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Research on the Archaeoacoustic Simulation of Daxiong Main Halls in Chinese Buddhist Temples Through Comsol Tool

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ABSTRACT

The acoustic analysis plays an irreplaceable role in obtaining information on Chinese Buddhist main halls tradition and relative practice that includes sound, deepening our comprehension of Chinese Buddhist architectural heritage. Various ceremonies and dojos constitute rich types of Buddhist main halls' sound fields. In this paper, the indoor sound fields of four main halls in the Buddhist temples are researched and compared. This paper used Sketchup to build the models and simulate sound fields when conducting ceremonies and dojos using Comsol Multiphysics software. The four main halls are Chongshan temple main hall, Xiantong temple main hall, Shuxiang temple Manjusri hall and Bodhisattva Top main hall, which are located in separately four temples of Shanxi Wutai mountain in China. Targeting three acoustic parameters including the reverberation time(RT), the first ray arrival time(Re1first) and surface sound pressure level(SPL) distribution, we simulated the acoustic effect of the space occupancy, Buddha realm space and worship space, indicating that the acoustic wave diffusion rate was positively correlated with proportion of hall height to depth, while the first arrival time is exactly the opposite. The largest RT at 2000Hz(about 1.3s)in the shortest period for 500Hz voice was observed in the main hall of Pusa Peak, while T_{60} even reached 4s in Xiantong temple main hall. The acoustic wave transmission rate was positively correlated with proportion of hall's height to depth, but the first ray arrival time was the opposite. The main hall of Pusa Peak had the shortest (0.0150s) first ray arrival time， the Shuxiang temple main hall had the longest time(0.0381s). In all the cases, appearing of the "sound shadow area" of the surface SPL distribution and the uneven sound energy distribution showed pillars in the middle space exerting significant impact on the acoustics of the Daxiong main hall.

ARTICLE INFO

Keywords:
Chinese Buddhist Daxiong main hall; Sketchup models; Comsol Models; reverberation time; first ray arrival time; surface SPL Distribution; architectural heritage; acoustic simulation.

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Intoduction

The multidisciplinary field of archaeoacoustics tends to introduce the balance of our understanding of the historical building by taking into account the aural environment influenced by various interconnected factors-including peculiar activities-that create human experience in historical buildings, thus also arguing that such acoustic heritage should be considered as an intangible and inseparable layer of architectural heritage (Đorđević, 2016), (R Suárez, Alonso, & Sendra, n.d.) Various Buddhist ceremonies, meetings and compassion dojos as well as water-land dojos constitute abundant sound types of Chinese Buddhist temple. Such as the pursuit of the deceased "Merit Lord", eliminating disaster and avoid difficulties for the survivors, and the Avalokitesvara meeting, there are broad varieties of praying activities inclusively. Other ceremonies frequently held there cover playing Avalokitesvara seven (called as Avalokitesvara holy saying, round Buddha), then returning to the position (sitting down to continue chanting Buddha), lastly being quiet and so on. Another assembly meeting in temples is " Hungry ghosts who spit fire ", while in the implementation of more than 4 hours, singing, chanting and reciting alternately proceed. All kinds of dharma assemblies are held in the powered Daxiong main halls or in the fields outside the main halls, which acoustic features perceptible or unnoticeable occur in this environment (Serizel, Bisot, Essid, & Richard, 2018).

The main function of the Chinese Buddhist temple is to place the Buddha statue for worshippers to worship. Its indoor space can be divided into two parts: Buddha realm space and worship space, while the Daxiong main hall is generally dominated by Buddha realm space (D. Zhang, Zhang, Liu, & Kang, 2018). The scale of the Buddha statues is larger, and the altar usually occupies the whole inner slot space or most central space. It could be regarded as a large room constructed by wood and comply with room acoustic regulation (Cremer & Müller, 1982), (Vorländer, 2013) in some meaning. Generally, one method which could be used to examine the quality of simulated acoustic evaluation is to analyze the grids division of the places situated in model's interior field, far field and interface. We find the characteristics of the spatial structural forms of the four main halls are not only limited to the linear geometry, but also applicable to the nonlinear geometry form. Therefore, we tried to directly apply the Comsol multiphysics to conduct and examine the sound field analysis in most accuracy degree, targeting Chongshan temple main hall (CTH), Xiantong temple main hall (XTH), Shuxiang temple Manjusri hall (STMH) and Pusa Peak main hall (PPH), as the four objectives.

