CHARACTERISTICS OF A CAVE-STYLE TRADITIONAL STAGE IN SHANXI PROVINCE, CHINA

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Résumé

Les scènes traditionnelles chinoises sont uniques dans l'histoire des théâtres antiques. Elles ont donc une grande valeur pour la recherche des caractéristiques acoustiques de scènes. Parmi les nombreuses scènes traditionnelles chinoises, les scènes en forme de grotte et murs en écailles de la province du Shanxi ont des effets acoustiques particuliers, qui sont simulés dans cet article à l'aide d'une approche temporelle à différences finies. Une technique conventionnelle combinée à des couches parfaitement adaptées est introduite dans les différences finies de l'équations d'onde prisent dans le domaine temporel. Cela permet de résoudre le problème acoustique d'une limite courbée en espace ouvert. Pour vérifier la validité du modèle temporel à différences finies, des valeurs simulées sont comparées à des valeurs mesurées. De plus, la distribution de la pression acoustique est simulée pour plusieurs modèles de scènes de type caverne et murs écaillé. En fonction des réponses impulsionnelles, plusieurs paramètres acoustiques de la pièce, tels que l'intensité sonore, la clarté et le temps de réverbération, sont analysés. Enfin, un test d'écoute basé sur une méthode de comparaison par paires est effectué.

Mots clefs : Chinois, scène traditionnelle, style grotte, mur d'écailles, domaine temporel à différences finies, acoustique, frontière courbe

Abstract

Chinese traditional stages are unique in the history of the world's ancient theaters, so they have significant meaning in research on their acoustical characteristics. Among the many Chinese traditional stages, the cave-style stages and splay walls in Shanxi Province have special acoustic effects, which are simulated using a finite-difference time-domain approach in this paper. The conformal technique combined with perfectly matched layers is introduced into finite-difference time-domain equations for sound waves, which solves the acoustic problem of a curved boundary in open space. To verify the validity of the finite-difference time-domain model, simulated values are compared with measured values. Furthermore, the sound pressure distribution of several cave-style stage models and splay walls are simulated. According to the impulse responses, several room acoustical parameters, such as loudness, clarity and reverberation time, are analyzed. Moreover, a listening test based on a paired comparison method is conducted.

Keywords: Chinese, traditional stage, cave-style, splay wall, finite-difference time-domain, acoustic, curved boundary

1 Introduction

Ancient theatres have been investigated for several decades in some fields, including architecture, archaeology, drama and acoustics [1]. However, most of these acoustic researches are on ancient Greek and Roman theatres [2-4], and very little on traditional Chinese theatres.

In ancient Chinese buildings, acoustic buildings are mostly attached to other architectural types, which can be divided into open-air theatres, courtyard theatres and indoor theatres, for example [5]. The courtyard theatre is the most important form of ancient Chinese acoustic buildings. In addition to their important historical and cultural value, ancient Chinese acoustic buildings also contain the ancient Chinese understanding of architectural acoustics and the application of architectural acoustics technology. The study of ancient Chinese acoustic buildings has a positive significance for us to understand the architectural wisdom of the ancient Chinese and better use the principles and techniques of modern architectural acoustics.

A few scholars have carried out preliminary research on ancient Chinese acoustic architecture in China [6, 7]. However, most of these studies are from the perspectives of history, culture, architectural structure, building repair and protection, and seldom from the architectural acoustic point of view. Due to reasons of culture, history and climate, most of the remaining ancient Chinese acoustic buildings are in Shanxi Province. There are many cave-style stages in the middle and the west of Shanxi Province. The structure of this kind of stage is related to the cave buildings where the local people live, and its structure is similar to the coupling space in the hall, which has certain significance to exploring its acoustic properties. Since the Qing Dynasty, the architectural form of the traditional stages has tended to mature; meanwhile, traditional stages in Shanxi Province with splay walls on two sides of the stage mouth became popular. The shape of splay walls is various and their sizes are different; furthermore, the splay walls are set at the stage mouth similar to the reflected boards at the modern stage mouth, which not

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only beautifies the stage but also improves the sound quality of the stage.

