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Architectural categories and acoustic characteristics of traditional Chinese theatres

Jie He, Jian Kang

School of Architecture, University of Sheffield, Sheffield S10 2TN, United Kingdom

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ABSTRACT

Chinese opera, with distinctive Chinese characteristics, plays an important role in traditional Chinese culture, and forms a unique part of the treasure-house in world history. Correspondingly, traditional Chinese theatrical buildings, closely related to Chinese opera, have also attracted great attention. In terms of architectural shape, they can be classified into three main types: open-air theatres, courtyard theatres and indoor theatres. Among them, courtyard theatres made up the majority of all types of traditional theatre. In this paper, firstly, the categories and architectural characteristics of traditional Chinese theatres are reviewed. Secondly, this paper discusses the acoustic characteristics of traditional Chinese theatres according to these three different types. A number of acoustic indices, such as EDT, T_{15}, T_{30}, D_{50}, C_{80}, G, SPL, LF and STI have been analysed and compared through computer simulation.

INTRODUCTION

Cultural and historical values of Chinese opera and traditional theatres

Chinese opera which originated from Yuewu, Paiyou and Baixi drama (Chinese: 乐舞、俳优、百戏) of the Qin and Han dynasties is a unique performing art that integrates singing, dialogue, acting and acrobatics (Chinese: 唱、念、做、打). Of this assortment, singing is the focus, and different tunes are represented in different kinds of local operas. In addition, the characters of various types of local opera were mostly divided into four groups. They were Sheng, Dan, Jing, and Chou (Chinese: 生、旦、净、丑), where Sheng was the male role, Dan was the female role, Jing was the martial role and Chou was the clown. Traditional Chinese opera did not only reflect many fields ranging from politics, economy and culture of all the past dynasties, but it is also regarded as one of the three oldest types of drama in the world, together with Greek tragedy, Greek comedy and Indian Sanskrit drama [1].

Traditional Chinese theatres closely relating to all these kinds of local opera were also declared World Heritage Sites by UNESCO and are included in the list of monuments that should be preserved. Being places for performance through the ages, they were important active centers of social and cultural life. Therefore, they obtained various names and forms in different times and areas, and took a special role in Chinese architectural history [2].

Architectural categories and characteristics of traditional Chinese theatres

Chinese opera originated from activities of religious sacrifice, and did not become mature until modern times. Therefore, temple theatres all around China made up the majority of various categories of traditional theatre. In the following period of theatrical development, some commercial theatres appeared that made the theatrical troupe professional. Simultaneously, some guild halls which helped countrymen meet together also had stages. They regularly held various kinds of dramatic performances and activities, which mainly occurred for social networking. Furthermore, there was a large opera tower in the palace used for celebrating festivals and some small and medium theatres provided dramatic performances for the pleasure of emperors. In addition, the stage was a tasteful fashion that made an appearance in mansions, private houses and homesteads.

From the above, many different scales and categories of theatres appeared, according to the evolution of local operas, changing with the times and with the advancement of architectural technology. In terms of the architectural shape, they can be divided into three main types described briefly below: open-air theatres, courtyard theatres and indoor theatres.

1. Open-air theatres

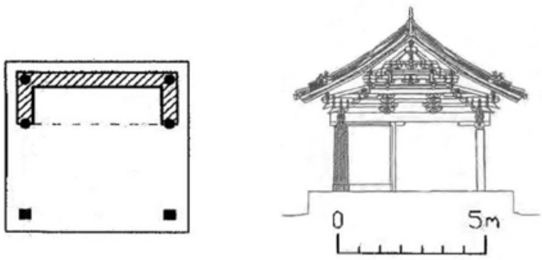
The early location for performance of Chinese opera was similar to the original theatrical performance places in other parts of the world, and was simply a crude and open square trampled out by people. And the audience watching the dramatic plays crowded around the square to form a harmonious performance environment [3]. Because the square-style show has always been an important form of entertainment, it continues to exist in virtually every region, especially in the rural area of southern China. Figure 1 shows the opera troupe played a local opera named The Yang Saga (Chinese: 杨家将) in the field.

Source: (Xin Hua Net, 2008)
http://www.njxhw.com/content/2008-2/25/2008225132030.htm
Figure 1. A local opera show held in the field of Baojiatun village, Daxiqiao town, Xixiu district, An'shun city, Guizhou province (贵州省安顺市西秀区大西桥镇鲍家屯村)

After the maturation period of traditional theatrical buildings, open-air theatres with a stage in the center, surrounded by open land, were still more common than nowadays, especially for some temporary stages. The audience standing on the ground watched the dramatic performance from the front or from the three sides of the stage. This type of traditional theatrical building could not only be seen in many ancient paintings, but also may be investigated from historic sites of the Jin and Yuan dynasties of 800 years ago [4]. Because of their simple architectural layout, they were also highly visible in northern and southern rural areas, and lots of dramatic performances were still held there frequently.

Figure 2 shows the stage of Niu Wang Temple (Chinese: 牛王庙), which was the oldest existing stage in China built in 1293, Yuan dynasty. The plan of the stage was square, and the structure constructed in a well-shaped frame (Chinese: "井"字形框架). The top of the stage is covered with two types of roof which are firstly the gable and hip roof with single eaves (Chinese: 单檐歇山顶) and secondly the cross-shaped gable and hip roof (Chinese: 十字歇山顶).

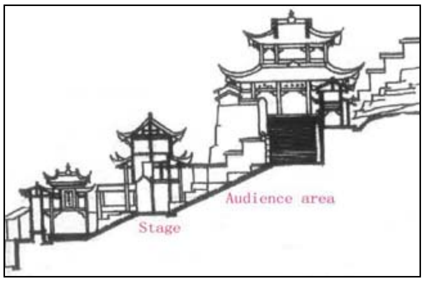
(a)



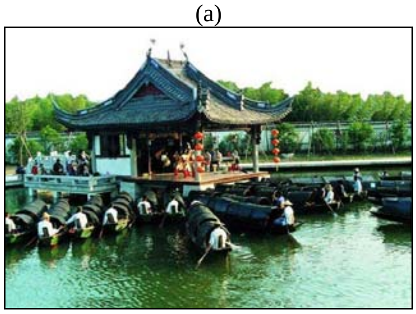
(b)

Source (a): (Bing Jian, 2006)
http://www.3608.com/Article/2007-6-28/093025886.html
Source (b): (Linping Xue, 2003)
Figure 2. Stage of Niu Wang Temple in Wei village, Raodu district, Linfen city, Shanxi province (山西省临汾市尧都区魏村牛王庙戏台)

Some open-air theatres made use of geological conditions to set the audience area on the side of a hill. This is more beneficial for the audience's audiovisual experience. A typical example is Er Wang Temple theatre (Chinese: 二王庙戏台), showed in Figure 3(a). Other exceptional open-air theatres which are called waterside-pavilion stages (Chinese: 水榭戏台) were built by the side of a lake or river in southern Chinese riverside towns, especially in the region of Shaoxing city and Yangzhou city, as shown in Figure 3(b). Because of the reflection of sound from the water surface, the river or lake could also increase the loudness of the sound and diffuse the sound further from the stage. Consequently, watching the dramatic performance from boats or the opposite bank could also make the play more exciting for the audience.



(a)



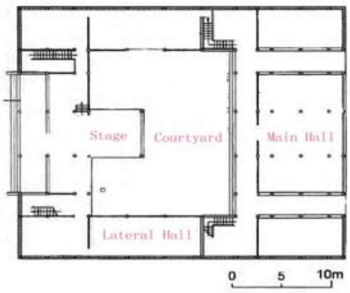
(b)

Source (a): (Linping Xue, 2003)
Source (b): (Wen Hui Daily, 2008)
http://szb.northnews.cn/bfxb/html/2008-08/21/content_129972.htm
Figure 3. Er Wang Temple theatre in Dujiangyan city, Sichuan Province (四川省都江堰市二王庙戏台) (a), and Xing Lai stage in Xi Hu pond, Shaoxing city, Zhejiang province (浙江省绍兴市西湖塘"幸来戏台") (b)

2. Courtyard theatres

The architectural style of the traditional Chinese courtyard was, over many centuries, found largely among temples in economically developed regions. Because of the confined space of the courtyard theatre, the size of the audience could be effectively restricted and separated from the neighbouring environment and public order could be maintained easily [5].

