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Dongxu Zhang, Yue Feng, Mei Zhang, Jian Kang

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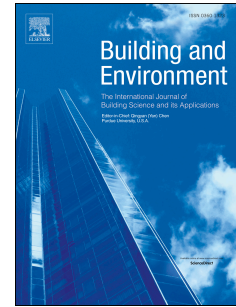
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Sound Field of a Traditional Chinese Palace Courtyard Theatre

Zhang Dongxu^a, Feng Yue^b, Zhang MEI^c, Kang Jian^{d,*}

^a*School of Architecture and Urban Planning, Guangzhou University, Guangzhou, 510006, China*

^b*Hunan Liangang Engineering Technology Co., Ltd., Loudi, 417000, China*

^c*School of East Asia Studies, University of Sheffield, Sheffield, S10 2TD, United Kingdom*

^d*Institute of Environmental Design and Engineering, The Bartlett, University College London, London WC1H 0NN, United Kingdom*

Abstract: Chinese Palace theatres mostly adopt a semi-open courtyard layout, where sound field quality is crucial for the performance of Chinese dramas. This study conducted field measurements and a simulation of the Jiayintang Theatre sound field in the Shenyang Imperial Palace to determine the basic parameters of traditional courtyard theatre sound fields. Moreover, the effects of sound source directivity and the spatial elements on the sound field of the theatre were analysed. The results indicate that the acoustic parameters of the Jiayintang Theatre meet the performance requirements of traditional Beijing Operas, as the acoustic conditions are similar to those of modern Beijing Opera theatres with good listening features. Removing the roof and sidewalls reduces the sound intensity and reverberation time in the aisles. Changing the stage position from the current projecting style to the embedded style would result in a 1.6 and 2.6 dB decrease in the sound intensity in mid-frequency in the main hall and aisles, respectively, while the musical clarity (C80) as well as the speech transition index (STI) in the main hall would decrease, which would negatively affect the audience perception of acoustic quality. The pavilion roof primarily serves to support the actors considering acoustics. If the singing direction of the actors changes from the main hall to the aisles, the sound intensity in the main hall would decrease by 1.8 dB, and the STI and C80 values would also significantly decrease.

Keywords: Chinese Palace courtyard theatre, sound field, stage form, enclosing interface, sound source directivity.

1. Introduction

Traditional Chinese operas have a history and corresponding performing arts venues, such as traditional Chinese theatres, are widely distributed in various areas of China, where exquisite theatres have been preserved and are now significant architectural cultural heritage sites. Most traditional Chinese theatres are open or semi-open outdoor theatres. The palace theatres during the Qing Dynasty represented the highest development level of ancient traditional Chinese theatres considering the architectural style and level. They generally adopted a semi-open courtyard-style layout. In an era that lacked electroacoustic amplification systems, the quality of the sound field in traditional theatres was critical for the performance effect of dramas.

Regarding the acoustic characteristics of ancient theatres, significant studies regarding ancient Greek and Roman theatres have been conducted. In particular, considering the relationship between the ancient theatre form and sound field, a study by Chourmouziadou and Kang demonstrated that changes in the materials and theatre design generally resulted in acoustic improvements in the evolution of ancient Greek and Roman theatres [1]. Through the historically informed digital reconstruction of the Roman theatre of Verona, Tronchin, and Bevilacqua unveiled the acoustics of the original shape and proposed that compared to current times, better listening conditions would exist if a live performance was attended during the ages of the Roman Empire [2]. Iannace and Trematerra reported the acoustic history of the Benevento Roman theatre from its origins in the Roman period until today and argued that the legendary 'good acoustics' of the theatres in the Greek and Roman periods was owing to the absence of background noise and the features of the building materials, as well as the layout of the rows of seating [3]. Farnetani et al. proposed that the evolution of acoustics in ancient theatres could be qualified by architectural details

and quantified by acoustical measurements [4]. Furthermore, Berardi et al. reconstructed the original acoustics of the Pompeii theatre during the Roman period to compare the various acoustical characteristics of its 'theatrum tectum' over the 2000 years of its history [5]. Till demonstrated that the ancient architects had considered acoustics in the design of the Paphos Theatre in Cyprus, which was 2000 years old and had a significantly refined sound that could be comparable to that of a concert hall [6]. Regarding the sound parameters of ancient open-air theatres, the ancient Syracuse open-air theatre in Italy was considered as a case study by Bo et al., who investigated the accuracy of the predicted acoustical parameters, including the reverberation time, clarity (C80), and sound strength (G) through in-situ measurements and acoustic simulations [7]. The ERATO project investigated the acoustics of the open-air ancient Greek and Roman theatres and concluded that the sounding vessels had no practical importance in Roman theatres [8]. Furthermore, Psarras et al. concluded that the high speech intelligibility and strong sound of the ancient open theatre of Epidaurus were due to the integration of the direct sound, floor reflection, and forward and backscattering of the seating area [9]. Giron et al. studied the acoustic environment of two Roman theatres of Hispania; the acoustic characterisation encompassed a parametric and spatial description of their sound fields and a comparison of their acoustic atmospheres was justified by their different states of recovery rehabilitation [10]. In a study by Astolfi et al., the outcomes of a measurement campaign of the acoustical parameters in an ancient theatre in Italy were obtained according to ISO 3382-1 and were presented and compared with datasets from other sites [11]. Moreover, considering the impact of the scenic elements of a theatre on the sound field, Barkas attempted to demonstrate the positive role of scenery (particularly the scenic front, theatre floor, and back panels) in improving the acoustic comfort using data from a sample of 20 ancient theatres in Greece [12]. Prodi clarified the acoustical impact of the theatre settings in ancient theatres of Syracuse (Italy) using scale model measurements [13]. Bo et al. conducted a parametric study by adding different scenic elements in the Greek theatre of Syracuse to evaluate their influence on acoustic quality [14]. In addition, scholars analysed the influence of sound source positions on the sound field of the Roman theatre and amphitheatre in Spain [15]. The methods used in these studies are noteworthy. However, owing to the differences in the architectural forms and materials, the sound fields of traditional theatres in China and the West are considerably different. Traditional Chinese buildings, including courtyard style theatres, are primarily composed of wood. The main apparent features of Chinese buildings include overhanging eaves and bucket arch structures; these traditional theatres are generally composed of a stage with a ceiling, aisles, main hall, and courtyard. In comparison, western ancient buildings, including traditional ancient Greek and Roman theatres, are primarily composed of stone. An open-air theatre without a roof can be built on a mountain with a more open space and larger building volume. Therefore, these research results regarding the sound fields of traditional theatres in the West cannot be directly applied to the study of traditional theatres in China.

According to their locations, traditional Chinese theatres can be classified as a palace, guildhall, or folk theatre. Furthermore, they can be divided into the following two types according to their architectural forms: courtyard theatres (without roof) and hall theatres (with roof), where courtyard theatres are more popular. Scholars have recently recognised the precious architectural heritage of traditional Chinese theatres, analysed their development history and forms, and proposed certain protection measures [16], in addition to considering their sound fields. Regarding the acoustic parameters of traditional theatres, acoustical measurements were obtained at six courtyard-type traditional Chinese theatres and three theatres were integrated with Chinese gardens. Parameters such as strength (G), early decay time (EDT), and early support (ST_E) were analysed [17-18]. Zhu et al. compared the evaluation dimensions of Western and traditional Chinese performance buildings and demonstrated that the preference for loudness and brightness was higher in the Chinese evaluation system than that in the Western system [19]. Considering the acoustic function of theatre facilities, a study of Chinese traditional theatres revealed that the low theatre ceiling and back wall of a pavilion theatre may function as a reflective shell. This increases the

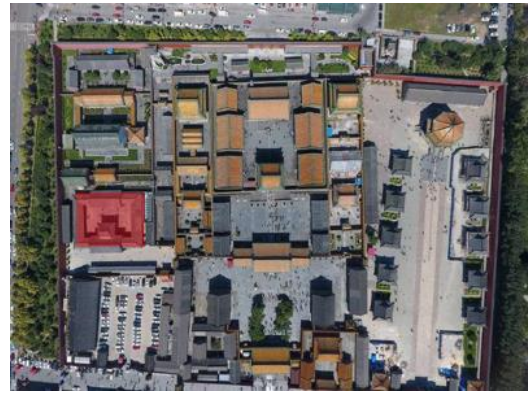
early reflections and intensity of the sound to the audience while providing sufficient support to the singer [20]. He and Kang conducted a sound field simulation to investigate the relationship between the width and depth of a theatre and the acoustic parameters of a traditional Chinese theatre [21], as well as the acoustic effect of the hemispherical and octagonal caisson ceilings on the actor and the audience [22]. Current studies regarding the sound field of traditional Chinese theatres generally focus more on folk or guild hall theatres. However, courtyard theatres from the Qing Dynasty are of the highest level and the most representative traditional theatre performance venues in China. They follow a courtyard layout surrounded by aisles and the main hall. The auditorium is set in a main hall and aisles, the stage is of the projecting type, and a caisson is located in the ceiling of the stage roof. The actors face the main hall while performing. The main halls of these palace theatres are different from those of traditional indoor theatres with a hall layout and traditional outdoor folk theatres with an open layout considering the form and grade of architecture, the number and position of the audience, and the singing style of actors. The acoustic characteristics of the theatres are also significantly different. Studies regarding palace theatres from the Qing Dynasty are limited, especially those combining actual measurements with simulations, which results in a lack of understanding of the sound field characteristics of these theatres.