Ancient Chinese acoustic buildings have some characteristics. They are mostly open space or roofless, making it difficult to describe the acoustic characteristics using traditional acoustic parameters. A majority of ancient Chinese acoustic buildings fail to be preserved because of the climate, wars caused by dynasty change and other reasons, which makes measurements impossible. However, we can refer to historical materials to restore the sizes of the building structures, obtain the acoustic characteristics through measuring the sound absorption coefficient, and then build computational models. Currently popular acoustic simulation software includes EASE, Odeon, CATT and so on [8, 9], but they can only simulate large space acoustics and high frequency sound. For low frequency and small room acoustics, wave acoustic method is required. The space dimensions of ancient Chinese acoustic buildings are generally not large, so it is suitable to apply a computer research method based on wave acoustics.

The research methods based on wave acoustics mainly include the finite element method [10], the boundary element method [11], and the finite-difference time-domain method (FDTD) [12, 13]. The first two methods are calculated in the frequency domain first and then converted into time domain results, which are more complex. FDTD is based on the numerical calculation of the time domain, whose calculation is simple, and the sound field distribution can be calculated. In this paper, we build several kinds of cave-style models to compute the impulse response of receiving points through FDTD. The cave-style stages are curved boundary and the splay walls are tilt boundary, which cannot be represented in a Cartesian grid. The curved boundary, which is traditionally represented in a stair-step fashion, has a low accuracy [14], hence a locally conformal technique is used to solve the curved boundary. The acoustical parameters such as loudness and clarity are analyzed from the impulse response. At the same time, a subjective evaluation test is carried out to verify the parametric analysis and study the sound effect of cave-style stages.

2 Numerical methods

In a Cartesian grid, the three-dimensional acoustic wave equation and the continuity equation in an ideal air medium are discretized with finite differences [15]. The finite-difference scheme for these equations in a uniform staggered grid can be written as difference equations (12)-(15) in reference [16]. Generally, the space step Δh is less than one tenth of the wave length λ to guarantee the computational stability; that is, $\Delta h \leqslant \lambda/10$. Meanwhile, the time step and space step should also satisfy the stability condition shown as the equation (18) in reference [16]. In this paper, the space step Δh was set to 0.07 m; thus, the time step Δt was set to 117 μs.

2.1 Excitation source model

When there is a sound disturbance in a room, the propagation of sound waves in the room can be calculated recursively according to the wave difference equations. Temporal evolution of the sound pressure value observed at all time steps of a point in the room is the impulse response of that point. The sound pressure of all points in the room at a certain moment is the sound field distribution. To calculate the impulse response of the receiving point, the sound source is generally set as the derivative of a Gaussian function of equation (28) in reference [16], and the parameters were set to α=0.711 49×10^6, β=2.683 18×10^{-3} in this paper.

2.2 Boundary conditions

Impedance boundary

Limited by computer memory and computing time, when wave difference equations are used to recurse the sound pressure and vibration velocity of some point in the sound field, it needs to be limited within a certain space, which requires the corresponding boundary conditions. Boundary conditions are an important part of FDTD research. In the previous study, impedance boundary conditions related to the sound absorption coefficient are shown in reference [17].

Conformal-PML boundary

The actual building boundary is usually a curved surface, which is dealt with using the traditional method of stair-step approximation. As the approximation can cause some errors, locally conformal FDTD equations for a 3D acoustic wave motion with rigid boundaries were presented by Tolan [18]. The rigid boundary is treated by setting the particle velocity to zero. The walls of ancient stages are mostly made of black brick, with an absorption coefficient from 0.03 to 0.07. Since the absorption coefficient is very small, the building surfaces are treated as rigid boundaries. The ground, which is mainly mud, is set as an impedance boundary with the absorption coefficient of 0.2. In contrast to the rigid boundary, the perfectly matched layer (PML) absorption boundary completely absorbs the incident wave, which was used to simulate the free field boundary. The PML equations shown in reference [19] which can directly replace the wave difference equations.