(a) (b)



(c)

Source (a): (China Net, 2006)
http://www.china.com.cn/chinese/zhuanti/gdyl/566668.htm
Source (b): (Qiming Li, 2007)
http://pt.tuke.com/photo/C22916989.html
Source (c): (Linping Xue, 2003)
Figure 4. Tianyi Pavilion of Qin's ancestral shrine in Ningbo city, Zhejiang province (浙江宁波秦氏支祠天一阁)

The main hall (Chinese: 主殿) of the temple was principally used to dedicate to the gods. Because the purpose of dramatic performance was normally rewarding and praying to the god for a blessing, the stage was certainly on the opposite side of the main hall. The separation space in the middle of them was the courtyard which was also the audience area. The stage was open on three sides thrusting into the courtyard. Because of its location set on the central axis of the courtyard, the only entrance of the whole building was usually installed under the stage. The ground level of the stage was therefore raised up. The audiovisual effects of the whole theatre were consequently changed for the better with regards to the audience, especially for those standing far away from the stage. Lateral halls (Chinese: 配殿) which were located on both sides of the courtyard were also served as Langfang (Chinese: 廊坊) where some female relatives could watch the dramatic plays clearly. In addition, most of these courtyard theatres were single story buildings, but some of them were constructed with two-story buildings on the part of Langfang. The classic example is Tianyi Pavilion theatre (Chinese: 天一阁戏场), as shown in Figure 4(a) above. It was built in 1923~1925. The bottom of the stage was supported by a pair of stone square columns, while the proscenium arch was sustained by two round wooden pillars. The top of the stage was covered with a gable and hip roof with single eaves (Chinese: 单檐歇山顶), and it can be seen from Figure 4(b) that the canopy on the direction above the stage was equipped with a caisson ceiling which constructed in a hemispherical shape. The whole theatre included the stage, lateral halls, main hall and courtyard.

3. Indoor theatres

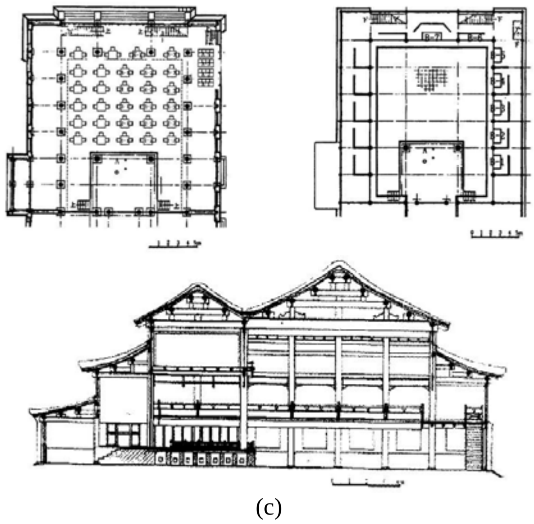
Due to the development of architectural structure, the stage and audience area were able to be set together under a long-span roof in a large hall. Therefore, dramatic performances were able to be held in this type of fully-enclosed theatre all day long, whether on windy or rainy days. It was particularly necessary for profit-making professional theatres at this point and also beneficial to the advancement of dramatic performance.

Because traditional indoor theatres have only existed since around 200 years ago, their stages were still preserved in the same pattern as courtyard theatres, so they were open on three sides and were prominent into the audience area. The only difference with open-air theatres and courtyard theatres was the carefully arranged tables and chairs in the audience area. Spectators would eat and have a pleasant chat over a cup of tea as they saw the dramatic performances. So it also improved service conditions and enhanced the audience's enjoyment in this regard. Accordingly, the indoor theatre not only improved its musical quality, but also became prevalent throughout China after the middle of the Qing dynasty. When the dramatic singing tune became an important part of the development of opera, the musical quality of the theatre was naturally required to be improved. In order to increase the capacity of theatre and also keep the sight distance close to the stage, the balcony was constructed in the auditorium in most traditional indoor theatres during the end of the Qing dynasty and the beginning of the Ming dynasty. The balcony, which was also called Bao Xiang (Chinese: 包厢), took up a key position overlooking the whole stage and so had good audio-visual conditions. Because these key positions were separated from normal spectator seats, this special properties and status were given to the balcony. Simultaneously, the balcony also specially offered female relatives were able to watch the performance even when feudal custom required the male audience to be sat separated from females in the same theatre. In addition, there were just 200~300 seats in the traditional indoor theatres resulting from the large tables, big chairs and aisles between seating sections which all occupied a siginificant area.

There are four typical traditional indoor theatres still existed well in Beijing [6-7]. Among them, the largest one is the Hu Guang guild hall (Chinese: 湖广会馆), as shown in Figure 5 below. It was founded in 1808 with a total area of more than 43,000 square meters. It was a place inhabited by students and merchants from Hunan and Hubei provinces, which had a long history and profound cultural connotation and also carried forward and developed such excellent cultural traditions of Peking Opera. The width of guild hall is 5 bays (Chinese: 间) wide, while the depth up to 7 bays long. The building is two-storys high with a wooden post and lintel construction (Chinese: 抬梁式木结构) and covered with a suspension roof with double volumed eaves (Chinese: 双卷重檐悬山顶). Originally, there were no ceiling boards in the hall, whereas a big wooden ceiling board with some lanterns hanging is installed nowadays. Furthermore, the volume capacity of the hall was only around 400 seats. Of course, according to the different arrangement of chairs and tables, the hall would have different capacities, but no matter how the layout changed, upstairs and downstairs chairs combined in total to fewer than 500 seats.


(a)


(b)


(c)

Source (a): (Jin Shun, 2005)
http://www.lvye.info/modules/newbb/viewtopic.php?viewmode=flat&topic_id=163709&move=next
Source (b): (Xinhua Wu, 2005)
http://pt.tuke.com/photo/C44000135.html
Source (c): (Shiren Wang, 1997)

Figure 5. Hu Guang guild hall in Beijing (北京湖广会馆)

On the whole, open-air, courtyard and indoor theatres always coexisted in history. To approximately trace their evolving processes, theatres underwent two transformation processes from open-air to courtyard theatre and then from courtyard to indoor theatre. Of course, this issue still remains to be discussed. However, for almost all of the original theatres, their first performance places were squares. Therefore, the open-air theatre was the source of the courtyard and the indoor theatre.

RESEARCH METHODOLOGY

Acoustic simulation tool

Detailed simulations were made by using acoustic software CATT-Acoustic (Version 8.0d). CATT is based on the combination of image source model for early part echogram qualitative detail and ray-tracing [8].

Acoustic indices

According to the theatrical acoustic theory, this paper mainly uses the following acoustic indices to make the qualitative and quantitative research below. They are: early decay time (EDT), reverberation time (T_{15} and T_{30}), sound pressure level (SPL), strength factor (G), lateral fraction (LF), definition (D_{50}), clarity (C_{80}) and speech transmission index (STI). Among all these indices proposed above, there are six which are referred to in detail below, selected because of their attractable phenomena only appeared in the traditional Chinese theatres.

1. Reverberation time (RT) and early decay time (EDT)

The quantity of RT is measured by using the Schroeder integrated impulse response technique [9], and linear regression between -5 and -35dB (or -25dB when the dynamic range is insufficient). EDT, proposed by Jordan [10], is measured by a similar method as RT, but between 0 and -10dB. For theatrical buildings the impression of reverberation, which is an audience feeling, is probably the most important and widely used measurement criterion for judging acoustic qualities. Traditionally RT is mainly proposed for enclosed spaces. While it is still applicable for traditional indoor theatres, traditional courtyard and open-air theatres were all semi-open or fully open spaces and the characteristics of their sound fields are vastly different from those of enclosed spaces. Therefore, RT here is inappropriate to be used to measure their acoustic qualities. Selecting EDT should be somewhat more reasonable to characterise the audience's impression of reverberation of traditional courtyard and open-air theatres. Nevertheless, in order to achieve a comprehensive research on this topic, EDT, T_{15} and T_{30} of various types of traditional Chinese theatres were still taken for a careful comparison and analysis in this paper.