This study investigates the acoustic parameters of palace theatres during the Qing Dynasty, as well as the effect of the mechanisms of the space form and sound source elements on the sound field. These include the effect of the aisle setting on the sound field of the main hall and aisles, the difference in the sound field between the projecting and embedded stages, the acoustic effect of setting a caisson in the theatre ceiling, and the effect of the direction of the actors singing on the sound field in the main hall and aisles. This study also compares the differences between palace theatres from the Qing Dynasty and those of traditional theatres in the East and West considering the sound field characteristics. The sound field of the Jiayintang Theatre, which is the most significant opera performance venue in the Shenyang Imperial Palace, a world cultural heritage site, was chosen as the research object because its architectural form and scale are representative of the palace theatres. The building dimensions and sound field parameters of the theatre were first measured. An acoustic simulation software was used to establish the sound field model of the theatre, and the simulated parameters were fitted and verified with the measured parameters. Subsequently, factors of the model such as the enclosing interface, stage form, stage ceiling setting, and sound source directivity were changed, and the variation law of the sound field parameters was analysed.

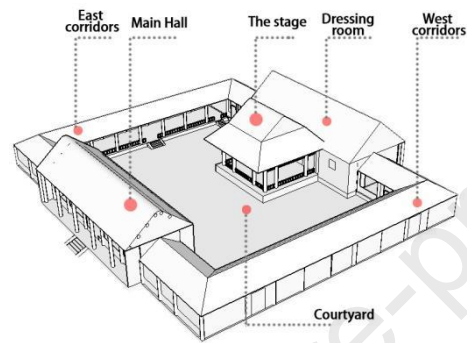
2. Methods

2.1 Introduction and measurement of Jiayintang architecture

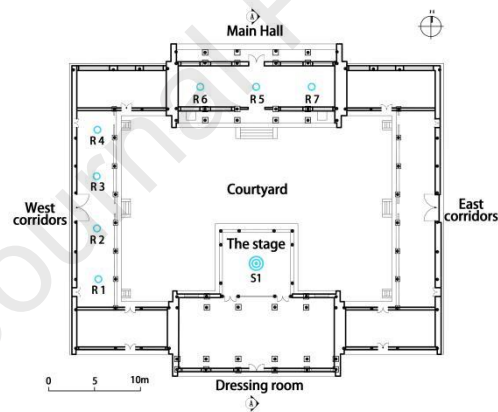
The Shenyang Imperial Palace, a world cultural heritage site, was established in 1625. It is the largest and best-preserved ancient architectural complex in northern China. In particular, the Shenyang Imperial Palace and Beijing Imperial Palace are the two famous royal palaces of the Ming and Qing Dynasties. The Jiayintang Courtyard Theatre was built during the Qing Dynasty in 1781, and is located on the West Road in the Shenyang Imperial Palace (red square in Fig. 1(a)). The entire building complex is a quadrangle, surrounded by the stage, make-up room, Jiayintang hall (main hall), and east and west aisles. Currently, as a national cultural relic and world cultural heritage, the Shenyang Imperial Palace and its inner Jiayintang Theater have been well protected. This theatre is only for sightseeing and no longer for performing Peking Opera. The plane dimension of the outer edge of the entire courtyard is 31.3 m (north-south length) \times 38.3 m (east-west width). The dimensions of the inner courtyard are 22.2



(a)



(b)



(c)



(d)

Fig. 1. The Jiayintang Theatre and its Measured Plane

m (north-south length) \times 29.3 m (east-west width), and the area of the open courtyard is 523 m². This is a medium-sized Qing palace theatre and can accommodate dozens of individuals. The pavilion-style stage with the Xieshan roof on top of the Qingwaxie Hill faces the south and north and projects deep into the open courtyard. The stage is 8.9 m wide, 7.8 m long, and 0.9 m above the ground. Actors perform on

this stage, which is open in three directions. This type of enclosed semi-open courtyard theatre and the projecting stage include the most representative forms of ancient Chinese palace theatres. The largest and second largest theatres, which are the Changyinge Theatre and the Shufangzhai Theatre in the Beijing Forbidden City, respectively, are also world cultural heritage sites, both of which follow this form.

As a typical representative of traditional Chinese palace theatres, the Jiayintang Theatre is considerably different from the outdoor open-air theatres of ancient Greece and Rome considering the architectural form and performance space. Beijing Opera represents a performing art form whose scenes depend on imagination. It is mainly performed by actors singing, and its props and scenes are relatively simple; therefore, it does not require a large theatre or stage to restore realistic settings. A small stage can also highlight the actors' importance. The stage of the Jiayintang Theatre has a ceiling, which is 4.5 m above the stage, and a regular octagonal caisson is formed upward in the middle, with a side length of approximately 1250 mm and a single-layer caisson depth of 0.47 m. The theatre has five backstage rooms for the actors to apply make-up and rest. The main hall on the north side of the courtyard is directly located on the opposite side of the stage, with seats for the emperor and his immediate family members to watch the opera. The total height of the main hall is 7.58 m, and the indoor net height is approximately 4 m. Ministers and extended royal family members would watch the opera in the open, roofed aisles on the east and west sides of the courtyard. Wooden columns and wooden railings are set on the side of the aisles facing the courtyard. The outside of the aisles is surrounded by brick walls, with a wall height of 3.3 m, a total height of 5 m, a width of 4.5 m, and a net height under the beams of only 2.6 m. The aisles are relatively low to accentuate the height of the main hall where the emperor would be seated. The main buildings of the Jiayintang Theater, including the stage, make-up room, aisles, and main hall, are all wooden structures. The roofs of all the buildings are covered with glazed tile. The entire theater ground, including the courtyard, is paved by smooth bluestone.

There are no seats in the outdoor courtyard of the theatre, which reflects the important difference between palace and folk theatres. Because palace theatres typically have a small audience, they watch the opera only in the main hall and aisles on the opposite side of the stage. Conversely, courtyard-style folk theatres usually have seats in the outdoor courtyard to accommodate more audience members. Additionally, the scale and grade of palace theatre buildings are often higher than those of folk theatres. See Figs. 1(a), (b), (c), and (d) for the general plan of the Shenyang Imperial Palace, its axonometric view, plan view, and the stage photo of the Jiayintang Theatre.

2.2 Sound field evaluation parameters

Herein, the following acoustic parameters were selected as the evaluation indicators of the sound field performance. Note, although the architectural forms and performance contents of Chinese and Western theatres are different, current studies regarding various traditional Chinese theatres basically adopt the Western sound field evaluation index system [16,17,18,20]. This index system considers the performance of various aspects of the sound field and is representative and comprehensive. To facilitate the comparison of various sound fields, including between different forms of traditional Chinese theatres, and between Western and Chinese theatres, the Western common acoustic index system was adopted in this study for the Chinese traditional palace courtyard theatres. Furthermore, previous studies have analysed the particularity of the requirements for sound fields in Chinese traditional theatrical performances, which demonstrated that the evaluation systems in China and the West were generally consistent. However, the specific evaluation dimensions were different; that is, the importance of different sound field parameters in the evaluation of Eastern and Western theatres varied [19]. A detailed analysis of the role and evaluation effect of various indicators of the sound field of Chinese traditional theatres will be conducted in a future study.

- (1) Early reverberation time (EDT):

EDT refers to the time required for the sound to decay to -60 dB by a sound attenuation curve of -10 dB after the sound source stops producing sound. The EDT has been recognised as a better measure of subjectively perceived reverberance than the reverberation time (RT) [23-24]. A previous study has also shown that the EDT is more suitable than RT30 for evaluating the reverberation time of Chinese courtyard theatres [25]; other relevant studies have drawn the similar conclusions [26,27,28]. Owing to the rapid decline in the outdoor sound energy and the presence of background noise, the EDT was adopted as the reverberation index in the previous field measurement and fitting process presented in this study to ensure that the test process meets the requirements of the signal-to-noise ratio given in the international standard ISO3382. Simultaneously, referring to the analysis of the Beijing Opera's sound spectrum (Section 2.6), the representative low-, mid-, and high-frequency EDT values (average values of 500 Hz, 1000 Hz, and 2000 Hz, defined as EDT₃) were selected as the acoustic parameters of this theatre for the analysis and comparison.

(2) STRENGTH (G):

As an acoustic parameter of loudness, the value of sound intensity (G) can be used to evaluate the sound energy in an auditorium; it is considered one of the important acoustic parameters of traditional Chinese courtyard theatres [25]. According to previous studies, the preference for loudness is significantly higher in traditional performance spaces in China than that in the West [19], and loudness ratings are significantly related to the overall G values [23]. With the same loudness of sounds made by actors on stage, the audience will hear the sounds at a higher loudness at positions with higher G values. Thus, it is generally believed that if G is less than -2 dB, the loudness will be insufficient. According to the measurement data of 76 concert halls globally, the optimal G value of the middle frequencies (average in 500 Hz and 1 kHz octave bands) ranged between 4 dB to 5.5 dB [29].