The traditional stage is not a closed space; hence, the boundaries of these non-architectural interfaces can be treated as PML boundaries. Combining locally conformal equations [18] with the PML boundaries [19], the pressure update equation is obtained

$$p_x^{n+1}(i,j,k) = e_x^{(1)}(i,j,k)p_x^n(i,j,k) - e_x^{(2)}(i,j,k) \\ \times[A_x(i,j,k)u_x^{n+1/2}(i,j,k) - A_x(i-1,j,k)u_x^{n+1/2}(i-1,j,k)]/V(i,j,k) \quad (1)$$

where u_x is gas particle velocity in x direction; p_x is the pressure of gas in x direction; the coefficient e_x is listed in reference [19]; $V(i, j, k)$ is the cell volume outside the rigid boundary, $A_x(i, j, k)$ is the area of a cell face outside the rigid boundary. Eq. (1) is the conformal-PML equation in x direction and the update equations in y and z directions are analogized.

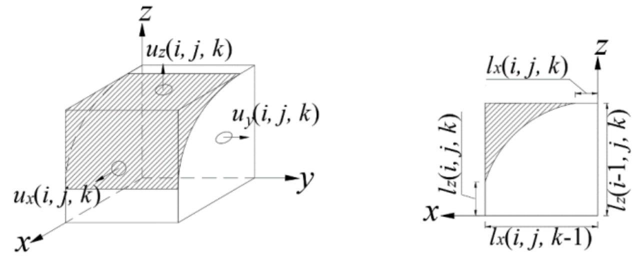


Figure 1: 3D conformal mesh and its projection. Left is a conformal grid cell and right is its projection on the *xoz* plane.

As Tolan suggested previously, the grid cell was subdivided into smaller subcells, and the total number of subcells were then counted to determine the area $A(i, j, k)$ and volume $V(i, j, k)$. This method is time-consuming and complex, therefore, in this paper, the volume and area of the boundary of the curved surface were calculated by the projection method shown in Figure 1. Setting the vault as a semicircle, we use the intersection between the equation of the semicircle and the grid to find the length of each edge $l_m(i, j, k)$, from which we can obtain the area $A_m(i, j, k)$ and volume $V(i, j, k)$ from the product between $A_m(i, j, k)$ and the grid length, where m represents one of the surface normal directions x, y, or z.

3 Site measurement and verification

There are hundreds of cave-style traditional stages in Jinzhong City, Shanxi Province. There are single-hole and multi-hole cave-style traditional stages, among which the four-hole-intersection style is the most complex. The front view of the traditional stage of Chaoshan Temple in Xiaohu Village, Pingyao County, Shanxi Province, is depicted in Figure 2. The stage is four-hole intersecting, and the internal structure of the backstage is shown in Figure 3. According to local residents, the original length of proscenium was 5 m, but now it has been removed and only a 2.2 m long proscenium is left. On the opposite side of the stage is a cave-style wing, on its right side is a living bungalow, and on its left side is a brick wall, which is enclosed on all sides.

Figure 2: Front view of the traditional stage of Chaoshan Temple.

Figure 3: Internal structure of the backstage.

3.1 Site measurement

With reference to international standard ISO 3382-1:2009 [20], a starting gun was used as the pulse sound source, and the sound source was located on the central axis of the stage at a height of 1.5 m from the ground. A convenient microphone was placed at the receiving point at a height of 1.3 m from the ground. Due to the symmetrical structure of the stage, the receiving points were only located on one side of the central axis of the stage, and there were 11 receiving points arranged at equal intervals. Audition software was used to record the measured pulse responses, and the yard was empty except for our three measurers during the measurement. The distribution of receiving points is shown in Figure 4.

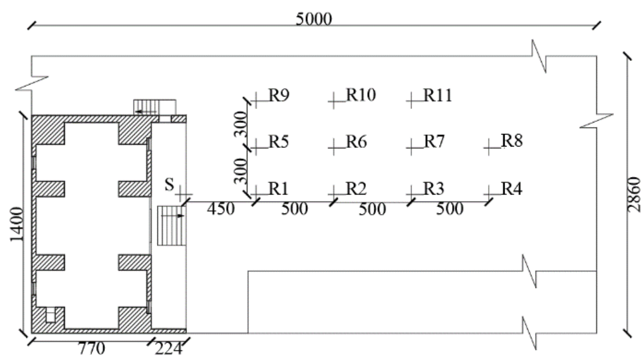


Figure 4: Distribution map of receiving points at the Chaoshan Temple stage, Xiaohu Village.