2. Clarity index (C_{80}) and Definition (D_{50})

C_{80}, proposed by Reichardt et al. [11], is a measure of the ratio, expressed in dB, of early energy (before 80ms) to late energy (after 80ms):

$$C_{80} = 10\lg\left[\frac{\int_0^{80ms} h^2(t)\mathrm{d}t}{\int_{80ms}^{+\infty} h^2(t)\mathrm{d}t}\right]$$

Where *h(t)* is the impulse response. D_{50}, introduced by Thiele [12], is the ratio of the early energy with a time limit of 50ms to the total energy, and is commonly expressed as a percentage:

$$D_{50} = \frac{\int_0^{50ms} h^2(t)\mathrm{d}t}{\int_0^{+\infty} h^2(t)\mathrm{d}t}$$

For practical reasons their integration time in CATT simulation is all restricted to 200ms. In addition, for the sound fields mainly based on the instrumental music, the evaluation time is usually taken 80ms as its limitation. However, to those mainly based on speech, the evaluation time is taken to be 50ms. Chinese traditional opera mainly adopts singing and dialogue as its performance form, and also because the audience have already formed over a long period a habit of opera listening in such a short reverberation time condition, it would be more appropriate to take C_{50} and D_{50} as their evaluation indices of acoustic quality. However, C_{50} cannot be acquired from the CATT simulation, consequently, C_{80} was still carried out to be analysed in this paper.

3. Strength index (G)

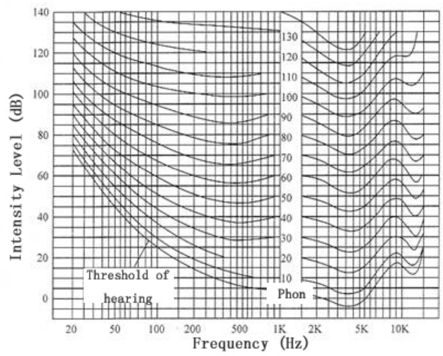
The physical quantity measuring the role of buildings on the loudness of sound intensity is strength index (G) [13, 14]. It is expressed as the difference, in dB, between the sound pressure level and the sound power level of the sound source:

$$\mathrm{G} = Lp - Lw$$

Lw can be measured or calculated using the sound pressure level at 1m from the source and the directivity factor *Q* of the sound source below:

$$Lw = Lp(1\mathrm{m}) + 10\lg(4\pi) - 10\lg(Q)$$

As has well been studied, loudness is a very important factor of all acoustic quality evaluation indices. From a physical point of view, loudness of sound is related to three main factors: the distance from the source, the size of the amplitude of the source itself and the diffusion degree of the sound. In addition, studies have already shown that there is an intrinsic link existing between the frequency and the loudness of sound. That is, people's subjective feeling of the magnitude of loudness is not proportional to the objective sound pressure level, but has some connections with the characteristics of the frequency of the sound source that cannot be ignored [15]. It can be seen from Figure 6 that human auditory perception is particularly sensitive to the voice within 2000~5000Hz, whereas for voices below 500Hz, the lower the frequency, the more insensitive the human auditory perception.



Source (a): (Architectural Acoustics and Audio Engineering, 2007)

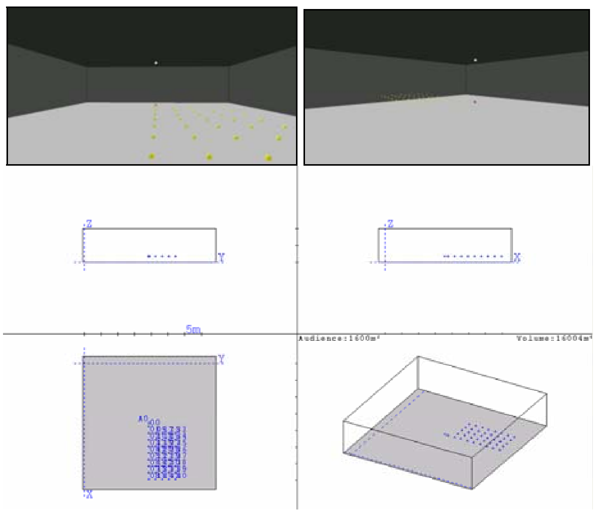
Figure 6. The curve of the same subjective loudness feeling at different frequencies

In the mid 1980's, a measurement based on the singing characteristics of Peking Opera was done by the Research Institute of Acoustics of the Chinese Academy of Building Science (Chinese: 中国建筑科学研究院声学研究所) [16]. This measurement not only proved that the average linear sound pressure level of opera actors is much higher than that of the average person, but also testified that the characteristic of the singing frequency of actors is different from that of the speaking frequency of the average person: the main frequency range of average people with normal speech usually is concentrated in the frequency range of around 500Hz, while it falls sharply around the range of high-frequency. Even though the main frequency range of the people with a naturally high voice is concentrated around 1000Hz, it also declines rapidly above 1000Hz. In comparison, most Chinese dramatic singing tunes were very highly pitched, the main frequencies concentrated on the high frequency spectrum. Simultaneously, basic skills of dramatic singing emphasised on the breath of the Dantian elixir field (Chinese: 丹田之气) transmitting the voice further and clearer. Skills of dramatic dialogue also differed from normal speech, particularly concerning articulation. Therefore, the opera actor has a large frequency range which even goes up to about 4000Hz, and this is approximately consistent with the sensitive range of human auditory perception. These two different points indicate that in terms of the sound source itself, opera actors in traditional theatres are sure to supply an adequate sunjective loudness for the audience. Therefore, selecting 1000Hz as the main frequency operated in the CATT simulation should be more appropriate for traditional Chinese theatres.

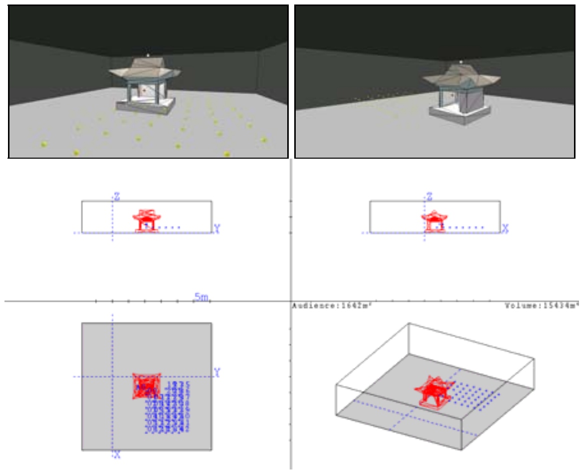
4. Background noise

In addition to meeting a certain acoustic quality requirement, contemporary theatre usually requires the background noise to be low enough, whereas traditional Chinese theatres did not attach much importance to this [17]. Firstly, the objective nature of traditional Chinese theatre has already determined that it is impossible to lower the background noise. Theatres were all built in relatively noisy places, such as the temple theatre in which one can easily see many people passing by while one watches the plays. Even specialised performing places also coexisted with other functional buildings which certainly resulted in higher background noise. Secondly, it can be seen from the development process of the opera that people were already familiar with many opera plays especially when the traditional opera excerpt (Chinese: 折子戏) came out. Moreover, from the Qing dynasty, theatergoing has already been called Opera Listening (Chinese: 听戏). Therefore, it was not necessary to hear the plays extremely clearly. Thirdly, Chinese opera had a great affinity for the people who never regarded it as an unattainable art and thereby never held their breath to ensure silence reigned through the whole theatre. On the contrary, they all watched a play while they drank tea or ate melon seeds. As the play worked up to a climax, almost all the audience would break out into loud cheers with greatly uninhibited enjoyment. Based on the above mentioned points, the intimate interaction between the audience and the actors was established by this way of opera listening, and the whole theatre also spontaneously filled with an active atmosphere. In a word, background noise is a unique characteristic of traditional Chinese theatres which is the most typical difference from Western theatres.