(3) C80:

The C80 parameter is used to describe the clarity of music. Generally, the larger the value of C80, the higher is the clarity of the music. According to the analysis of the singing frequency spectrum of the actors in the Beijing Opera (Section 2.6), this study obtained the average of 500, 1000, and 2000 frequency bands and termed it C80 (3) to evaluate whether listeners feel the music is clear or whether the reverberation time is too long or short [30]. A previous study has demonstrated that the clarity is one of most valued indices in the acoustic quality evaluation of a Peking opera by the audience [31]. In Western concert halls with relatively good sound effects, the clarity under the vacant state is generally between -1 and -4 dB [29]. Contrary to Western operas, in traditional Chinese operas, the audience pays more attention to the lyrics and specific syllables of music while watching the operas, especially those in Beijing; therefore, a higher clarity is needed. Regarding the two traditional Chinese indoor theatres that are generally considered to have relatively good performances, the measured C80 of the Shijia Theatre auditorium is 3.2 dB, and that of the Beijing Gongwangfu Theatre is 0.67 dB [32]. This indicates that the optimal value range of C80 in Chinese traditional theaters may be higher than that in Western concert halls.

(4) STI:

The STI is an objective parameter that indicates the quality of speech transmission and is associated with speech intelligibility with a value ranging from zero to one. Following the international standard, if the STI value is above 0.75, the speech intelligibility rating is excellent; furthermore, ranges 0.60–0.75, 0.45–0.60, and 0.30–0.45 correspond to good, fair, and poor, respectively. Moreover, a value less than 0.30 is bad [33]. Considering that there are several spoken parts in a Beijing Opera performance, speech intelligibility is equally important to the sound quality of the theatre.

(5) Early support:

The 'Early Support Degree (ST_E)' is an index proposed by Gade to evaluate the degree of support theatrical facilities provide to actors performing on stage in terms of sound. This is the ratio, in decibels, of the reflected energy within the first 0.1 s relative to the direct sound (including the floor reflection),

both measured at a distance of 1.0 m from the acoustic centre of an omnidirectional sound source. The subscript E (Early) is used because this value is derived from the early reflected acoustic energy, and the average of four-octave bands ranging from 250 to 2000 Hz (specifically 250, 500, 1000, and 2000 Hz) is usually obtained as a single-valued evaluation index. A higher value indicates a greater support for the performers on stage [34]. According to the data accumulated on concert hall stages over the years, an average value of ST_E ranging between -11 and -13 dB is satisfactory for the actors [35].

The just noticeable difference (JND) of each acoustic parameter is as follows: 1 dB for G (0.5k–1k Hz), 5% for EDT (0.5k–1k Hz), 0.03 for STI, 1 dB for C80 (0.5k–1k Hz), and 3 dB for the sound pressure level (SPL) [36,37,38,39,40].

2.3 Measurement of the sound field

The sound field parameters of the Jiayintang Theatre were first measured in this study, and the experimental measurements were conducted with the instrumentation and data analysis methods compliant with the ISO3382/2009 standard [40]. A relatively simple sound field test method was adopted in this study for accuracy and stability, where an average value was obtained after multiple measurements. The aim of the measurement was to preliminarily understand the characteristics of the sound field of the Jiayintang Theater, and to guide and adjust the parameters to set in the next simulation process for basically consistent simulated and measured results. The measuring instruments included a dodecahedron sound source (manufacturer: Hangzhou Aihua Instruments Co.,Ltd., model: AWA5510), a sound level metre (manufacturer: Brüel & Kjær, model: BK2240), and a real-time signal analyser (manufacturer: Brüel & Kjær, model: 2270). The instruments were calibrated in advance, and the errors were within 0.3 dB. The theatre was measured in the vacant state when the surrounding environment was quiet in the morning or evening. According to previous studies, the sound field parameters of theatres are considerably different in occupied and vacant states [41]. When the reverberation time is used to evaluate the sound quality, the occupied state should be adopted for measurements [29]. However, the uniqueness of royal theatres from the Qing Dynasty lies in the small audience; accordingly, the sound field parameters measured in the occupied and vacant states are not significantly different.

In the measurement process, a dodecahedron undirected sound source was placed in the centre of the stage at a height of 1.5 m, which played pink noise. Four receiving points (R1 to R4) were sequentially set in the aisles where the ministers would watch the opera, and two receiving points (R5 and R6) were set in the main hall where the emperor would watch the opera. R7 was located in the symmetrical position of R5 about the central axis. Considering that the sound field distribution was also symmetrical on the left and right under the conditions of this study, R7 was not considered in the measurement and fitting process. When analysing the sound field of the main hall, the parameter of point R7 was added, and the parameter value of R7 was equal to that of R5. The receiving point was at a height of 1.2 m above the floor, and the distance from the nearest reflecting surface was more than 1 m. See Fig.1(c) for the locations of the sound source and receiving points. As the outdoor courtyard lacked audience seating, no sound receiving point was set. The EDT and SPL were selected as the acoustic parameters of the theatre for the actual measurement. An average of five measurements were obtained for the EDT and SPL of each point. Before the measurement, the sound field of the external environment was first measured, and the background noise on the six frequency bands was 14.1, 24.3, 21.7, 22.4, 17.3, and 14.6 dB, respectively.

2.4 Sound field simulation and verification

The acoustic software Odeon (version 13.04) was used in this study to simulate the sound field of the Jiayintang Theatre. Odeon is based on a hybrid calculation method. The early reflections were calculated through a mixture of the image source method and the ray-tracing method (RTM) using a stochastic scattering process that uses secondary sources [7]. The applicable object types of the software include sound fields of closed buildings, semi-closed buildings, open squares, and other buildings. The calculation results cover multiple acoustic parameters, and provide comprehensive reference data for an acoustic analysis. Scholars have used this software to simulate the sound fields of ancient open-air theatres [7-8].

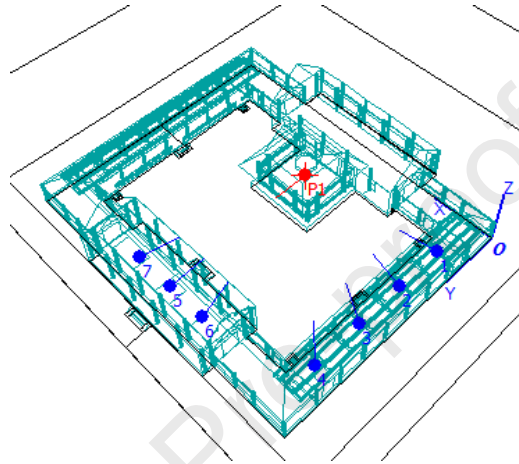
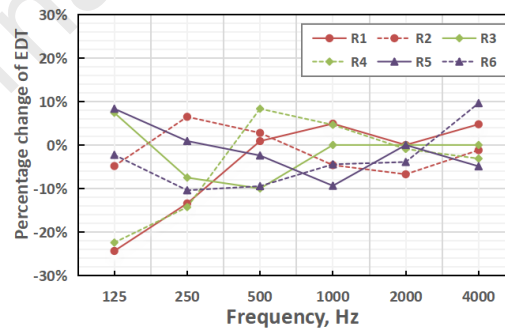
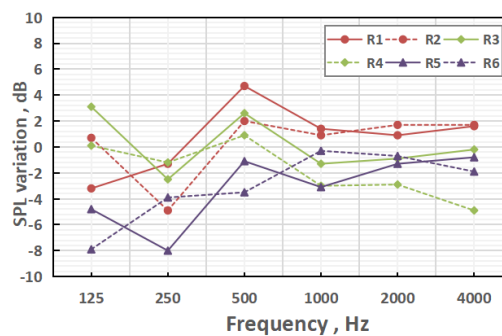


Fig. 2. Sound field model of Jiayintang Theatre



(a)



(b)

Fig. 3. Comparison of difference between simulation and measurement

First, the model of the Jiayintang Theatre created by using the Sketch Up software was imported

Table 1

Sound absorption and reflection coefficients of material parameters in the model

Material	Sound absorption coefficient under the following frequencies (Hz)						Scattering coefficient
	125	250	500	1 k	2 k	4 k	
Glazed tile roof covering	0.01	0.01	0.01	0.01	0.02	0.02	0.50
Glazed window	0.35	0.25	0.18	0.12	0.07	0.04	0.10
Wooden door leaf	0.16	0.15	0.10	0.10	0.10	0.10	0.20
Carpet	0.13	0.22	0.33	0.46	0.59	0.53	0.10
Ganged brick wall	0.05	0.04	0.02	0.04	0.05	0.05	0.05
Brick wall plastering	0.03	0.03	0.03	0.04	0.05	0.07	0.05
Stage curtain	0.11	0.32	0.54	0.64	0.55	0.70	0.25
Brackets	0.19	0.43	0.44	0.40	0.42	0.40	0.40
Stone steps	0.01	0.01	0.02	0.02	0.02	0.05	0.15
Wooden eave columns	0.10	0.07	0.05	0.05	0.05	0.05	0.30
Hard floor paving	0.01	0.01	0.02	0.02	0.02	0.05	0.05
Hardwood material	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Caisson and ceiling	0.16	0.15	0.10	0.10	0.10	0.10	0.40

into the Odeon software (see Fig.2). The acoustic parameters of each enclosed interface material in the sound field model primarily include the sound absorption and scattering coefficients. When setting the parameters, we referred to the results of our previous study regarding the sound fields of ancient traditional Chinese buildings (Table 1) [42-43]. Before starting the simulation, the parameters were set according to the characteristics of the Odeon software. The maximum reflection order of the sound rays was set to be higher than the number of rays estimated at the precision calculation level. The impulse response length was used as the standard to ensure the disappearance of sound waves; a 0.1 m interior margin was adopted, which is directly related to the model fineness. During simulation, the sound source and receiving points were set according to the actual measurement process, and a non-directional sound source was adopted. The simulations were performed using the same thermo-hygrometric conditions as the actual measurements (temperature: 20 °C, humidity: 50 %), which were kept consistent as typical conditions. The change in the thermo-hygrometric conditions was not considered in the simulation process of this study because previous studies have indicated that the influence of these conditions on the acoustic field parameters, such as the STI in a church, is negligible [44]. In addition, the thermo-hygrometric conditions in North China, where the theatre is located, usually change slightly. This study also used various possible extreme thermo-hygrometric parameters in the simulation, and the results demonstrated that it had little influence on the parameter changes of the Jiayintang Theatre sound field.