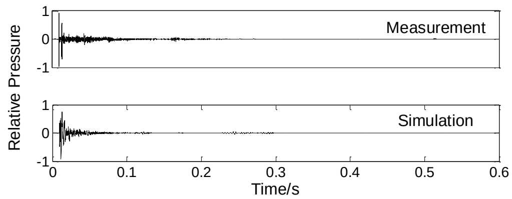
3.2 Simulation Model

According to the size in the distribution map of receiving points at the Chaoshan Temple stage, the simulation models containing the surrounding walls were established. Several trees in the yard were ignored in the model, and the houses in the yard were treated as brick walls. The ground was set as the impedance boundary with a sound absorption coefficient of 0.55, and the surrounding brick walls whose height was 2.1 m were set as the impedance boundary with a sound absorption coefficient of 0.11. To facilitate programming, the brick walls of the stage were set as the rigid boundaries. The sound source point and the receiving points were set as shown in Figure 4.

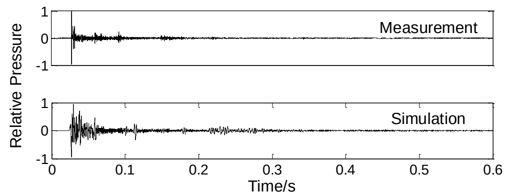
3.3 Comparison between measured and simulated results

The impulse response of each receiving point can be obtained after simulation calculations, and a receiving point was selected from each column to be compared with the measured results, as shown in Figure 5.

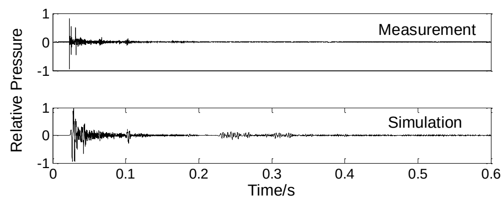
As Figure 5 shows, the sound pressure attenuation trend of impulse responses obtained by the simulation and the measurement are similar. Because the stage was set to a rigid boundary in the simulation model, the late reflected sound pressure of the simulated results caused by the cave backstage was bigger. On the contrary, the measured result of reflected sound pressure was small owing to air absorption and sound absorption of plants.



(a) Receiving point R1



(b) Receiving point R6



(c) Receiving point R9

Figure 5: The measured and simulated impulse responses of three receiving points.

Some parametric analyses were made to the impulse response of the 11 receiving points, their average was calculated and the measured and simulated results were listed in Table 1. From the data, the clarity C_{80}, the early decay time EDT, and the reverberation time RT of the measured results were basically consistent with the simulated results, which illustrated that the finite-difference time-domain method applied to the architectural acoustics was accurate and the boundary model set up in this paper was valid.

Table 1: Parameter analysis of measured and simulated results.

	C_{80} (dB)	EDT (s)	RT (s)
Measurement	10.75	0.63	0.78
Simulation	8.62	0.77	0.76

4 Subjective listening test

4.1 Experimental models

Based on the structure and size of the traditional stage of Chaoshan Temple, as well as literature and field trips, four stage models with different kinds of backstage structure were built. Model 1 had no cave in the backstage; that is, the hole was blocked with a wall. The backstage cave of Model 2 was vaulted with a single longitudinal cavity facing the auditorium. Similarly, the backstage cave of Model 3 was vaulted, with a two-hole-intersection style. Likewise, the backstage cave of Model 4 was vaulted, with three vertical and one horizontal cavity in a four-hole-intersection style. Model 4 was the model closest to the backstage of the traditional stage of Chaoshan Temple, whose 3D scenograph is shown in Figure 6.

