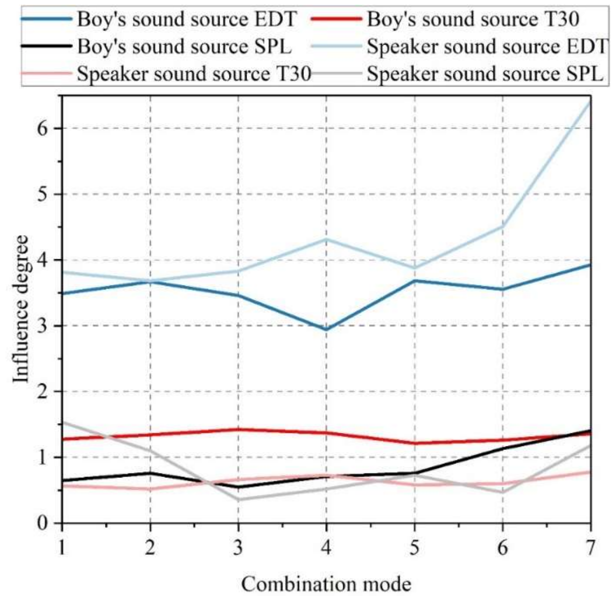

Figure 3: Effect of step (2) combination on EDT, T30, SPL

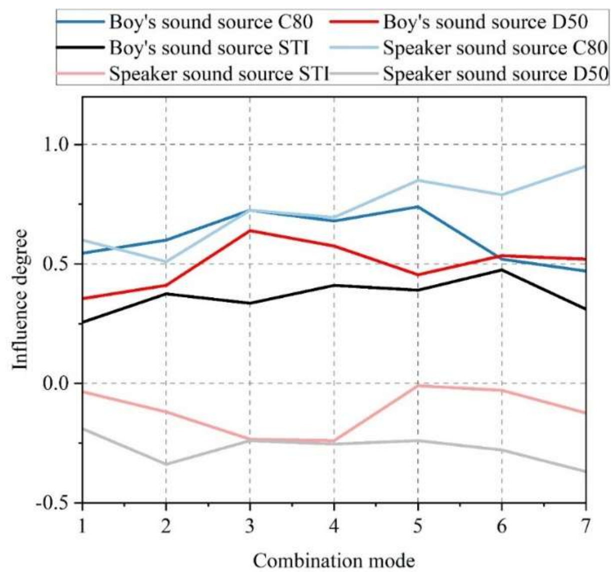

Figure 4: Effect of step (2) combination on C80, D50, STI

Table 2: Step 2 must calculate the results

Combination mode	Ordinary men's voices are always divided	The speaker's sound source has to be divided
1	22	20
2	28	32
3	32	24
4	19	37
5	18	22
6	24	19
7	21	28

III. B. Sound field diffusivity simulation results

In order to verify the diffusion performance of the above diffuser design, the sound field at 4 measurement points was simulated and analyzed using the architectural acoustic design software (Odeon). After calculation and simulation, the modal distributions of the four measurement points are shown in Fig. 5-Fig. 8. The modal density distribution of all measurement points is dense and uniform, which indicates that the sound field in the reverberation laboratory has good diffusivity. The average modal densities of all measurement points at the acoustic window of the reverberation laboratory are shown in Table 3. The modal density in each 1/3-octave band can meet the requirements of sound field diffusion.

