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Advances of acoustic research in coupled spaces

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Abstract: Coupled space widely exists in theatres, concert halls, large religious buildings, factories and other buildings, and its sound field is complex. Although some scholars have carried out relevant studies by means of sound field computer simulation, acoustic scale model test and field measurement, there are still a lot of problems unsolved. In this paper, the characteristics of coupled space sound field and the research progress of coupled space sound field in concert hall and theater are reviewed.

Keywords: Coupled spaces; Acoustical characteristics; Sound energy decay; Theatre; Concert hall.

1. Introduction

Good sound quality is the key to the success of performance architecture. The coupled space in theater and concert hall has a significant influence on the sound quality of sound field. There are three kinds of coupled spaces in traditional framed stage theater: the coupling between stage and auditorium, the coupling between auditorium and balcony, and the coupling between balcony space and auditorium. The coupling effect between stage and auditorium is the most obvious among the three coupling phenomena. Due to the needs of performance functions, the stage space of the theater is extremely complex. The large stage space and numerous screens and scenery make the limited natural sound energy on the stage be dispersed and absorbed. Without sound design, the sound environment of the stage will not only affect the strength and balance of the actors and musicians in the stage, but also affect the sound quality of the auditorium. At the end of 1960s, Artec acoustics consulting company in the United States started the application research of coupled reverberation space in concert hall, and called this kind of concert hall with coupled spaces "21st century hall". The acoustic environment of coupled space has gradually become one of the focuses of acoustic experts, mainly involving acoustic characteristics of coupled space and its influencing factors, including volume size of coupled space, coupled aperture size, acoustic properties of interfaces in coupled space, etc. In this paper, the characteristics of sound energy decay in coupled space and the research progress of coupled space sound field in concert hall and theater are reviewed.

2. Study on decay characteristics of sound energy in coupled space sound field

A significant acoustic property of coupled space is the double slope decay of sound energy. Schroeder's backward integration method is affected by background noise when calculating the last part of the double-slope decay function, and can not identify the different decay parts of the double-slope decay function well. To solve this problem, in 1998, Xiang Ning et al. applied the iterative regression method, which had previously been proved to improve the accuracy of reverberation time estimation [1], to the study of coupled space. By studying the convergence of nonlinear iterative regression, they revealed the potential feasibility and limitations of this method. And proposed a multi-slope decay model according to the calculation needs of double-slope decay function [2]. After that, Xiang Ning continued in-depth research in this aspect during the ten years from 2001 to 2011 and published a series of studies in the Journal of the Acoustical Society of America [3，4，5，6，7，8，9，10，11，12]. He applied the Bayesian parameter estimation method to estimate the decay time of coupled space and discussed the decay time and related parameter

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estimation under the Bayesian framework. By comparing with the measured data, it is proved that Bayesian probabilistic inference is a powerful tool for estimating the decay time of coupled space [5]. This is a parameter estimation method based on the nonlinear model of reverberation time decay curve. It does not need to estimate the initial value carefully, and can directly estimate multiple decay times in the decay function, significantly better than the nonlinear regression estimation method. In order to describe the decay of sound energy in multiple decay processes, Xiang Ning and Robinson et al. [10， 11， 12] used a coupled space system consisting of three coupled rooms to verify the Bayesian analysis method, using acoustic scale model and the numerical results based on diffusion equation model. And these analytical methods are applied to the geometric acoustic simulation of concert hall, the study shows that the Bayesian framework analysis method can determine more than two decay slopes and estimate the corresponding decay parameters. Zühre Sü [13] used field measurement, diffusion equation model, Bayesian analysis and other methods to study the indoor acoustic coupling in the whole space of Hagia Sophia. And The results showed that the distance between the receiving point and the sound source point and the distribution position in different subspaces would have an impact on the multi-slope sound energy decay in the church.