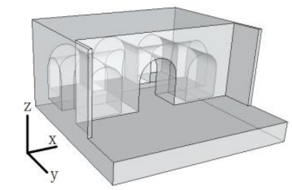


Figure 6: 3D scenograph of the ancient stage of Chaoshan Temple

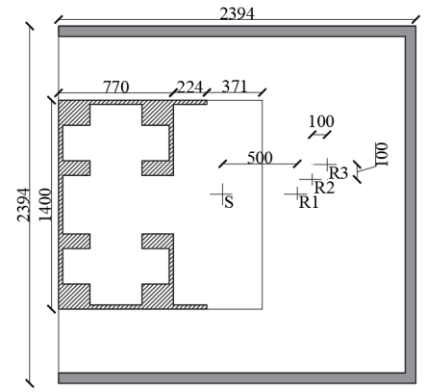


Figure 7: Positions of sound source point and all the receiving points in model 4. Dimensions in cm. The dark gray represents the PML boundary and the diagonal line represents the wall.

The computing space of the whole courtyard model was 23.94 m×23.94 m×7.49 m. There were two walls with a width of 2.52 m on both sides of the stage. The sound source point S was located on the central axis with a coordinate position of (11.97 m, 11 m, 3.01 m). The receiving point R1 with a height of 1.47 m was set in the auditorium 5 m away from the sound source; likewise, receiving points R2 and R3 were set at the same height of R1, as shown in Figure 7. The stage base is as high as these receiving points.

4.2 Listening test arrangement

To conduct the listening test, it is necessary to calculate the binaural impulse response of the listening position. Since it is very difficult to set the head model in the calculation model, in this paper two points with a distance of 0.21 m were taken as the left and right ear positions. As the spectrum of the excitation source was not straight, its impulse response, which was calculated by the finite-difference time-domain method, needed to be corrected. The sound sources selected from the signal library of Odeon software were convolved with the corrected impulse response to obtain the audio signals. Then, the audio signals were played through the headset for the test. Three sound sources that are similar to ancient Chinese opera were chosen for this test. The horn and flute are often used in the performance of ancient Chinese opera, and the soprano is close to the singing form of ancient Chinese opera. Therefore, we used Flugel's Amazing Grace and Bach's Badinerie and Soprano as sound sources, whose segments of 4 s, 5 s and 9 s were intercepted, respectively. The acoustic effects of the models were evaluated by the traditional paired comparison method. Any two models constitute a comparison pair; hence, each subject had to compare 90 pairs of signals of three receiving points.

The operation interface of the test was designed by Matlab GUI. The subjects wore headphones to complete the experiment on this interface and the data results were saved automatically. Four male and four female students whose age ranged from 21 to 29 were chosen to take part in the test. All of them had listening test experience. The test was conducted in a control room with ambient noise less than 40 dB. The AKG K702 headphone was used for listening, whose frequency response curve at 20 Hz~16 kHz is basically straight. On the operation interface, the sound signal of first model as A and the sound signal of second model as B were marked. The reference signal was labelled, which was copied from first model as A_0. The play order of A and B was generated randomly. Signals A, B and A_0 can be played after clicking. The subject was asked to choose the same signal as the reference signal A_0 between A and B, and judge the criterion, mainly from five subjective evaluation factors; that is, loudness, clarity, sense of space, sense of distance, and fullness.

Before the test, the subjects received the interpretation of acoustic evaluation indexes; in particular, reverberation sense and fullness. The formal test begins after several listening practices can be selected correctly. During the test, subjects were asked to listen to a signal at least three times. Subjects were forced to choose either A or B as much as possible, although they were allowed to choose nothing if they really could not hear the difference. Subjects clicked to play A_0, A or B until the final choice was made.

4.3 Results and Analyses

Acoustical parametric analyses

As the traditional stage is not an enclosed space, we considered the PML boundaries as walls with a sound absorption coefficient of 1 and then calculated the room impulse response. According to the room impulse responses, the sound quality of cave stages can be evaluated. In the performance of ancient Chinese opera, the volume should be large enough to deeply infect the audience. In this paper, we chose the sound strength G that is related to volume as the loudness indicator [21]. A Schroeder decay curve for each receiving point can be obtained by reverse-time integration of the squared impulse responses; from the decay curves, the reverberation time T_{30} and early decay time (EDT) can be calculated. The sound strength G, clarity, reverberation time and early decay time of each model calculated at three receiving points in the auditorium are listed in Table 2.