The differences between the sound level and EDT simulation values calculated by Odeon and the field measured values are shown in Fig. 3. Furthermore, the differences between the sound level and measured data were found to mostly range between -5 and 5 dB (the differences between medium and high frequencies were observed to be mostly between -3 and 3 dB). Moreover, the percentage differences between the EDT values (the ratio between the difference and measured value) were mostly between -20% and 20%; the differences between the medium and high frequencies were mostly between -10% and 10%. Overall, the errors under high frequencies were smaller than those under low frequencies. Considering that the measurements were obtained in a semi-outdoor space, the relative errors were significantly large. The next step in this study was to analyse the simulation results, primarily the values obtained with medium and high frequencies and compare the relative variation values of the various parameters. Therefore, this study demonstrates that the errors of the simulation results were within an acceptable range. Furthermore, the established Jiayintang sound field model was shown to be generally

consistent with the actual sound field characteristics and that it can be used for the next step of the analysis of the influencing factors of the sound field.

The simulation results of the sound field in this study demonstrated that the average value of the sound intensity in the middle frequency (G_{mid}) at each point in the model of the Jiayintang Theatre was 5.1 dB, which is in a good range. The average C80 value of the points in the model under medium frequencies was 3.0 dB, suggesting relatively good music clarity. The average simulated STI was 0.46 in the main hall and 0.42 in the aisles. The sound field parameter values in the main hall or the aisles were the average values of the internal receiving points. Because this is a semi-outdoor theatre, the language clarity reflected by the STI values is acceptable.

2.5 Acoustic model setting plan

As a typical Qing Dynasty theatre, the Jiayintang Theatre embodies the characteristics of royal theatres in terms of architectural space, sound source, and audience area, which are considerably different from those of traditional Chinese folk theatres and traditional Western theatres.

This study analysed the effect of various spatial and sound source elements on the sound field of the Jiayintang Theatre. Fig. 4 demonstrates the following four changes made to each element in the model proposed in this study: (a) removing the aisles or changing their height, (b) changing the projecting stage into an embedded stage, (c) changing the stage ceiling, including the caisson setting, and (d) changing the singing direction of the actors on stage. Furthermore, this study analysed the changes in the sound field parameters of the theatre with these four changes, including the sound field parameters at the viewing positions of the emperor or minister and those of the actors' performance area on stage.

The previous study indicated no significant effects from environmental factors, such as temperature, humidity, and wind variations across the open-air theatre [9]. The environmental setting of this model included a temperature of 20 °C, humidity of 50%, and wind speed of 0. The effects of the changes in these factors on the sound field were not considered. The background noise value in the simulation process was set as the measured background noise.

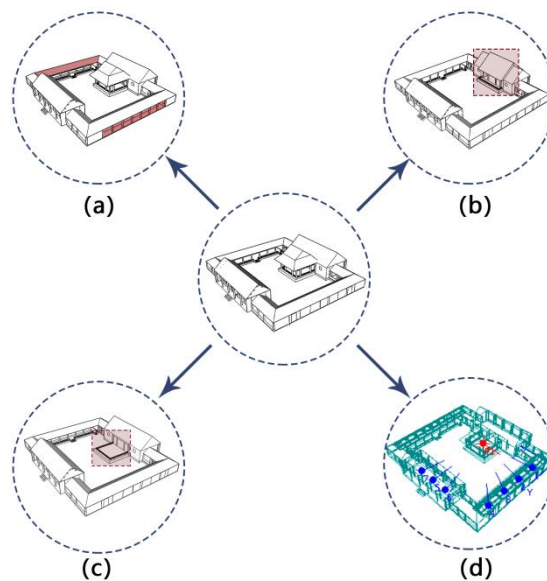


Fig. 4. Schematic of element changes

2.6 Setting of the sound source

The main repertoires performed in palace theatres during the Qing Dynasty were traditional Beijing Operas. The performance process of the Beijing Opera includes singing, dialogues, and action performance by actors as well as musical accompaniment by small bands, among which singing is the most important; the sound of instrumental music only plays a subordinate role in a Peking opera performance [32]. Therefore, when analysing the acoustic quality of the Peking Opera performance spaces, the singing voice is significantly more important compared to the instrumental sounds. The singing methods as well as singing frequency differ among actors. Herein, the representative singing voice of female roles in the Beijing Opera was chosen as the simulated sound source. First, six high-fidelity singing episodes of Mei Lanfang, the most famous Chinese Beijing Opera actor, were selected from the Chinese drama recording database (from three famous Beijing Opera tracks: ‘Cai Pei Lou’, ‘Fan Ma Ji’, and ‘Bao Lian Deng’); each episode lasted approximately 30 s. ARTEMIS software was used to analyse the frequency spectrum of the six segments; the results are shown in Fig. 5. Contrary to the frequency spectrum of the voice of normal people, which is generally between 500 and 1000 Hz, the frequency spectrum of Beijing Opera singing is mainly distributed in the 500–2000 Hz range, and can even reach 4000 Hz. The advantage of the main frequency of the Beijing Opera singing is that the sound can spread far and clear. Therefore, in ancient times, when amplifying the equipment was not possible, audience members distant from the theatre could also clearly hear the lyrics. This frequency band characteristic of the Beijing Opera singing is similar to the international standard band set at approximately 3 kHz, which is called the ‘singer’s formant’ [45]. This may be because the human ear is sensitive to sound in this frequency band. The presence of formants can enhance the clarity and penetrating power of the singer’s voice to avoid being masked by band accompaniment or other sounds.

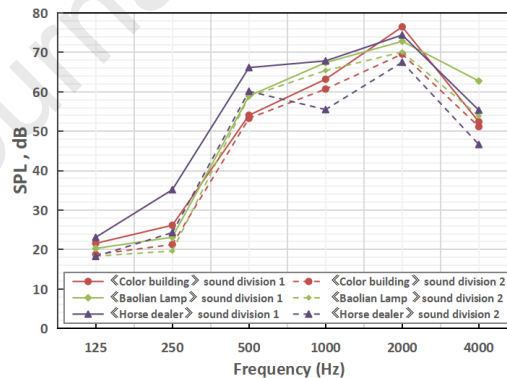


Fig.5. Spectrum analysis of 6 Peking Opera episodes sung by Mei Lanfang

Herein, the average sound level of each frequency band of the aforementioned six sound episodes from 125 to 4 kHz was 20, 24.9, 58.6, 63.3, 71.8, and 53.7 dB, respectively. Considering that the simulation results of the theatre sound field compared in this study are all relative values, these SPL values were used to replace the sound power value of each frequency band when considering the Beijing Opera actors’ singing as the simulated sound source. Simultaneously, considering that the actors generally face the main hall when singing, the simulated sound source was set as a directional sound source facing the main hall. During the performance of the Beijing Opera, the actors were located at the centre of the theatre and never left the spot. Therefore, only one sound source was set in the centre of the theatre in the model, at a height of 1.5 m, which meets the requirements of international standards [40].

Table 2

Mean and standard deviation of the EDT and SPL measured at each point in Jiayintang Theatre

	125 Hz	250 Hz	500 Hz	1 kHz	2k Hz	4 kHz
Mean value of the EDT (s)	1.29	1.26	1.2	1.14	1.07	0.92
Standard deviation of the EDT (s)	0.22	0.14	0.14	0.13	0.1	0.09
Standard deviation of the sound pressure level (dB)	2.2	3.8	1.4	3.4	3.1	3

3. Results

Herein, the sound field of the Jiayintang Theatre in the Shenyang Imperial Palace was first measured. Subsequently, the sound field model of the theatre was created and fitted with the measured values of the sound field. The effects of the spatial elements and the sound source on the sound field were analysed by changing the setting and height of the enclosed interface of the aisles, the stage position, caisson setting in the ceiling above the stage, and the singing direction of the actors on stage.