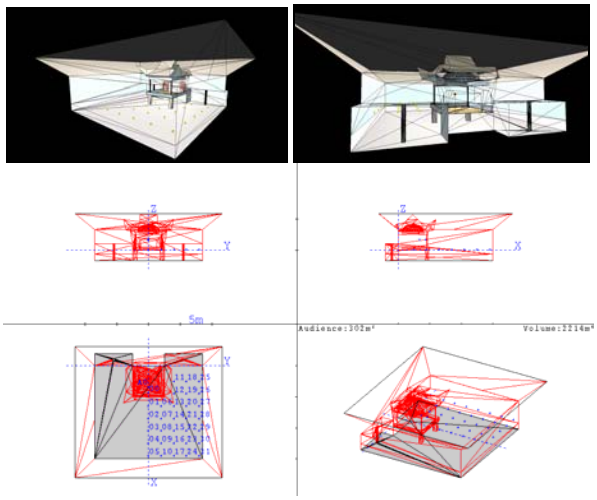
Model settings



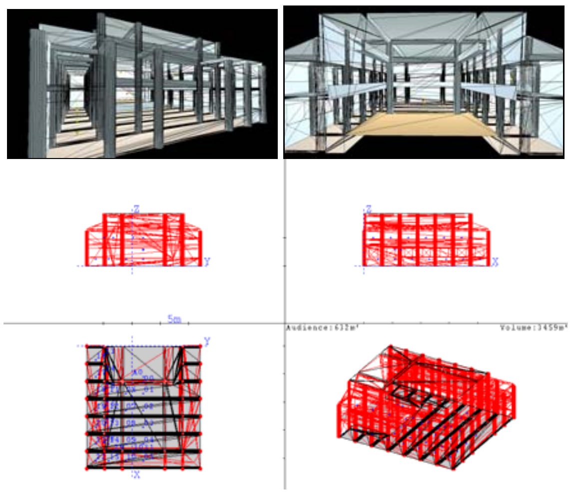
(a) Model of plaza-type theatre (see Figure 1)



(b) Model of pavilion-type theatre (see Figure 2)



(c) Model of courtyard theatre (see Figure 4)



(d) Model of indoor theatre (see Figure 5)

Figure 7. Models in CATT

According to the brief introduction of the three main types of traditional theatre above, four typical examples were designated as the key research objects in this paper, and each of them has been simulated and analysed.

Firstly, it was not intended to use accurate and detailed architectural CAD drawings for any particular theatres, rather, the required building sizes were obtained by using visual estimation based on the examples mentioned above, considering idealised situations, for relative comparisons.

Secondly, because the open-air and courtyard theatres are not enclosed spaces, the desired value of EDT, T_{15} and T_{30} can not be obtained by the CATT simulation directly. All the open sides, named “Void” below, were given an absorption coefficient of 99.9999%.

Thirdly, while the open-air theatre itself had three different architectural forms, including the most primitive plaza-type theatre (Figure 1), pavilion-type theatre (Figure 2) and water-side-pavilion theatre (Figure 3b), by making a general survey on the latter two, it is easy to find that their architectural forms are actually the same. Both were constructed with a separated pavilion stage. The only difference was the surface of the audience area which was ground for the former, and water for the latter. Therefore, only one simulation was made for this type.

Lastly, in the CATT model, the sound source (shown in red) was set at a height of 1.6 meters, 1.5 meters away from the centre of the proscenium. Meanwhile, receivers (shown in yellow) were arranged in a 2m × 2m grid in the audience area, and all set at a height of 1.2 meters. In addition, there was one more receiver with the same height as the source, which was set at 1 meter away from it on the stage. The following pictures in Figure 7 respectively show the CATT models of four typical examples of traditional Chinese theatre mentioned above.

Simulation settings

In the simulation, the sound source setting is based on the CATT-Acoustic (Version 8.0d) database, namely 70 73 76 79 82 95: 95 95. Meanwhile, the absorption coefficients (ABS) of the theatre are all assigned based on the database given in BB93 [18] and in CATT, as shown in Tables 1-4, where the two databases are referred as (a) and (b) respectively. The effects of surface diffusion have been intensively discussed in literature [19-20]. In the simulation, the average diffusion coefficients (D) of all the surfaces of four typical theatres are approximately set, as also shown in tables 1-4:

Table 1. Settings of plaza-type theatre (see Figure 1)

Surface	*ABS*						*D*
	125	250	500	1k	2k	4k	*Avg.*
Floor (a)	2	3	3	3	4	7	50
Void	99.9	99.9	99.9	99.9	99.9	99.9	100

Table 2. Settings of pavilion-type theatre (see Figure 2)

Surface	*ABS*						*D*
	125	250	500	1k	2k	4k	*Avg.*
Wall (a)	2	3	3	4	5	7	20
Roof (a)	8	9	12	16	22	24	80
Floor (a)	2	3	3	3	4	7	50
Stage (a)	2	3	3	4	5	7	20
Column (a)	25	5	4	3	3	2	10
Caisson (b)	30	20	15	13	10	8	80
Void	99.9	99.9	99.9	99.9	99.9	99.9	100

Table 3. Settings of courtyard theatre (see Figure 4)

Surface	*ABS*						*D*
	125	250	500	1k	2k	4k	*Avg.*
Wall (b)	32	10	8	6	4	2	70
Roof (a)	8	9	12	16	22	24	80
Floor (a)	2	3	3	3	4	7	50
Stage (b)	10	14	20	33	50	60	40
Stone (a)	2	3	3	4	5	7	20
Column (a)	25	5	4	3	3	2	10
Caisson (b)	30	20	15	13	10	8	80
Curtain (a)	30	45	65	56	59	71	60
Banister (b)	30	20	15	13	10	8	50
Void	99.9	99.9	99.9	99.9	99.9	99.9	100

Table 4. Settings of indoor theatre (see Figure 5)

Surface	*ABS*						*D*
	125	250	500	1k	2k	4k	*Avg.*
Wall (b)	30	20	15	13	10	8	40
Stage (b)	10	14	20	33	50	60	40
Column (a)	25	5	4	3	3	2	10
Window (b)	32	10	8	6	4	2	60
1st Floor (a)	8	9	12	16	22	24	40
2nd Floor (b)	30	20	15	13	10	8	50
1st Ceiling (b)	30	20	15	13	10	8	50
2nd Ceiling (b)	25	5	4	3	3	2	50
3rd Ceiling (b)	28	8	7	7	9	9	30

RESULTS AND DISCUSSIONS

Various acoustic indices of four typical traditional theatres have been compared systematically, as presented below, where a, b, c and d in the figures represent the simulation results of plaza-type, pavilion-type, courtyard and indoor theatre, respectively.

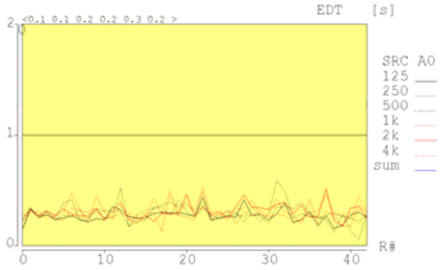
EDT

It can be seen from Figure 8c that the value of EDT_M (the average value of EDT of 500Hz and 1000Hz frequency) is about 0.8s, which is basically consistent with the measured value of 0.81s in an equivalent actual theatre [21]. This result shows that the simulation result of Tianyi Pavilion theatre is satisfactory.

In Figure 8a to 8d, it can be seen that the EDT value of the audience area of four typical traditional theatres increases gradually. Among all these charts, the minimum EDT_M value of audience area in Figure 8a is almost equal to 0s, while the maximum EDT_M value of audience area in Figure 8d is about 1.9s. This indicates that the EDT value of the sound field of the audience area has a certain relationship with the closure degree of the theatre space. This means the more enclosed the theatre space, the larger EDT value of the audience area.