From the perspective of wave acoustics, Yuezhe Zhao et al. [14] analyzed the low-frequency normal mode and its characteristics of coupled space by using finite element method, and presented the finite element calculation model of room impulse response. Huiqun Li et al. [15] studied the spatial variation of sound field decay under different coupling conditions through scale model test. The results showed that when the decay curve of the main space sound field presented an obvious double fold curve, the classical statistical energy analysis method was not applicable to the prediction of this kind of coupled sound field. Guorong Jiang et al. [16] proposed an improved acoustic emissivity simulation method for sound energy decay in coupled space. Then, Jie Zhou et al. [17] further study on the fast acoustic radiosity algorithm shows that the algorithm is not only suitable for two-space coupled systems, but also for multi-space coupled systems. Hongjie Pu et al. [18] studied the conditions for the generation of sound fields of different decay types in coupled space through numerical simulation and experiment.

3. Study on characteristics of coupled space sound field in concert hall and theater

The decay of sound energy in the reverberation process of building space will have an impact on human auditory perception, and the existence of two or more decay slopes will have a significant impact on the sound quality of the hall. Architectural acoustics experts regard coupled space as one of the means to adjust the acoustics quality of the hall to meet the requirements of acoustic conditions under different functions. It is used in the design of performance building space, such as setting up reverberation auxiliary rooms connected with the main auditorium of the concert hall, coupling effect between theater stage and auditorium, etc. Therefore, more and more attention has been paid to the acoustics of the coupled space. Acoustors use computer simulation of sound field, acoustic scale model test and field measurement to study the coupled space volume, sound absorption and coupled aperture size.

In 2001, Harrison et al. [19] used CATT - Acoustic software to analyze the effects of volume, shape, coupled aperture size, and the location of source and receiver points on the acoustic characteristics of variable acoustic coupled space. This paper mainly optimizes the design of the Concert Hall of Goshen College in Indiana, and determines the validity of using the coupled space in the concert hall of Goshen College. The results showed that the coupled space volume has the greatest influence on the double-slope decay phenomenon. The influence of coupled space shape, coupled aperture size and the location of the source and the receiving point on the acoustic performance of the coupled space is smaller than that of the coupled volume. David and Wang [20-23] used ODEON computer simulation to study the effects of different volumes, sound absorption and coupled aperture size on sound energy decay in coupled space. This research focuses

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on verifying the effectiveness of sound field computer technology in analyzing coupled spatial sound field. By changing the aperture size, they studied the accuracy of predicting reverberation time and clarity in coupled concert hall by computer simulation [24]. The results showed that the accuracy is high in the high frequency range, but poor in the low frequency range. Then, in order to quantify the double-slope effect in concert halls with coupled spaces, David and Wang [25] use ODEON computer simulation and objective indicators such as coupling coefficient (T30/T15), decay rate (the ratio of slopes of two decay curves), and ΔdB (the difference of y-intercept of two decay curves) to describe the sound energy decay generated in the coupling concert hall.

Luizard et al. conducted a study on subjective listening evaluation in coupled space [26]. By changing the coupled aperture size between the main space and the secondary space of the concert hall to change the reverberation in the coupled concert hall, and discussing the audience's perception of reverberation changes when different types of music are played in the concert hall. Zhiyong Deng [27] systematically analyzed the objective sound quality parameters of a concert hall with coupled space under four typical conditions by means of multivariate variance analysis and ODEON. The four cases are the open-close states of the coupled space, the different layout positions of the coupled space, the different coupled aperture sizes and the interface materials in the coupled space with different sound absorption properties.