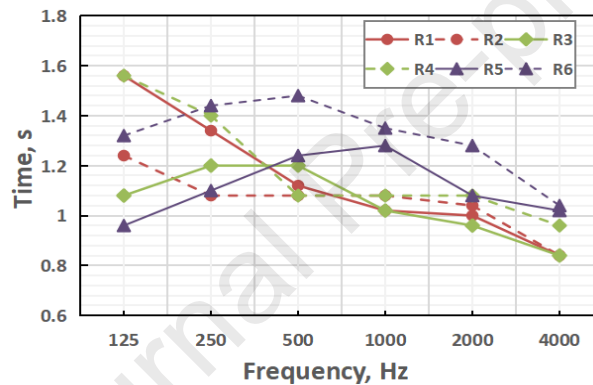


Fig.6. Measured EDT at each point of Jiayintang Theatre

3.1 Results of acoustic field measurements

As the largest theatre in the Shenyang Imperial Palace, a world cultural heritage, the Jiayintang Theatre is currently well preserved. Its overall layout, architectural interface materials, and sound field characteristics are consistent with those of the Qing Dynasty. Herein, the sound field of Jiayintang was tested on the spot, and several receiving points were set in the aisles and the main hall (please see Fig. 1(c)). The EDT and SPL results obtained from the test are shown in Fig. 6 and Table 2.

The test results present the following:

1. The reverberation time curve of each point is generally flat and straight, and the reverberation time under low frequencies is higher than that under high frequencies. The mean value of the intermediate frequency EDT (500 and 1000 Hz) at each point is 1.17 s (the standard deviation is approximately 0.14 s), and a reverberation time of approximately 1 s remains in the 2 and 4 kHz frequency bands. Compared to the sound field of the inner courtyard of the traditional Korean Palace, which is similar to the Jiayintang Theatre in terms of the layout and building materials, in the front yard of the Injeongjeon Hall at the Changdeokgung Palace in South Korea, the values of RT30 from 125 to 4 kHz are 1.8, 1.9, 1.76, 1.55, 1.53, and 1.19 s, respectively[46]. The reverberation time curve in various frequency bands is also generally flat and straight, which may be a feature of the courtyard sound field. Traditional Chinese dramas are performed primarily in the form of actors singing. In a semi-outdoor performance, to deliver

the sound to the audience at a long distance, the vocal frequencies of the actors are mainly concentrated in medium and high frequencies. Furthermore, a theatre with a long reverberation time at high frequencies can ensure that the actors' voices provide the audience with a fuller hearing experience. A study regarding the optimal values of the acoustic parameters in Peking opera theatres has demonstrated that the frequency characteristics with more reverberation in high frequencies is most preferred by the audiences [31]. Certain scholars have suggested that the average reverberation time of Beijing Opera performance venues with a good performance effect is 1.1 to 1.2 s [47]. The measured reverberation time of typical traditional Chinese drama performance venues is approximately 1.0 s in the main frequency band, which is the best reverberation time for occupied halls of moderate size [20]. Therefore, the reverberation time parameters of the Jiayintang Theatre in each frequency band are considerably suitable for the needs of Chinese opera performance. Additionally, a longer low-frequency reverberation time can make the bass sound 'fuller'. The ratio of the sum of the reverberation time at 125 and 250 Hz to that of the reverberation time at 500 and 1000 Hz is called the bass ratio. The range of the bass ratio in theatres is usually required to be between 1.10 and 1.40, where the sound quality of the performance space has a good 'warm' feeling. The test results demonstrate that the bass ratio of the Jiayintang Theatre is 1.1, which is in a relatively good range.

This study compares the sound field of the Jiayintang Theater with that of the Kabuki theater "Playhouse" in Japan (the Playhouse usually has a roof but the airtightness of the room is poor). Previous studies demonstrated that the reverberation time of the "Playhouse" in Japan was significantly short, as low as 0.5 s; however, traditional Japanese Kabuki music can be best performed only when it is played in the "Playhouse" [48]. Based on the measurements and simulations of the sound field in eight Japanese Kabuki theatres built between 1827 and 1921, another study demonstrated that the EDT_M of each theatre is distributed between 0.5 and 0.9 s; therefore, it is speculated that the acoustic conditions consistently seem to be designed for optimal speech intelligence [49]. This further confirms that the sound field characteristics of traditional theatres in China and Japan are closely related to the acoustic needs of the corresponding performances.

2. The measured medium frequency reverberation time in the main hall of the Jiayintang Theatre is higher than that in the aisles, which may be a result of the relatively closed space and multiple reflections of the sound inside the main hall. Moreover, one interface of the aisles is open to the courtyard; the sound accordingly dissipates quickly.

3. The standard deviation of the SPL at each point of the Jiayintang Theatre is relatively small. The average medium SPL frequency is approximately 2.4 dB, which is less than the JND (3 dB) of the SPL [37], suggesting that the Jiayintang Theatre has good sound field uniformity.

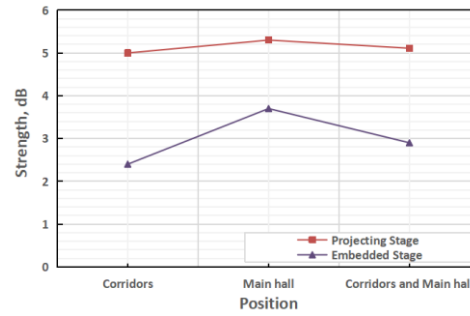
3.2 Results of acoustic field simulations

3.2.1 Enclosing interface of the aisles

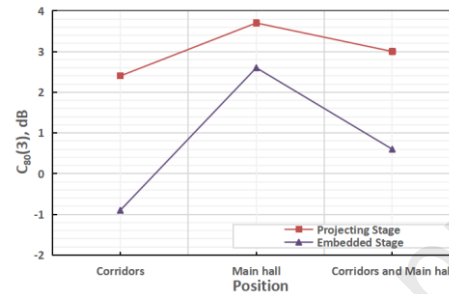
As the enclosing interface on both sides of the Jiayintang Theatre, the aisles have a roof and a brick wall on the outside. This study analysed the effects of changing the enclosing interface of the Jiayintang Theatre, including removing the ceiling and sidewalls of the aisles and changing the height of the sidewalls, on the sound field of the theatre's main hall and aisles.

The results of the sound field simulation reveal that when the ceiling of the aisles is removed, the average G value of each receiving point in the aisles decreases from 5.0 to 2.8 dB, the EDT_3 decreases by 21.9%, and the C80(3) increases from 2.4 dB to 5.3 dB. When the sidewalls of the aisles are removed, the G value of the aisles decreases to 2.4 dB, the EDT_3 decreases by 23.7%, and the C80(3) increases to 5.3 dB. With both the ceiling and sidewalls removed, the G value decreases to 1 dB, the EDT_3 decreases

by 29.8%, and the $C_{80}(3)$ increases to 6.7 dB. Furthermore, the STI changes in the aisles with these two changes are less than the JND values. The aforementioned results, especially the decrease in the sound



(a)



(b)

Fig.7. Analysis of the effects of stage changes

intensity and reverberation time, which may have a negative impact on the experience of the audience watching the performance in the aisles, demonstrate that the enclosed interface has a substantial effect on the sound field in the aisles. Removing only the ceiling of the aisles has little effect on the EDT_3 of the main hall. When the sidewalls or both the sidewalls and the ceiling are removed, the EDT_3 in the main hall decreases by 7.4% and 13.9%, respectively, which has certain effects. However, these three changes in the interface of the aisles have little effect on the values of G , $C_{80}(3)$, $SPL(A)$, and STI in the main hall, and the change in values are all smaller than the JND values.

The sidewalls of the aisles in the theatre are 3.3 m high, which is relatively low. This study simulated changes in the sound field in the auditorium of the theatre when the height of the aisles is increased. The simulation results show that when the height of the sidewalls of the aisles changes from 3.3 to 5.3 m and 7.3 m, the EDT_3 in the aisles increases by 8.8% and 11.4%, respectively, and the EDT_3 in the main hall increases by 11.1% and 17.6%, respectively. However, the increase in the height of the aisles has no significant effect on the G , $C_{80}(3)$, $SPL(A)$, and STI of the receiving points in the main hall and aisles; moreover, the changes in all the parameters are less than the JND values. This indicates that the effects of increasing the height of the aisles on the sound field of the Jiayintang Theatre are only reflected in the EDT parameters.

3.2.2 Stage forms

Stages in traditional Chinese drama performance theatres can be classified into two forms, the projecting and embedded forms, and the number of traditional theatres adopting these two-stage forms is roughly the same. Palace theatres, including Jiayintang, generally adopt a projecting stage extending into the courtyard, which enables the audience to watch the drama from all three sides. However, several folk theatres adopted an embedded stage parallel to the make-up room behind the stage. Thus, the space in front of the stage can accommodate more audience members. Herein, changes in the sound field parameters were simulated in the Jiayintang Theatre when the stage form of the theatre was changed

from the projecting to the embedded form.

When the stage was changed into an embedded stage, the G value in the main hall in which the emperor would watch the opera decreases from 5.3 dB to 3.7 dB. In the aisles in which the ministers would watch the opera, it decreases from 5.0 dB to 2.4 dB (Fig. 7(a)). Simultaneously, the EDT in the theatre's audience area increases, with a 21.3% increase in the main hall and a 15.8% increase in the aisles. Changing the stage into an embedded type also reduces the music clarity. The C80(3) decreases from 2.4 dB to -0.90 dB in the aisles, and from 3.7 dB to 2.6 dB in the main hall (Fig. 7(b)). Furthermore, the STI value in the main hall decreases from 0.46 to 0.43. All these values are greater than the JND values. Generally, if the stage was to be changed into an embedded type, the changes in sound intensity, music clarity, and language clarity in the audience area would have a negative impact on the opera-watching experience of the emperor and ministers.