The EDT value of the stage of four typical traditional theatres also increases gradually. In all of these charts, the minimum EDT value of the stage, as can be seen in Figure 8a, is almost equal to 0s, while the maximum EDT value of the stage, as can be seen in Figure 8d, is about 1.2s. This indicates that the EDT value of the sound field of the stage also has a certain relationship with the closure degree of the theatre space. This means the more enclosed the theatre space is, the larger the EDT value of the stage is. In addition, it can be easily seen from Figure 8c and 8d that the EDT value of the stage is smaller than that of the audience area. This is because the magnitude of the difference between the direct sound energy received by the receiver and the early reflection energy received by the same receiver on the stage is slightly greater than that in the audience area. As a result, the slope of the sound decay curve of the stage is greater than that of the audience area, as can be seen approximately from the echograms shown in Figure 9.

(a)



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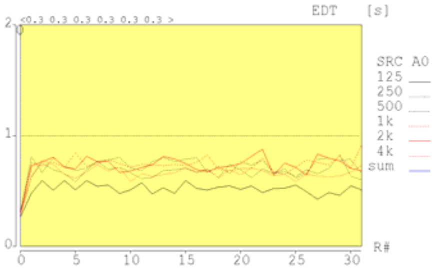
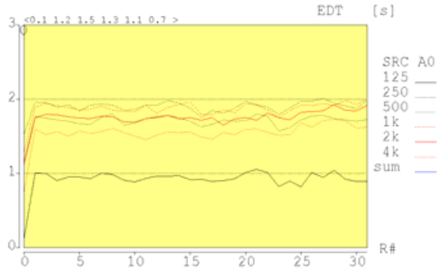
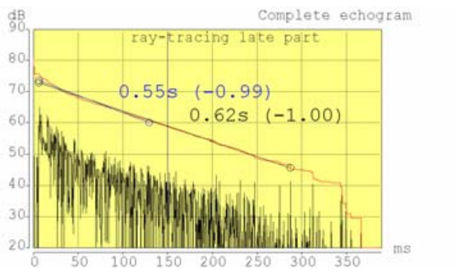


(c)

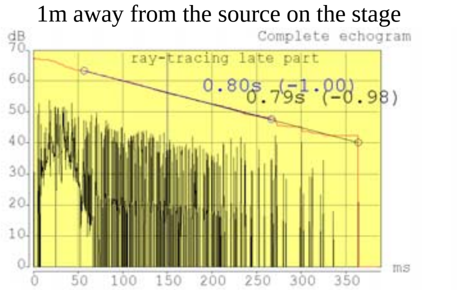


(d)

Figure 8. EDT of four typical traditional theatres



1m away from the source on the stage



7m away from the source in the audience area

Figure 9. Echogram of two different receivers in the court-yard theatre

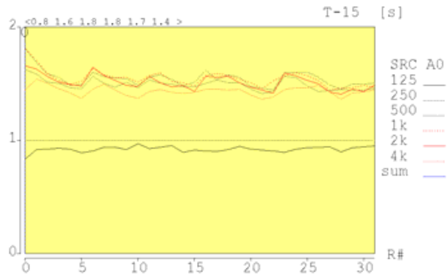
T_{15}

From Figure 10a to 10d, it can be seen that the trend of the value of T_{15} of the audience area is overall consistent with the trend of EDT of the audience area. It also indicates that the T_{15} value of the sound field of the audience area has a certain relationship with the closure degree of the theatre space. Thus, the more enclosed the theatre space is, the larger the T_{15} value of the audience area is.

(a)

(b)

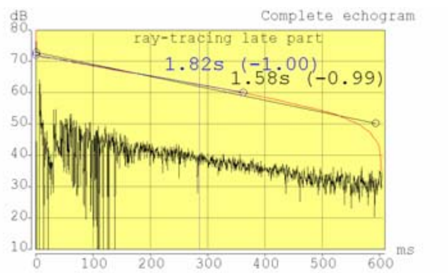
(c)



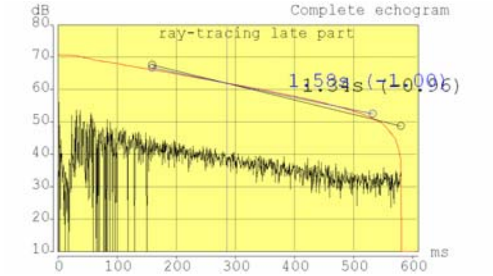
(d)

Figure 10. T15 of four typical traditional theatres

The overall trend of the value of T_{15} of the stage is also consistent with the trend of EDT of the stage. The only difference is that the value of T_{15} of the stage in Figure 10d is slightly larger than that of the audience area. This is because the slope of T_{15} part of the sound decay curve at the stage is less than that of the audience area in the traditional indoor theatre, as can be seen approximately in the echgram in Figure 11.



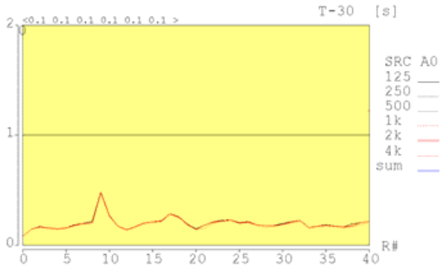
1m away from the source on the stage



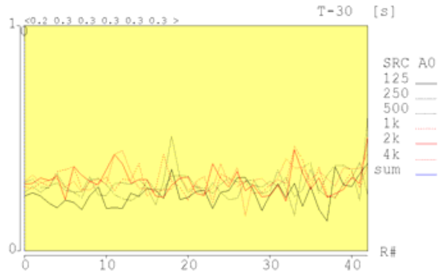
9m away from the source in the audience area

Figure 11. Echogram of two different receivers in the indoor theatre

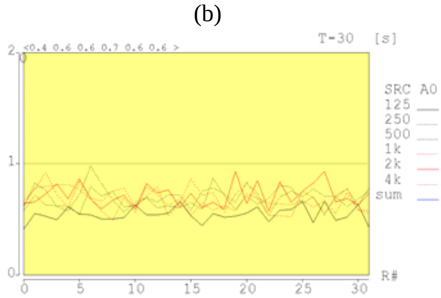
T_{30}



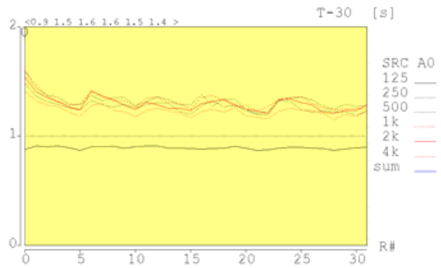
(a)



(b)



(c)



(d)

Figure 12. T_{30} of four typical traditional theatres

It can be seen from Figure 12d that the value of T_{30M} (the average value of T_{30} of 500Hz and 1000Hz frequency) is about 1.3s, which is longer compared with the measured value of 1s in an equivalent actual theatre [22]. The reason might be that there are more sound absorption components in the actual theatre, such as the tables and chairs in the audience area. There might also be a resonance phenomenon of thin plates, because the ceiling, most doors and windows were all fabricated from thin wooden plates.

From Figure 12a to 12d, the overall trend of T_{30} is also consistent with the trend of T_{15}. This also shows that T_{30} also has a certain relationship with the closure degree of the theatre space. The more closed the theatre space is, the larger the T_{30} value is. In addition, the only difference with the trend of T_{15} is that the T_{30} of the stage is larger than that of the audience area. This is perhaps because the slope of T_{30} part of the sound decay curve at the stage is less than that of the audience area in the traditional indoor theatre, as can be seen approximately in the echgram in Figure 11.

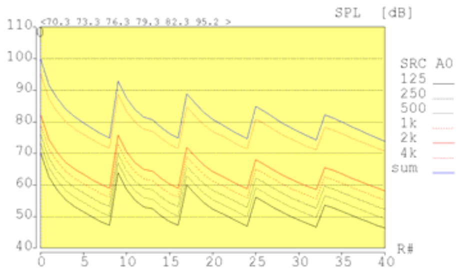
Consider all the figures of EDT, T_{15} and T_{30} above, it can be seen that EDT$\approx T_{15} \approx T_{30}$ in charts (a), (b) and (c), while EDT$>T_{15}>T_{30}$ in charts (d). This indicates the difference in sound field between the open and enclosed space.