The results show that G of Model 2 is significantly larger than that of other models. The vertical cave can provide a sound energy supplement to the auditorium as a form of coupling space, which can enhance the value of G in the auditorium as well. Because the lateral cave retains a certain amount of sound energy, the values of G in Model 3 and Model 4, which have both a vertical cave and a lateral cave, are similar to that of Model 1 because the vertical cave provides a sound energy supplement to the auditorium, which reduces the clarity (C_{80}) of the latter three models. However, because the auditorium is open, the C_{80} of all models are positive; that is, the clarity of the auditorium is good. The values of reverberation time T_{30} of all models range from 1.70 s to 1.83 s, which are larger than the optimal value proposed by Barron [22]. The optimal value of reverberation time proposed by Barron is for modern closed theatre halls, while most traditional Chinese stages are not closed; therefore, the optimal value does not fit here. T_{30} of Model 1 is larger than the latter three models; however, the reverberation time of the latter three should be larger because there are vertical caves in their backstage providing an acoustic energy supplement, which can enhance the sense of reverberation. Therefore, reverberation time T_{30} is not accurate to describe the reverberation of ancient Chinese stages. Another indicator related to reverberation time is the EDT, shown in Table 2 for all models ranging from 0.96 s to 1.42 s. The values of EDT for the latter three models are larger than that of Model 1, and they are smaller than their corresponding T_{30}, so the EDT can better explain the reverberation sense than T_{30} for open ancient stages.

Table 2: G、C_{80}、T_{30} and EDT of four models.

	Receiving point	Model 1	Model 2	Model 3	Model 4
G	R1	6.93	7.55	7.20	6.92
	R2	5.75	6.08	5.74	5.74
	R3	4.80	5.29	5.00	5.10
C_{80}	R1	6.87	5.24	5.48	5.32
	R2	5.44	3.78	4.87	4.55
	R3	4.34	3.24	3.83	3.34
T_{30}	R1	1.83	1.75	1.78	1.79
	R2	1.78	1.72	1.77	1.76
	R3	1.74	1.70	1.72	1.71
EDT	R1	0.96	0.98	0.96	0.99
	R2	1.25	1.42	1.28	1.37
	R3	1.25	1.29	1.37	1.4

Subjective listening results

Each time point compares a signal pair (a_i, a_j), where a_j acts as the reference signal. A score of 1 is given if the selected signal is consistent with the reference signal, while a score of 0 is given if the selected signal is wrong, while a score of 0.5 is given if the subject chooses nothing. The rate of accuracy can be obtained by dividing the total test number by the score of all subjects, and the results are shown in Table 3.

Table 3: Accuracy of the listening test.

a_j	a_i			
	Model 1	Model 2	Model 3	Model 4
Model 1	----	0.958	0.937	1
Model 2	0.042	----	0.791	0.889
Model 3	0.063	0.209	----	0.868
Model 4	0	0.111	0.132	----

After the data for all subjects are statistically analyzed, the accuracies of flute, horn and soprano are 0.88, 0.85 and 0.78, respectively. The accuracy of three kinds of material exceeds 0.7, while internationally accepted criteria for judging and evaluating test ranges from 0.6 to 0.7 [23], which shows that the species of listening materials had little influence on the test, and the results of the three materials were all effective.

The correct selection of subjective evaluation factors was statistically analyzed, as shown in Fig. 8. The probabilities of correct selection according to the sense of space and fullness were 0.69 and 0.74, respectively, which were in the range of the credibility index; however, the accuracy rate of the other three evaluation factors was lower than 0.5. This result shows that the effect of a cave-style stage on the sense of space and fullness was obvious, but the effect on loudness, clarity and distance was not obvious.