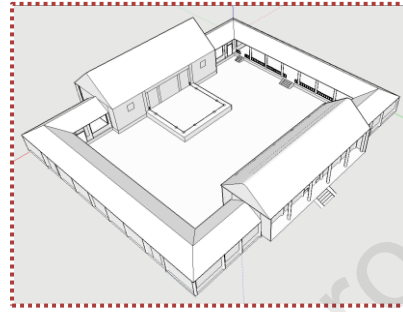
Additionally, when the stage form is changed into the embedded type, it affects the sound field and has a negative impact on the visual aspects of the performance for the audience in Jiayintang. Research has shown that the distance between the Beijing Opera actors and the audience should not exceed 22–24 m at most because the actors' movements and expressions are clearly visible at this distance. The average distance from the projecting stage centre of Jiayintang Theatre to each receiving point in the main hall is approximately 19.7 m, and that to the aisles is approximately 21.1 m. When the stage is changed into an embedded format, the average distance from the stage centre to the main hall and the aisles increases to 26.6 m and 25.4 m, respectively. This could have hampered the emperor and ministers from seeing the actors' expressions clearly. All these indicate that the ancient design had a certain rationale in terms of hearing and visual perception for adopting the form of a projecting stage in the Jiayintang Theatre.

3.2.3 Stage roof height and caisson setting

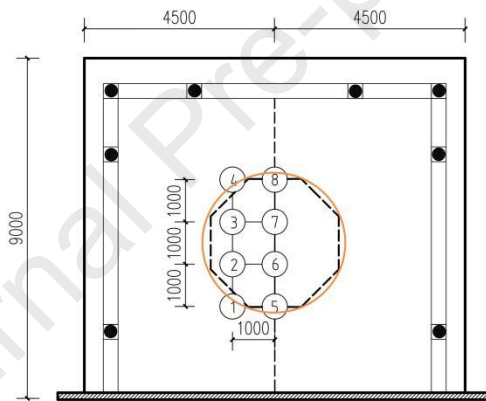
Traditional courtyard theatres in China are mostly equipped with a pavilion-type stage with a roof, which has the dual functions of decoration as well as shielding the actors from wind and rain. The



(a)



(b)



(c)

Fig.8. Stage caisson and stage plan of Jiayintang

theatre's ceiling is mostly equipped with ornate decoration with a beautiful appearance, an octagonal or a dome caisson, which increases the visual and artistic effect of the theatre (Fig. 8(a)). The roof area of the Jiayintang Theatre only accounts for 8% of the entire courtyard area. If the ceiling above the stage in the Jiayintang Theatre were to be removed, and the actors were to perform on an open-air stage (see Fig. 8(b)), the results of the sound field simulation show that the average G values of the receiving points in the aisles and the main hall would decrease by approximately 1.0 dB and 0.9 dB, respectively, which are approximately equal to the JND. However, the changes in the EDT_3 , $C80$ (3), $SPL(A)$, and STI of the sound fields in the main hall and the aisles after removing the stage ceiling are all less than the JND. These indicate that the effect of the stage roof on the sound field in the audience area of the Jiayintang Theatre is insignificant.

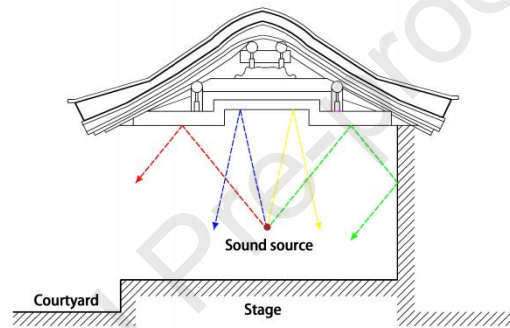
Previous studies have demonstrated that the dome on the stages of traditional Chinese folk theatres provides an early reflection support to the singers. This effect of gathering sounds is often praised by performers [50]. Research has shown that the support provided by the caisson to the actors on the stage is dependent on its size, depth, and height, as well as the sound absorption and reflection coefficient of materials[22]. To further analyse the degree of support of the caissons to the actors in palace theatres, this study set eight undirected sound sources in the centre of the stage with an interval of 1 m to simulate the actors' singing positions (Fig. 8(c)). It set receiving points with an interval of 1 m in four vertical

Table 3

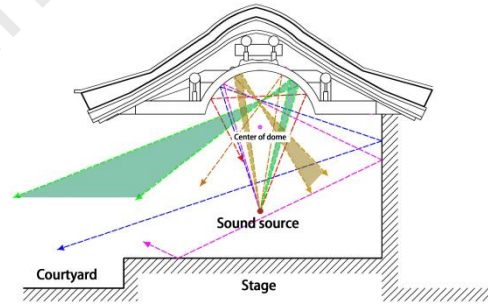
Degree of stage support of each point in Jiayintang

	1	2	3	4	5	6	7	8	Mean	SD
No ceiling	-26.2	-24.6	-21.7	-21.1	-20.6	-20.8	-24.6	-26.5	-23.3	2.3
Flat ceiling	-6.9	-6.2	-6.6	-6.9	-7.2	-6.9	-6.8	-7.2	-6.8	0.3
Octagonal caisson	-7.2	-6.1	-6.7	-7.4	-7.7	-7.3	-7.1	-7.7	-7.2	0.5
Dome caisson	-10.9	-10.5	-11.5	-12.1	-12.2	-12.2	-11.9	-12.3	-11.7	0.6

directions for all eight points. The undirected sound sources and receiving points are both 1.5 m high, and the ST_E value of each point is the average of the four receiving points in the four directions around it. Herein, the actors' support degree (ST_E) at each point on the stage was simulated under the following four conditions: no roof, flat ceiling, octagonal caisson roof (current status), and hemispherical dome. Furthermore, the size of the hemispherical dome is close to the current octagonal caisson, with the central



(a) Octagonal caisson (smooth surface)



(b) Dome (smooth surface)

Fig.9. Schematic diagram of reflection of sound waves by the caisson

circle diameter being 1600 mm. See Figs. 9(a) and (b) for the sound wave reflection schematic diagram of the two types of caisson. The simulation results of the sound field are shown in Table 3. The ST_E of each point below the dome caisson is between -10.5 and -12.3 dB, which is in the optimal range [35]. Moreover, the ST_E values of the flat ceiling and the current octagonal caisson are roughly equal. The ST_E value of each point is between -6.1 and -7.7 dB, whereas it is between -20.6 and -26.5 dB without the ceiling, which is relatively low. This demonstrates that the octagonal caisson currently used in Jiayintang is not as effective as a dome caisson in terms of acoustics; however, it is better than a stage with no ceiling.

A further simulation analysis demonstrates the following condition. If the octagonal caisson with a diameter of 2.5 m in the stage ceiling of Jiayintang is enlarged into a single-layer caisson with a diameter

of 5 m or changed into a double-layer caisson with a diameter of 5 m, it will have little effect on the acoustic parameters of each receiving point in the aisles and the main hall. Additionally, it will have little effect on the ST_E value, with the change value being lower than 1 dB.

According to the shape of the caisson, the scattering coefficient is assumed to be 0.4 in the aforementioned simulation. If this scattering coefficient is changed to 0.2, 0.6, or 0.8, the simulation results present the following under the different scattering coefficients: the acoustic parameters of each receiving point in the aisles and the main hall change slightly, the ST_E value of each point on the stage changes slightly; the changes in several cases are less than 0.5 dB. This indicates that the caisson's scattering coefficient does not significantly affect its acoustic function.

If the theatre roof is raised from 3.5 to 4.5 m or 5.5 m, there will be no significant changes in the acoustic parameters of each receiving point in the aisles and main hall. This result is different from those of a previous study regarding the sound field of Chinese folk theatres [22], possibly because contrary to

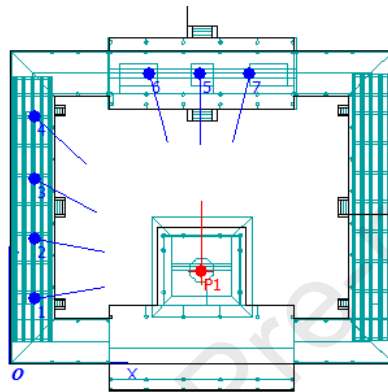


Fig.10. Sound source points to the main hall

folk theatres, the audience area of Jiayintang, which is a palace theatre, is not located in the courtyard. When the theatre roof is raised from 3.5 to 4.5 m and 5.5 m, the ST_E value on the stage decreases from -7.2 to -8.4 and -10.0, respectively, which tends to be better numerically.

Note that the shapes and materials of stage caissons in traditional Chinese theatres vary considerably depending on the theatre type. This study only focused on theatres with the same materials and similar caisson sizes as those in Jiayintang; further tests and analyses are needed to determine the acoustic effects of other types of caissons on the stage and audience areas.

3.2.4 Sound source direction

Actors performing the Beijing Opera in traditional Chinese theatres usually sing in front of the main hall, and the sound source points to that area, as shown in Fig. 10. If the sound source faces two sides when the actors perform, the sound field changes after the direction is rotated by 90 degrees, as shown in Table 4.