SPL and G

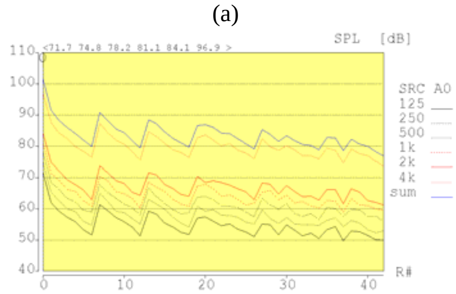
It can be seen from the wavy curves in Figures 13 and 14 that the SPL and G have a certain relationship with the source-receiver distance. The further away from the source is, the less the SPL and G are, as expected.

It can also be seen from Figure 13 and 14 that the amplitude range of wavy curves becomes smaller and smaller from chart (a) to chart (d). This indicates that the distribution of the value of SPL and G in the theatre becomes more and more uniform from chart (a) to chart (d). Therefore, the uniformity degree of the distribution of the value of SPL and G has a certain relationship with the closure degree of the theatre space. The more enclosed a theatre space is, the more uniform the distribution of the values of SPL and G is.

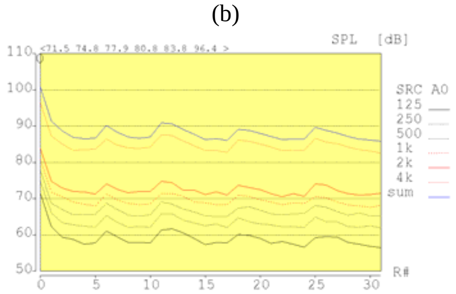
Figure 15 shows the colormap of SPL and G, again indicating that the more enclosed a theatre space is, the higher average values of SPL and G are. Moreover, in the traditional indoor theatres the average values of SPL and G on the first floor are slightly higher than those on the second floor.



(a)



(b)



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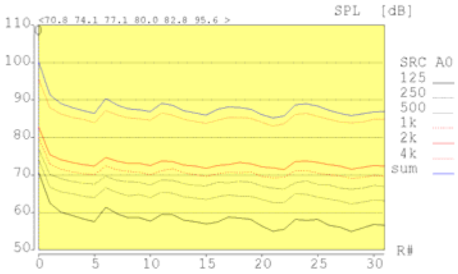
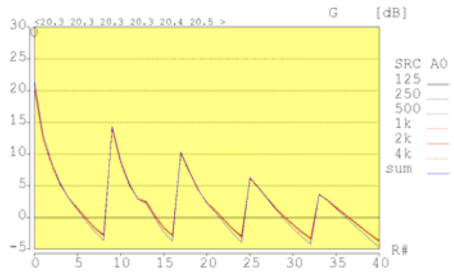
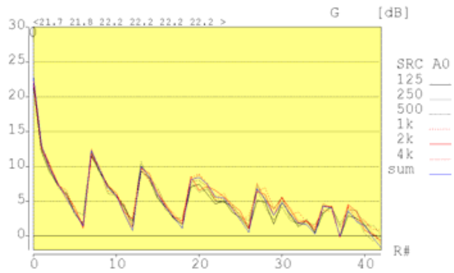


(d)

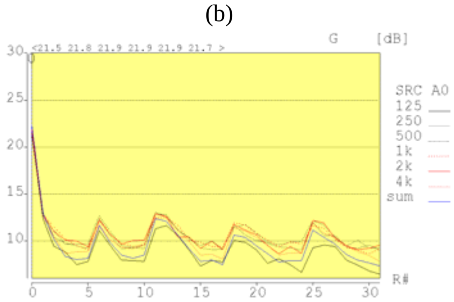
Figure 13. SPL of four typical traditional theatres



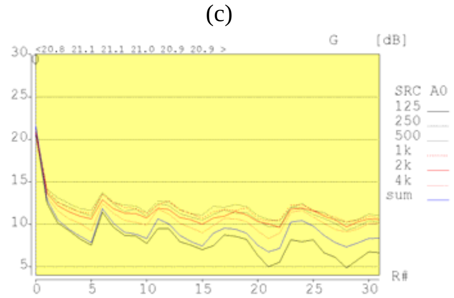
(a)



(b)

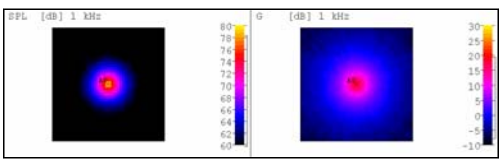


(c)

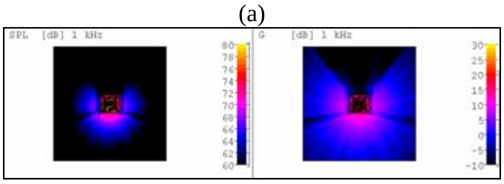


(d)

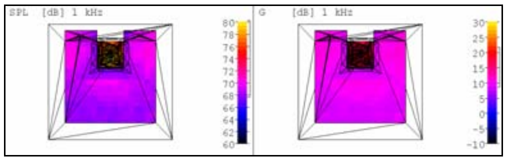
Figure 14. G of four typical traditional theatres



(a)



(b)



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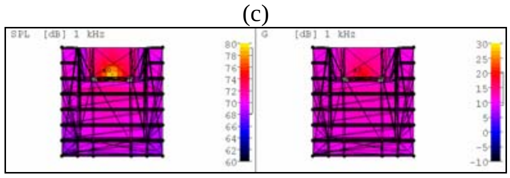
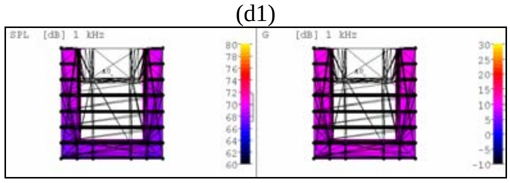


(d1)



(d2)

Figure 15. SPL of four typical traditional theatres

D_{50} and C_{80}

Figure 16 shows the D_{50} distribution. It can be seen that the average value of D_{50} of the audience area becomes smaller and smaller from 16a to 16d. This is again because the more enclosed the theatre is, the more surfaces can reflect sound. Therefore, the D_{50} naturally decreases when the theatre becomes more enclosed from the open-air theatre to indoor theatre.

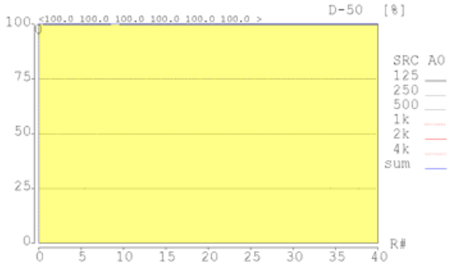
It can also be seen that the value of D_{50} of the stage, which is almost equal to 100, is higher than that of the audience area. This indicates that the change of reflected sound energy has almost no effect on the value of D_{50} of the stage. This is perhaps because the difference between the direct sound energy at the receiver and the reflection energy received by the same receiver on the stage is much greater than the difference in the audience area.

From Figure 16a to 16d the range of the amplitude of D_{50} curve becomes larger. This indicates that the distribution of D_{50} in the audience area becomes increasingly uneven. Therefore, the distribution of D_{50} has a certain relationship with the closure degree of the theatre. That is the opposite to the distribution of the value of SPL, because the more enclosed the theatre space is, the more uneven the distribution of the value of D_{50}. One principal reason for this phenomenon is perhaps the distribution state of SPL in the sound field during 0~50ms. In the open-air theatre, there is less reflection sound energy in the sound field, while the direct sound is dominant. Therefore, the value of D_{50} is very high and also evenly distributed.