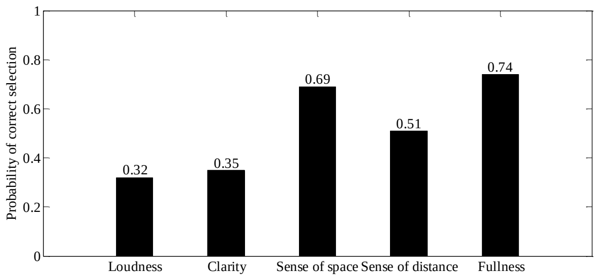


Figure 8: Probability of correct selection of five factors

The accuracy in the first row of Table 3 is above 0.937; that is, the latter three models with a cave backstage bring more fullness and sense of space than Model 1 without a cave backstage. By comparing the second and third rows in Table 3, the accuracy is almost above 0.8, which implies that the four-hole intersecting type and the two-hole intersecting type can be distinguished clearly from the single-hole longitudinal type; that is, it is easier to judge fullness and sense of space with the horizontal cave. In the last row of Table 3, the accuracy is 0.868, which shows that it is easy to distinguish the four-hole intersecting type from the two-hole intersecting type. Above all, the traditional stage with the four-hole intersecting type has the best fullness and sense of space. In parametric analyses section, the EDT of the latter three models is larger than in Model 1, which means that their reverberation and sense of space will be stronger. The subjective evaluation results are consistent with the EDT analysis in parametric analyses section, which further indicates that EDT is better than T_{30} to describe the reverberation of the traditional stage without a roof.

5 Splay walls

Since the Qing Dynasty, the traditional stages in Shanxi Province have been equipped generally with splay walls. Fig. 9 shows the traditional stage of Houtu Temple in Jiexiu City, Shanxi Province. The entablature has splay walls with a 1.4 m length above the stage on both sides (marked with red circles in Figure 9), and there is a 45-degree angle between the splay walls and the north-south axis. The structure of the splay wall is similar to the sound reflection boards in both sides of the stage mouth in a modern theater, which can gather sound and enhance the lateral reflection sound. The following part will discuss the acoustic effect of the splayed wall by establishing models according to the traditional stage of Houtu Temple.

Figure 9: Traditional stage of Houtu Temple in Jiexiu City, Shanxi Province.

5.1 Splay-wall models

At the ends of walls on both sides of the cave-style stages, connect the splay walls with a height of 3 m, a thickness of 0.28 m and a width of 3 m or 5 m. Due to the symmetry of the stage, it is enough to set receiving points on one side of the auditorium for investigation. The positions of 15 receiving points are shown in Figure 10.

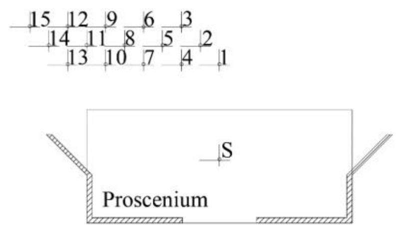


Figure 10: Coordinate positions of 15 receiving points in the auditorium.

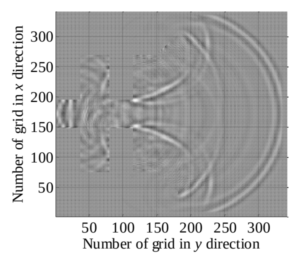


Figure 11: Waveform distribution of cave Model 3 with splay walls. At a height of 2.1 m above the ground, the sound source propagates for 40 ms.

Figure 11 shows the waveform distribution of cave Model 3 with splay walls whose width is 3 m. In this figure, the intensity of the sound wave is represented in gray scale. The waveform shows that the splayed walls reflect part of the sound wave back to the audience area, which can enhance the sound energy of some parts.

5.2 Results and Analyses

Laterally reflected sound energy is related to sense of space, and the definition of lateral energy factor is

$$LEF = \int_{5ms}^{80ms} p_L^2(t)\,dt \Big/ \int_0^{80ms} p_0^2(t)\,dt \ . \qquad (2)$$

Eq. 2 indicates that the ratio of the energy delayed within 5~80 ms after the arrival of direct sound to the total energy arrived within 80 ms. To determine the contribution of splay walls to the early sound energy, for the same receiving point, the effect of early reflection sound before and after the splay walls is added was compared. The early sound energy ratio is defined as

$$R_e = \int_0^{50ms} p_1^2(t)dt \Big/ \int_0^{50ms} p_0^2(t)dt \qquad (3)$$

where p_0 represents the sound pressure when there are no splay walls and p_1 represents the sound pressure when there are splay walls. When R_e is greater than 1, it means that the reflected sound energy with splay walls is greater than that without splay walls. Since the difference of *LEF* and R_e of each model obtained after simulation is not large, the results are averaged and listed in Figure 12 and Figure 13.