The simulation results of the sound field demonstrate that when the sound source points from the main hall to the aisle with the receiving points, the average value of G of the receiving points in the aisle increases by 2.3 dB, the EDT decreases by 20.2%, $C80(3)$ increases by 3.1 dB, STI increases by 0.07, and SPL increases by 4.1 dBA. If the sound source turns to the other aisle, singing with the actors' backs facing the aisle with the receiving points, compared to the sound source facing the main hall, the G value of the receiving points in the aisle decreases by 2.9 dB. Furthermore, the EDT increases by 7.9%, $C80(3)$ decreases by 3.3 dB, and STI decreases by 0.05. This shows that the actors' voice directivity has significant effects on the sound field in the aisles. The sound intensity, sound level, and music and language clarity improve in the aisle faced by the actors, which is favourable for the ministers in the

aisles watching the drama.

If the sound source faces the aisles, compared to the sound source facing the main hall, the G value of the receiving points in the main hall decreases by 1.8 dB. Furthermore, the EDT increases by approximately 15.7%, C80(3) decreases by 3.6 dB, STI decreases by 0.11, and the SPL decreases by 6.0 dBA. This indicates that if the actors sing towards the aisles, the sound intensity, music, and language clarity of the sound field in the main hall would decrease, which would have had a negative impact on the emperor watching the drama in the main hall.

Table 4

Simulation values of receiving points with different sound source directions

Parameter	Sound source points to the main hall		Sound source points to the aisle		Sound source points to the other aisle	
	Aisles	Main hall	Aisles	Main hall	Aisles	Main hall
G	5	5.3	7.3	3.5	2.1	3.5
EDT3	1.14	1.08	0.91	1.24	1.23	1.25
C80 (3)	2.4	3.7	5.5	0.1	-0.9	0.1
STI	0.42	0.46	0.49	0.35	0.37	0.35
SPL (A)	47.6	50.8	51.7	44.6	45	44.8

4. Discussion: Comparison with other traditional theatres

Sound quality is crucial for the theatrical experience of an audience. As the highest-ranking theatres in ancient China, courtyard-style palace theatres are different from courtyard-style folk and Western traditional theatres in terms of architectural form, audience position, and sound field characteristics. By comparing the sound field parameters of different types of theatres, we can better understand traditional Chinese theatres.

4.1 Comparison of sound fields between traditional palace theatres and Chinese folk theatres

First, when comparing the Jiayintang Theatre with Chinese folk theatres, previous scholars measured three courtyard folk theatres in Chinese gardens. The results demonstrated an average strength (G) of 4.7 dB, an average EDT_{mid} of 0.74 s (Rt30_{mid} is 0.81 s), C80_{mid} of 5.9 dB, and an average STE of -9.3 dB [17]. The measured sound field results of the other six Chinese folk courtyard theatres demonstrated an average strength (G) of 2.4 dB, an average EDT of 0.8 s, and an average STE of -9.2 dB [18]. The G and EDT values of the Jiayintang Theatre are higher than those of the aforementioned folk theatres, indicating that the Jiayintang Theatre, which is a royal theatre, has a better sound field performance. The STE of Jiayintang is -7.2 dB, which is not significantly different from that of folk theatres, demonstrating that both Chinese palace and traditional folk theatres adopted measures to enhance the sound field perception of the actors on stage.

4.2 Comparison of sound fields between traditional palace theatres and Western traditional open-air theatres

Herein, the sound field parameters of the Jiayintang Theatre and traditional Western open-air theatres were compared. Unlike the Western traditional open-air theatres, which can accommodate thousands or even tens of thousands of audiences at the same time, traditional Chinese Palace courtyard

theatres, including the Jiayintang Theatre, were made to only meet the requirements of dozens of royal audiences. Therefore, the sound field parameters of the two types of theatres should be significantly different. Studies have shown that the reverberation time of early ancient Greek theatres was relatively low, and the RT30 was only 0.3–0.6 s [1]. The reverberation Time (RT20) in an Italian ancient theatre having Greek origins was 0.57 s, and the values of G in the mid-frequency range went from -1 to -8 dB [11]. An analysis of the sound field in three ancient Greek open-air theatres was performed, and acoustic simulations were conducted using well-established computer-aided tools. The results demonstrated that the RT60 values under the vacant state ranged between 0.13 and 0.2 s [51]. A shorter reverberation time was observed because the traditional open-air theatre in ancient Greece was larger and more open than the traditional Palace courtyard theatre in China, resulting in a lack of reflected waves from the top and sides. In the evolution process, a more enclosed form, steeper seating area, harder materials, and a higher theatre have been useful for improving the acoustics. The evolution also corresponded to a general increase in reverberation, along with the wide use of theatres for performing drama. In ancient Rome, the reverberation at the upper seats of the theatres could reach 1.5 s; the acoustic indices were good considering that they were close to the modern theatres [1]. Another simulation analysis of three Roman semi-circular open-air theatres demonstrated that with an occupied auditorium in ancient times, RT30_M was 1.44 s, G_M was -5.22 dB, C80 was 6.4 dB, and the STI value was 0.67 [8]. The reverberation time of the Jiayintang Palace Theatre is higher than that of the early ancient Greek theatres but lower than that of the ancient Roman theatres. Only the G_M sound field parameter value of 5.1 dB is higher than that of the Roman open-air theatres. This indicates that the sound intensity in the auditorium of the Jiayintang Theatre is better than that of these three Roman semi-circular open-air theatres. A previous study aiming to establish a sound quality evaluation system for traditional Chinese performance buildings also demonstrated that the preference for loudness in the Chinese evaluation system was higher than that in the Western evaluation system, and culture was an important factor that caused the disparity between the two evaluation systems[19].

Considering the different scales of the theatres, this study compared the sound field parameters between the front seats (15.93 m away from the stage centre) in the ancient Greek theatres and the receiver points in the Jiayintang Theater. The average values of G at the front seats of the three ancient Greek theatres under the vacant state are 2.6, 2.5 and 0.0 dB, respectively [51], which are less than the average value of G in the Jiayintang Theater (5.1dB). This demonstrated that the sound intensity in the auditorium of the Jiayintang Theatre is stronger than that in the front seats of the ancient Greek theatre. The average values of C80 at the front seats of the three ancient Greek theatres are 14.6, 15.0 and 18.2 dB, respectively [51], which are higher than the average values of C80 in the Jiayintang Theater (3.0 dB). However, for a music performance, such a high C80 value may cause the music to sound significantly dry. Therefore, previous studies have shown that these three ancient Greek theatres are inappropriate for music performances [51].

Considering the enclosing structures of ancient Western theatres, specific areas of the Roman theatre (scaena, scaenae frons, orchestra, and cavea) are involved in sound perception for the intervals corresponding to early and late energy [10]. A study regarding the sound fields of two ancient theatres in Spain also demonstrated that the RT30_M value in one Roman-style semicircular theatre was 0.45 s as compared to 1.3 s in another amphitheatre, although both were enclosures without a roof [15]. The analysis of the Roman theatre of Verona demonstrated that the absence of the summa cavea, ambulatory, and upper gallery worsen the acoustic conditions [2]. Studies regarding the enclosing structures of ancient Greek and Roman open-air theatres demonstrated that the theatre wall and upper colonnade (or columned gallery) affect the sound field parameters of the theatre [4,12]. These research results are similar to those presented in our study. However, the upper colonnade is the main element maintaining the circulation of sound energy and prolonging the reverberation time [4]. Heightening the aisles of Chinese palace theatres

has little effect on the reverberation time in a theatre auditorium, which may be related to the varying seat distributions of the two theatre types.

Considering the setting of theatre equipment, in the study of ancient Greek theatres, Barkas demonstrated that scenery on the stage can improve the acoustic comfort in most theatres. The addition of a temporary, removable scenery during performance can provide a crucial auxiliary reflector (plus a sound barrier) of specific characteristics for the open-air theatre [12]. Bo et al. proposed obtaining acoustical improvements through the smart design of different scenery elements, particularly the scenic front, theatre floor, and back panels. This allows the reinforcement of the sound propagation [14]. The findings of our study show that regarding the stage design of traditional Chinese palace theatres, the function of the caisson is to provide an acoustic reflection for the actors. This may reflect the difference between the Chinese performance venues and those in the West because the theatre design in China considers the acoustic perception of the actors and not merely that of the audience.

4.3 Comparison of sound fields between traditional Chinese palace theatres and traditional Western indoor theatres

Farina et al. compared the acoustical properties of two different halls (a classical Italian Opera House and a typical Noh theatre in Japan), and the calculated results demonstrated different reverberation tails, which has been related to the varying shape of the audience area [52]. The eight Italian indoor theatres, which are opera venues, that were measured by previous scholars have an early reverberation time (EDT) of approximately 1.0 to 2.1 s, with an average of 1.41 s and a C80 of 1.99 dB [53]. By merging datasets from previous literature and more recent measurement campaigns, Prodi et al. found that the values of EDT_M in 22 Italian historical opera theatres isolating "unusually reverberant" were distributed between 1.07 s and 1.79 s, the average value of EDT_M was 1.39 s, and the average value of C80 (3) was 2.42 dB [54]. Beranek argued that the best reverberation time required by music in the classical style period was 1.6 to 1.8 s [29]. The average EDT in the six bands of Jiayintang is 1.15 s, and the average C80 is 3.0 dB. Although the reverberation time is shorter than that of indoor theatres, the C80 is higher than that of Western indoor opera houses. This may be because there are several spoken dialogues in a Beijing Opera, and the audience needs to hear what the actors say more clearly. Note, previous studies have demonstrated that the reverberation perception of theatres with and without roofs is inconsistent [24]. Thus, whether the comparison of reverberation time between the two theatre types is meaningful remains to be explored.