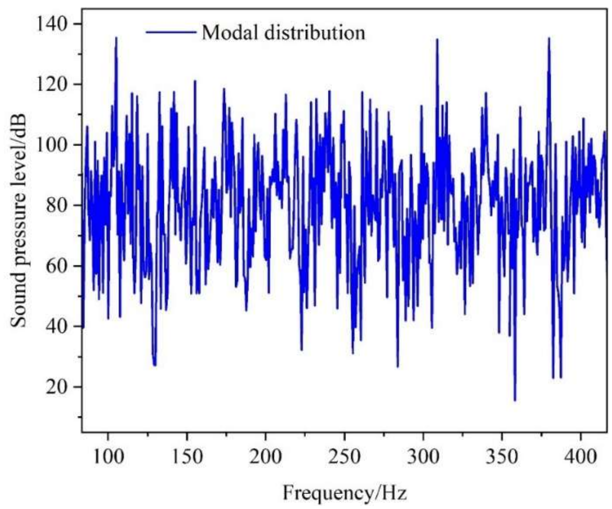

Figure 5: Modal distribution of point 1

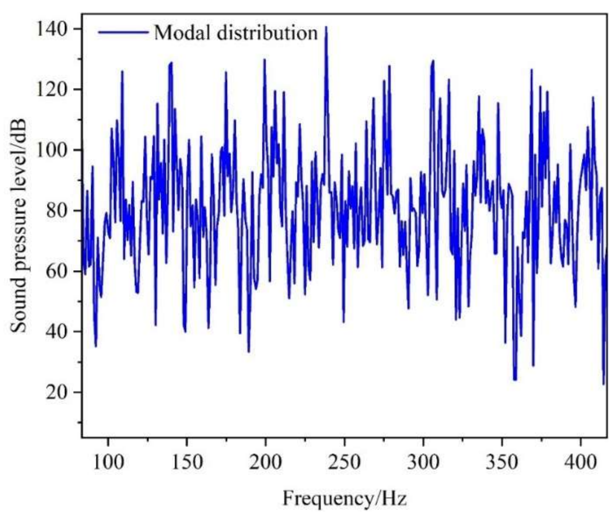

Figure 6: Modal distribution of point 2

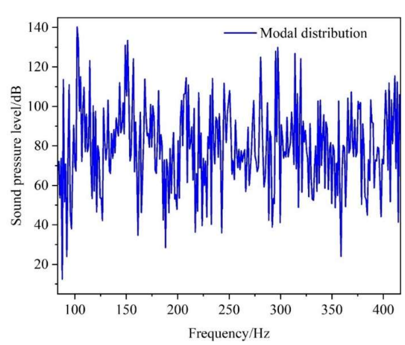

Figure 7: Modal distribution of point 3

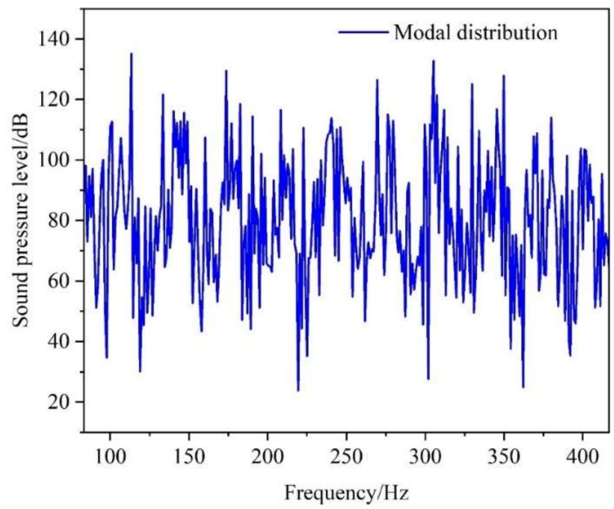

Figure 8: Modal distribution of point 4

Table 3: Average mode density of measuring points

The central frequency of the frequency range of the condition/Hz	Modal density
100	8
125	10
160	13
200	15
250	18
315	23
400	28
500	37
630	47
800	60
1000	75
1600	124
3200	211
4000	220
5000	208

IV. Conclusion

Through the systematic research on the configuration of sound-absorbing materials and sound field uniformity in indoor acoustic environments, this paper verifies the significant effect of reasonable material arrangement scheme on improving sound field distribution. The experimental data show that the background noise in the reverberation laboratory is controlled at the level of 20dB, which provides good basic conditions for testing. In the test frequency range of 200Hz-10000Hz, different arrangement schemes present obvious performance differences. Comparative analysis reveals that the material configurations of the side and rear walls affect the sound field uniformity to varying degrees, with the reasonable configuration of low-frequency sound-absorbing materials being a key factor in achieving excellent sound field distribution. The modal density analysis further confirms the effectiveness of the diffuser design, and the modal distribution at each measurement point is dense and uniform, which meets the basic requirements of sound field diffusion. The quantitative evaluation method established in the study provides a scientific analytical tool for acoustic design and can accurately predict the acoustic effects of different material configurations. The experimental results not only verify the correctness of the theoretical analysis, but also provide an important reference for practical engineering applications. The study is of great significance in promoting the scientific development of indoor acoustic environmental art design, and contributes new ideas and methods to the theoretical development and practical application in the field of architectural acoustics.

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