When the traditional theatre evolved from open-air theatre to courtyard and indoor theatres, the reflected sound energy was gradually increased and the reverberant field was accordingly established. However, the distribution of SPL in the sound field still shows wavy curves, and this also leads to the distribution of D_{50} in a corresponding wavy curve.

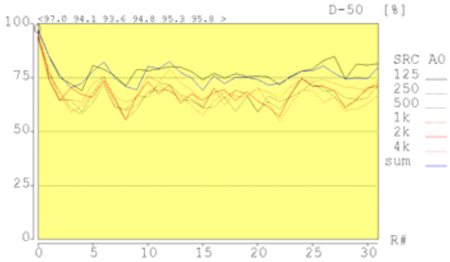
From Figure 17a to 17b the average value of C_{80} of the whole theatre became smaller. This is because the more enclosed the theatre space is, the more the reflected sound energy is. The C_{80} of the stage in Figure 17c and 17d is significantly higher than that of the audience area, while in Figure 17a and 17b is not obvious. This is because open-air theatre has less reflected sound energy, and its sound field is mainly dominated by the direct sound. The courtyard and indoor theatres have a certain amount of reflected sound energy in their sound field. The closer one is to the stage, the higher the SPL of direct sound one hears. Therefore, in the same reverberant field, the difference of the value of C_{80} between stage and audience area is clearly visible. Thus, the impact of the change of the reflected sound energy on the stage is less than that on the audience area.

It can be seen from the range of the amplitude of C_{80} curve in Figure 17 that the range in Figure 17a and 17b is significantly larger than that in 17c and 17d. This shows that the uniformity degree of the distribution of the value of C_{80} in the courtyard and indoor theatre is higher than that in the open-air theatre. This is possibly because the sound field of courtyard and indoor theatre is relatively closer to the diffuse field.



(a)

(b)



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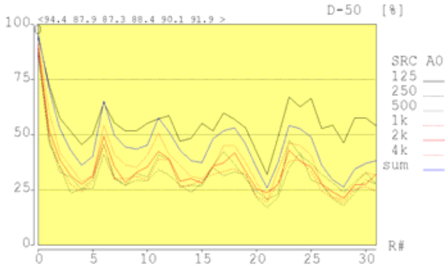
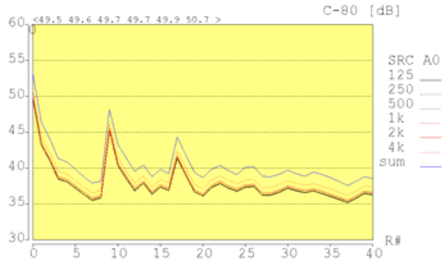
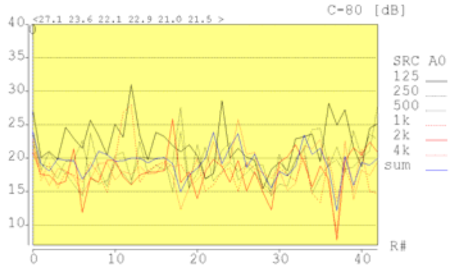


(d)

Figure 16. D_{50} of four typical traditional theatres



(a)



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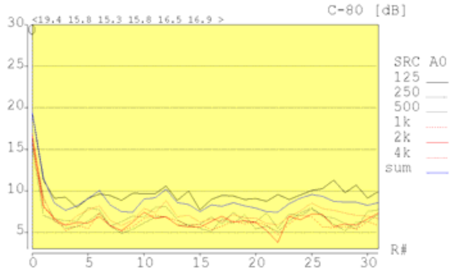

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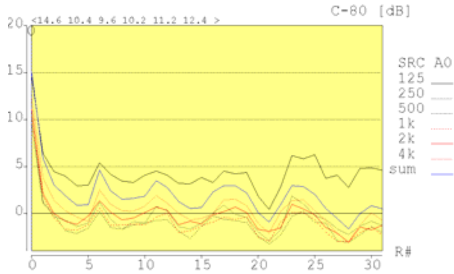
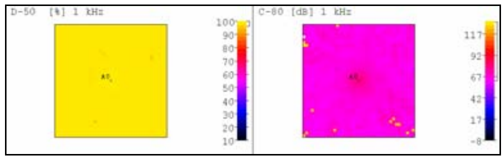
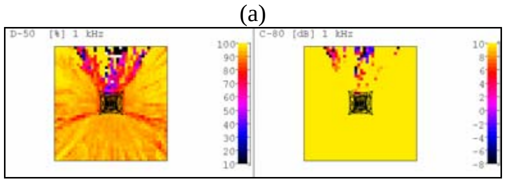


(d)

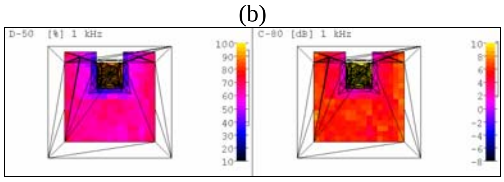
Figure 17. C_{80} of four typical traditional theatres



(a)



(b)



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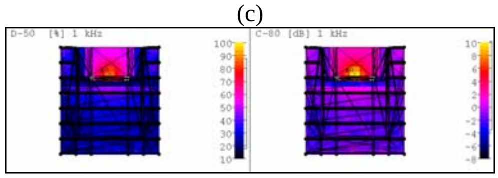
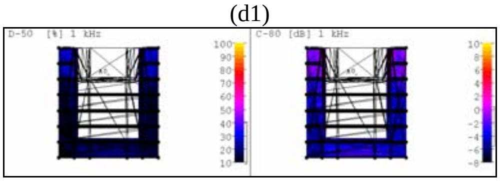


(d1)

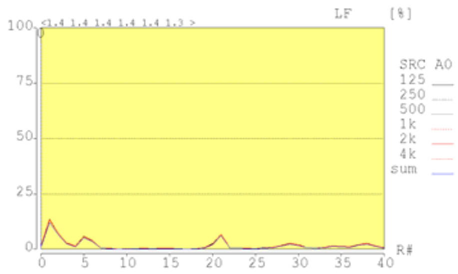


(d2)

Figure 18. D50 and C80 of four typical traditional theatres

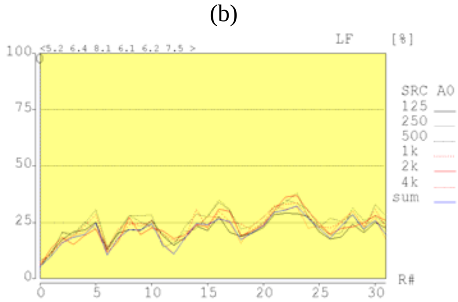
Figure 18 shows colormaps of C_{80} and D_{50}. It can be seen again that the average value of C_{80} and D_{50} decreases from open-air theatre to indoor theatre. Also, the average value of C_{80} and D_{50} on the second floor of the indoor theatre is lower than that on the first floor, especially for D_{50}, due to similar reasons discussed above.