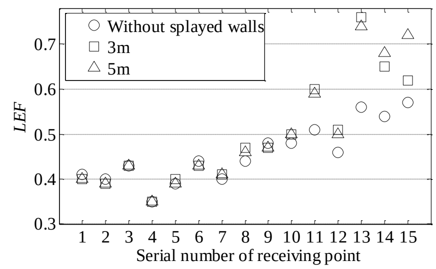


Figure 12 : The average lateral energy factor of all the models

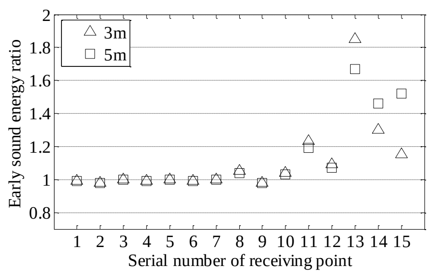


Figure 13 : Early sound energy ratios of all the models

From the two figures, the *LEFs* of these 15 receiving points are within 0.35~0.76, and the early sound energy ratios are within 0.98~1.85. For receiving points 1~7, the *LEF* and early sound energy of these three situations are almost similar, while for receiving points 8~15, the *LEF* and the early sound energy of models with splay walls are larger than those without splay walls, which shows that splay walls can strengthen the lateral reflection of sound on both sides of the auditorium but have little effect on the middle of the auditorium. If the length of the stage is shortened, it can enhance the acoustics of the middle part of the auditorium. Schroeder once noted that classical theater buildings are high and narrow, and boxes and large architectural decorations help to produce more lateral reflection sound, so the sound quality of these classical theaters is better. On the contrary, the modern theater always has a large horizontal span, and it lacks the early lateral reflection of sound, so its sound quality is poor. The same is true for the stage; that is, the horizontal span of the stage is smaller, and if there are splay walls on both sides of the stage, the auditorium can produce more lateral reflection sound, and the listening sense will be better. For receiving point 14 and receiving point 15, the *LEF* and early sound energy of splay walls with a width of 5 m is larger than that with a width of 3 m, which shows that the larger the width of the splayed walls, the greater the sound effect of the larger range of the auditorium. In conclusion, splay walls can not only enlarge the size of the stage and beautify the stage shape but also improve the sound quality of the stage.

6 Conclusion

In this paper, the recursive equations are improved by combining local conformal finite-difference time-domain equations of acoustic waves proposed by predecessors with the perfectly matched layer boundary. The results of objective acoustic parameter analysis of pulse responses and listening tests show that sense of space and reverberation of the stage with a cave are stronger. It is confirmed that the early decay time (EDT) is better than the reverberation time T_{30} to explain the reverberation of the court stage without a roof. Similar to the design concept of modern coupling space, this cave structure can improve the sound quality of the building.

The stages with a backstage of horizontal and longitudinal caves meet the architectural concept of Chinese architecture, and also provide more space for actors and performance equipment storage. There is no doubt that the longitudinal cave opening to the auditorium is designed to provide more and louder sound to the audience. The longitudinal cave-style stage adopted by the acoustical designers in ancient China fits the design concept of modern coupling space, which indicates that the cave-style stage is an earlier acousticcal building in China that adopts the form of coupling space.

In addition, the splay walls on both sides of the stage can enhance the sound energy of some parts of the auditorium, which is similar to the role of the reflector board in the modern stage. To summarize, it can be seen that the ancient people's architectural wisdom was advanced, which inspires us to further explore the technology of ancient Chinese acoustic architecture and apply it to modern stage architecture.

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