5. Conclusion

The pursuit of the sound field quality in traditional Chinese opera performance venues may have affected the evolution of architectural forms. This study analysed the Jiayintang Theatre in the Shenyang Imperial Palace, China, which is a world cultural heritage site. It is one of the most important traditional palace theatres in existence. First, the sound field of Jiayintang was measured, and the sound field model was then created and fitted. Subsequently, the effects of factors such as the enclosed interface of the aisles, stage position in the theatre, stage roof, and sound source direction on the sound field were analysed. The results present the following:

1. The reverberation time parameters of the Jiayintang Theatre are consistent with that of the Beijing Opera indoor theatres that have a good performance effect in modern times. Under the condition of a vacant auditorium, the average EDT₃ value at medium and high frequencies is 1.17 s, and the standard deviation of medium frequencies is 0.14 s. The EDT₃ in the main hall is higher than that in the aisles. Overall, the low-frequency reverberation time of each point is higher than the high-frequency reverberation time, the reverberation curve is generally straight, and the standard deviation of the SPL at

each point is small. This indicates that the sound field uniformity of the Jiayintang Theatre is relatively good.

2. The enclosed interface, stage position in the theatre, stage caisson, and sound source direction of a palace theatre affects the sound field of the theatre, especially the courtyard area. Through a simulation and analysis, the architectural form and sound source setting adopted by the existing Jiayintang Theatre were found to be conducive in creating good hearing experiences for the audience, especially for the emperor in the main hall when watching the drama. The details are as follows: (1) Removing the enclosed interface of the current theatre aisles would have a negative impact on the experience of the audience watching the performance from the aisles, including a decrease in sound intensity and reverberation time. (2) Changing the stage from the current projecting stage to an embedded stage would decrease the acoustic quality of each point in the theatre, which is mainly reflected in the G values in the main hall and the aisles decreasing by 1.6 dB and 2.6 dB, respectively, and the decrease of music clarity in the aisles and the language clarity in the main hall. (3) The main acoustic function of the octagonal caisson used in the stage ceiling of the current Jiayintang Theatre is to provide acoustic support for actors. The acoustic effect of an octagonal caisson is inferior to that of a dome caisson; however, it is better than that without a ceiling. (4) If actors on the stage were to change directivity from singing towards the main hall to singing towards the aisles, it would have had a negative impact on the emperor's experience while watching the opera in the main hall. The average G value of the receiving point in the main hall would decrease by 1.8 dB, the C80(3) by 3.6 dB, the STI by 0.11, and the SPL by 6.0 dBA.

3. Comparing Jiayintang with other traditional theatres, the sound field parameters of Jiayintang are more suitable for singing in traditional Chinese dramas. The G and EDT values of the Jiayintang Theatre are higher than those of several Chinese folk theatres measured by previous scholars. This indicates that the sound field performance of traditional Chinese Beijing Opera in palace theatres is better. Compared to Western semi-circular open-air theatres, the sound intensity in the audience area of the Jiayintang Theatre is stronger. Additionally, contrary to Western open-air theatres, the analysis of the stage roof of traditional Chinese palace theatres shows that the acoustic perception of the actors is considered, not merely the perception of the audience. Compared to traditional Western indoor theatres, although the reverberation time of the Jiayintang Theatre is shorter, the C80 is higher than that of Western indoor opera houses, which enables the audience to hear the long dialogues of the actors in the Beijing Opera.

This study analysed the acoustic parameters of traditional Chinese palace theatres and the effect of various elements on the sound field and compared them with Chinese folk theatres and traditional Western theatres in terms of acoustic performance. The results can help better understand the sound field characteristics of Chinese palace theatres and provide a reference for the design and protection of similar palace theatres in the future. So far, several studies have been conducted regarding European traditional theatres; however, studies regarding the sound field characteristics of Asian traditional theatres are limited, thus requiring more studies to analyse these theatres in the next period. Further experiments may be conducted by comparing the difference of the sound fields between traditional theatres in Asian countries, and then comparing the sound field of these Asian traditional theatres with that of traditional theatres in other parts of the world. These studies would play an important role in the protection of the architectural heritage of traditional theatres.

Appendix

A1. Sound field measured data of each point in the Jiayintang Theater

Table a-1 The measured values of EDT and SPL in the Jiayintang Theater

EDT(s) / SPL(dB)	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
R1	1.56/66.0	1.34/65.4	1.12/60.0	1.02/61.1	1.00/65.0	0.84/61.1
R2	1.24/63.0	1.08/69.9	1.08/63.4	1.08/62.4	1.04/65.0	0.84/61.8
R3	1.08/59.7	1.20/66.6	1.20/62.0	1.02/63.7	0.96/66.6	0.84/62.7
R4	1.56/60.5	1.40/63.1	1.08/61.3	1.08/62.8	1.08/66.0	0.96/64.1
R5 (R7)	0.96/63.9	1.10/68.2	1.24/61.8	1.28/61.6	1.08/63.4	1.02/59.6
R6	1.32/60.5	1.44/58.3	1.48/58.9	1.35/53.5	1.28/57.2	1.04/54.6

(1) Sound field simulation data corresponding to the measured data

Table a-2. Simulation average values of EDT and C80

The average values	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
EDT in the aisles	1.17	1.14	1.18	1.14	1.12	0.93
EDT in main hall	1.23	1.22	1.15	1.15	0.94	0.78
C80 in the aisles	2.5	2.8	2.3	3.0	2.0	2.9
C80 in main hall	0.9	1.0	2.8	2.5	5.8	6.9

(2) Simulation data to analyse the effect of the enclosure interface on the sound field

Table a-3. Simulation average values of EDT and C80 after removing the enclosure interface

The average values	125H z	250Hz	500Hz	1000H z	2000H z	4000H z
EDT in the aisles (Remove Sidewalls)	0.77	0.75	0.88	0.80	0.94	0.73
EDT in the aisles (Remove Roof)	0.77	0.78	0.86	0.91	0.90	0.72
EDT in the aisles (Remove Sidewalls and Roof)	0.59	0.56	0.76	0.72	0.91	0.74
C80 in the aisles (Remove Sidewalls)	6.3	6.7	5.4	6.7	3.9	4.8
C80 in the aisles (Remove Roof)	6.8	6.9	5.8	5.9	4.2	5.0
C80 in the aisles (Remove Sidewalls and Roof)	9.0	9.4	7.2	8.7	4.1	4.8

Table a-4. Simulation average values of EDT and C80 after changing the enclosure interface height

The average values	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
EDT in the aisles (5.3m)	1.24	1.22	1.27	1.23	1.21	1.01
EDT in the aisles (7.3m)	1.26	1.24	1.30	1.26	1.25	1.03
EDT in main hall (5.3m)	1.35	1.35	1.27	1.29	1.03	0.86
EDT in main hall (7.3m)	1.46	1.45	1.35	1.38	1.07	0.88

(3) Simulation data to analyse the effect of different stage forms on the sound field

Table a-5. Simulation average values of EDT and C80 after changing the stage forms

The average values	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
EDT in the aisles (Projecting stages)	1.48	1.48	1.41	1.27	1.27	1.02
EDT in the main hall (Projecting stages)	1.31	1.33	1.39	1.35	1.21	0.95
C80 in the aisles (Projecting stages)	-1.8	-1.9	-1.3	0.0	-1.3	0.2
C80 in the main hall (Projecting stages)	0.7	0.6	1.7	1.0	5.0	6.0

(4) Simulation data to analyse the effect of the sound source direction on the sound field

Table a-6. Simulation average values of EDT and C80 after changing the sound source direction

The average values	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
EDT in the aisles (Sound source toward the aisle)	1.17	1.14	0.96	0.96	0.81	0.66
EDT in main hall (Sound source toward the aisle)	1.23	1.22	1.31	1.11	1.31	1.17
EDT in the aisles (Sound source toward the other aisle)	1.17	1.14	1.27	1.23	1.20	1.08
EDT in main hall (Sound source toward the other aisle)	1.23	1.22	1.34	1.13	1.29	1.17
C80 in the aisles (Sound source toward the aisle)	2.5	2.8	5.0	4.7	6.7	8.0
C80 in main hall (Sound source toward the aisle)	0.9	1.0	-0.6	2.5	-1.5	-1.3
C80 in the aisles (Sound source toward the other aisle)	2.5	2.8	-0.6	0.1	-2.1	-1.3
C80 in main hall (Sound source toward the other aisle)	0.9	1.0	-0.3	2.1	-1.5	-1.3

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Highlights

- 1) removing roof and sidewall will negatively affect auditory experience in the aisle.
- 2) changing stage position would affect the audience's perception of acoustic quality.
- 3) octagonal caisson used in stage ceiling could provide acoustic support for actors.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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