In theater building, the stage and auditorium form a coupled space through proscenium arch. Jeon et al. [28] studied the influence of variable stage elements (such as sky curtain, side curtain and stage setting) on reverberation time of the auditorium through 1:50 scale model. The results showed that variable stage elements had a great influence on reverberation time of the auditorium. Taking Tianjin Cultural Center Variety Theater as an example, Jianliang Gao [29] discussed the influence of stage sound absorption on the main acoustic parameters of the auditorium through indoor three-dimensional computer simulation and scale model test technology. In order to explore the influence of coupling effect in theater on reverberation time of auditorium, Jun Hu [30] conducted field measurement in Xiaoshan Opera House and found that the coupling effect of stage space generally has the greatest influence on reverberation time of auditorium at medium frequency and the least influence at low frequency. Based on L. Cermer coupled space theory model, Xiaolan Zhang et al. [31] studied the effects of coupling aperture and sub-space volume on reverberation time of sound source space were studied, and were verified by scale model experiment. The results showed that the coupling aperture is the main parameter affecting reverberation time when the secondary space volume is larger than the main space volume by a certain proportion.

In addition, some scholars focused on the influence of stage space absorption on the proscenium arch absorption. Xiang Yan et al. [32] studied the influence of different sound absorption conditions on the proscenium arch sound absorption through 1:10 scale model, and made theoretical estimation and quantitative measurement. It came to the conclusion that the proscenium arch absorption depends on stage volume, stage space absorption volume, auditorium volume and auditorium space absorption volume. Based on the research of Xiang Yan et al. , Xiaojun Yang and others continued to study the absorption of theatre proscenium arch. They studied the sound absorption of the proscenium arch under different acoustic conditions of the auditorium and the stage space by computer simulation of a model of the same theater with or without the stage space, while ensuring the same reverberation time of the auditorium. Xiaojun Yang et al. [33] further studied the sound absorption of the stage mouth of the theater based on the research of Xiang Yan et al. They studied the sound absorption of the proscenium arch under different acoustic conditions of the auditorium and the stage space by computer simulation of a model of the same theater with or without the stage space, while ensuring the same reverberation time of the auditorium. Shengming Li et al. [34] further advanced the research of Xiang Yan et al. and Xiaojun Yang et al., derived the equivalent sound absorption coefficient of proscenium arch from the calculation of reverberation time of stage space and auditorium, and presented a set of new prediction formulas. The comparison between the ODEON simulation and the formula results shows that there is some deviation between them.

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4. Study on other coupled space sound field

In addition to concert halls and theaters, more and more other architectural types, such as churches, mosques, and even apartments, have also attracted scholars' attention. Zühre Sü et al. [13，35，36] have conducted relevant studies on churches and mosques with coupled spaces by means of field measurement and acoustic simulation. Zühre Sü et al. [35] revealed the possibility of multi-slope sound energy decay in a single closed space structure with specific geometric shapes and material distribution under different acoustic characteristics by measuring the space with multi-dome superstructure. Then, they continued to further expand the study on the phenomenon of multi-slope sound energy decay in coupled space [36]. Through field measurement and acoustic simulation of Süleymaniye Mosque, the non-exponential sound energy decay characteristics of multi-dome Mosque space were studied. The results showed that multi-slope decay curves can be generated in a very large single space with specific geometry and material distribution. Lukas Aspock et al. [37] simulated a coupled space consisting of a laboratory and reverberation chamber, and The results showed that the measured double slope could not match the geometrical acoustic model algorithm. Yuqi Yang et al. [38] used COMSOL Multyphysics software to conduct numerical simulation of an apartment, and studied spatial sound energy distribution and reverberation time variation when each space is coupled or uncoupled.

5. Summary

There have been many studies on the characteristics of sound field in coupled space. The existing researches mainly focus on the double-slope characteristics of sound energy decay in coupled space, and the coupling effect of typical coupled space, such as concert hall with coupled reverberation spaces, and the coupling effect between stage and auditorium in theater. The research methods include theoretical analysis, computer simulation of sound field, acoustic scale model test and field measurement. The coupled spatial sound field is complex, and most of the existing researches have obtained qualitative laws, but there is still a lack of quantitative conclusions. Most of the studies are about objective acoustic parameters, but the effects of coupled space on subjective auditory evaluation are relatively few.

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