LF

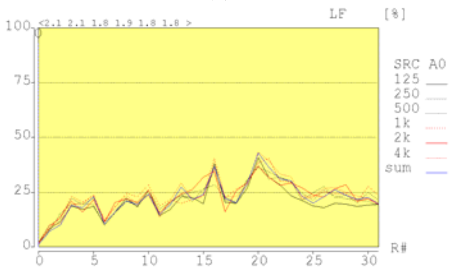


(a)

(b)

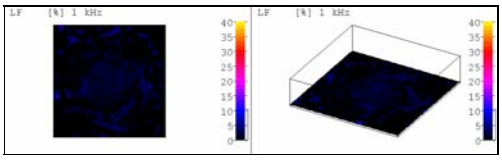


(c)

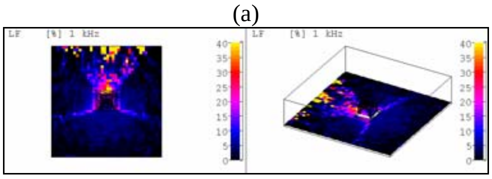


(d)

Figure 19. LF of four typical traditional theatres



(a)



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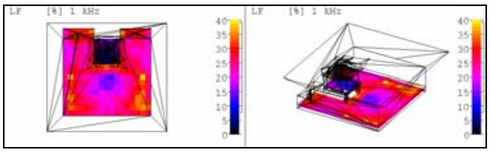
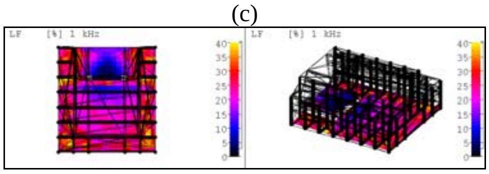
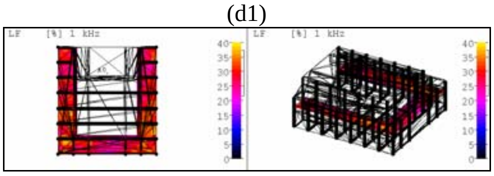


(c)



(d1)

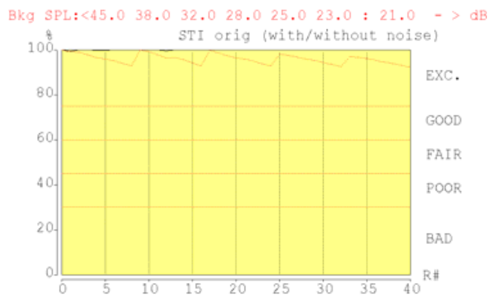


(d2)

Figure 20. LF of four typical traditional theatres

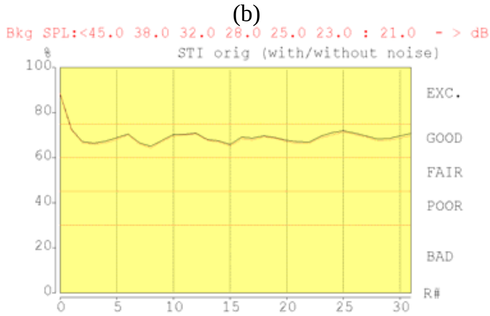
It can be seen from Figure 19a to 19c that the value of LF increases gradually, suggesting that the value of LF has a certain relationship with the closure degree of the theatre: the more enclosed the theatre is, the higher the value of LF is. In Figure 19c and 19d, it is seen that the value of LF does not change much, showing that the ceiling of the theatre does not much affect the value of LF. These can also be seen in the colormaps in Figure 20. It can also be seen that the closer one is to the centre of the theatre, the lower the value of LF.

STI



(a)

(b)



(c)

(d)

Figure 21. STI of four typical traditional theatres

From Figure 21a to 21d, it can be seen that the value of STI decreases gradually, but even the smallest value of STI is still in the range FAIR which is between 45 and 60. This indicates that the condition of the clarity in traditional Chinese theatre is very good. In other words, traditional Chinese theatres are appropriate performance places for the Chinese opera which is mainly based on singing and dialogue. The STI at the stage are all in the range of EXCELLENT, which are significantly higher than that of the audience area. This can improve the actor's self awareness when the opera play is being performed.

CONCLUSIONS

Compared with the plaza-type theatre, the pavilion-type theatre not only provided protection to the actors from the burning direct sunlight and from wind or rain, but also gave them a certain acoustic supports to some extent, because their self awareness can be improved by this semi-enclosed stage, which supports them by certain reflected sounds from three sides (ceiling, back wall and floor) of the stage, when the opera play is being performed. In addition, the audience could obtain a considerable amount of early reflections. This is helpful to enhance the loudness of the sound field of the open-air theatre.

Moreover, as mentioned above, the primitive stage of the pavilion-type theatre was open to three sides (front side and two lateral sides). The audience watched the dramatic performance by standing around the three sides of the stage. In addition, the space used for dressing up called the backstage was enclosed with a back wall and two lateral walls on the back of the whole stage. With the evolution of the backstage, two lateral walls extended to the proscenium of the stage gradually, even reached the border of the proscenium arch. During that time, downstage and backstage were still simply divided by a curtain. But after the Ming and Qing dynasties, the curtain was replaced by a wooden block. Therefore, the space of this one-side open stage was more propitious to enhance the reflected sound energy than that of three-side open stage.

Due to the reflected sound from the surrounding walls and buildings, the effect of acoustic quality on the audience watching dramatic performances in courtyard theatre was better than that in open-air theatre. However, the courtyard theatre was still an open-space building without sound reflection from the top of the courtyard, which was less effective than indoor theatres in terms of audiovisual effects. In conclusion, with the development of its own architectural form, the acoustic quality of the traditional Chinese theatre improved considerably.

REFERENCES

[1] Ben Liao, "About the origin and formation of Chinese Opera" *Hebei Academic Journal*, 59-66 (1991)
[2] Qiaomu Hu (Chief Editor), *China Great Encyclopedia* (Beijing: China Great Encyclopedia Press, 1988) pp. 465-466
[3] Ben Liao, *History of Ancient Chinese Theater* (Zhongzhou Ancient Books Publishing House, Zhengzhou 1997)
[4] Jiqing Wang, "Introduction of Chinese traditional theatrical buildings part A: history" *Journal of Tongji University*, 27-34 (2002)
[5] Linping Xue, "Study on acoustics and architecture of Chinese traditional courtyard theatrical buildings" *A Dissertation in Candidacy for a Doctorate in Engineering 2003*
[6] Chang Li, *Beijing Theatre of the Qing Dynasty* (Beijing Yanshan Press, Beijing 1998)
[7] Huabin Zhou, *Beijing Ancient Theatres* (China Ocean Press, Beijing 1993)
[8] CATT-Acoustic, "CATT-Acoustic v8 Room Acoustics Prediction and Desktop Auralization" *User's Manual* 2002
[9] Schroeder, M. R., "New method of measuring reverberation time" *J. Acoust. Soc. Am.*, 409-412 (1965)
[10] Jordan, V. L., "Room acoustics and architectural development in recent years" *Applied Acoustics*, 59-81 (1969)
[11] Reichardt, W., Alim, D. A. & Schmidt, W., "Definition und Messgrundlungen eines objektiven Masses zur Ermittlung der Grenze zwischen brauchbarer und unbrauchbarer Durchsichtigkeit bei Musikdarbeitungen". *Acustica*, 126-137 (1975)
[12] Thiele, R., "Richtungsverteilung und Zeitfolge der Schallrückwürfe in Räumen" *Acustica*, 100-112 (1953)
[13] Cremer, L. & Muller, H. A., *Principles and Applications of Room Acoustics* (transl. T. J. Schultz. Applied Science Publishers, London, 1982)
[14] Barron, M. & Lee, L. J., "Energy relations in concert auditoriums I" *J. Acoust. Soc. Am.*, 618-628 (1988)
[15] Zheng Wang & Jinjing, Wu, *Architectural Acoustics and Audio Engineering* (China Machine Press, 2007) pp.16-17
[16] Lin Han & Jie Lin, "Measurement of sound pressure level of Peking Opera actors" *Selected Papers of the Fifth Architectural Physics Conference 1987*
[17] "A study into the architectural and acoustic characters of traditional theatres in Shandong province" *Master Thesis of Shandong University 2008*
[18] Building Bulletin 93, *Acoustic Design of Schools / School Buildings and Design Unit, Department for Education and Skills* (London: TSO, c2003)
[19] Wang L.M. & Rathsam J., "The influence of absorption factors on the sensitivity of a virtual room's sound field to scattering coefficients" *Applied Acoustics 69*, pp.1249-1257, (2008)
[20] Kang J., *Acoustics of Long Spaces: Theory and Design Guidance* (Thomas Telford Publishing, London 2002)
[21] Linping Xue & Jiqing Wang, "Measurement and analysis of musical quality of eight thaditional courtyard theatre in Jiang-Zhe region" *Selected Papers of the Ninth Architectural Physics Conference 2004*
[22] Deyin Luo & Youguo Qin, "Reverberation and analysis of two aneient theatres" *Hua Zhong Architecture*, 62-63 (2001/2)