Architectural Design of Daxiong Main Hall in Chinese Buddhist Temple

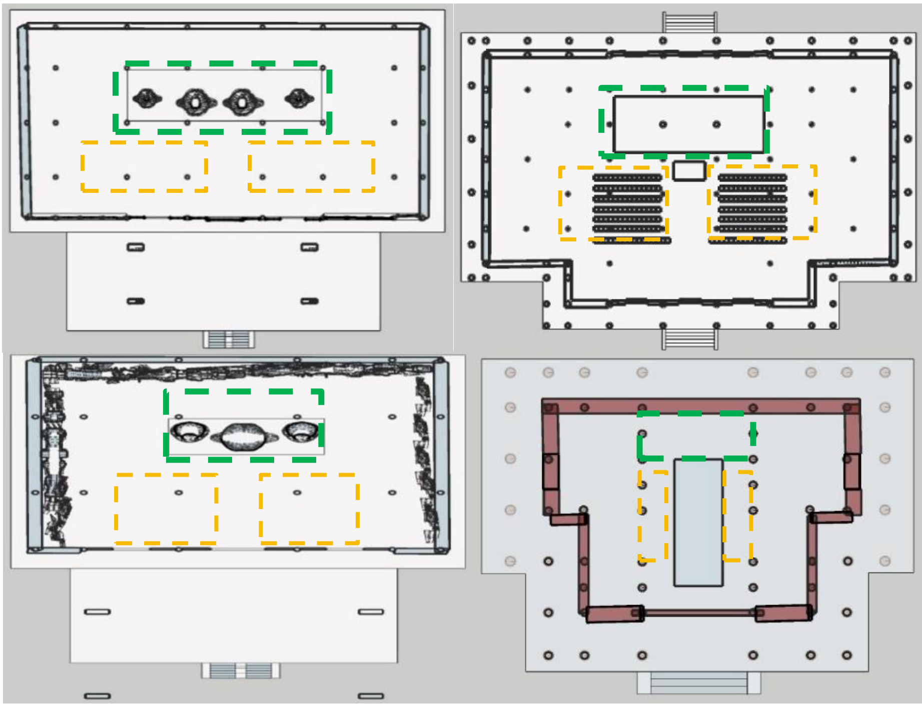
Daxiong Main Halls in Chinese Buddhist Temples located in Shanxi Wutai mountain were built in the ancient Chinese timber architectural manner: wooden dougong as ceiling, bricks walls all round with several wooden windows and doors, a circle of wooden colonnade outside, representing a high artistic level of indoor ceiling construction and symmetrical façade decoration, characteristic for the Chinese Buddhist temple wooden architectural style(**Error! Reference source not found.**). However, we focus on the interior space organization and applied materials for the purpose of acoustic analysis.

Figure 1 Exterior view of the four main halls (photo credits: author and Baidu)

Figure 2 Interior view of the four main halls studied (photo credits: author and Baidu)

Daxiong main hall has a heavy wooden dougong ceiling combined with the wooden fangzi and rafters. On the intersection of fang and beam or pillar rises one sequence of dougong (

Figure 2). In ancient China, thus in timber architecture as well, the wooden ceiling structure had a distinctive meaning on mechanics. It symbolized the concentration of flexibility and beauty and complemented the image of power absorption in the hall with the help of the top of the slope, ridges and cocked-up cornices. In hall, the ceiling is constructed on and supported by wooden pillars net which majority from the inside rand a circular from the outside rather than walls, thus earthquake force does not affect the structural steadiness of the hall. On the centeral part under the ceiling are the Buddha realm space that significantly facilitates the statue and worship space embracing the worshipers chanting, which



increase the holiness.

Figure 3 Plan of four main halls with marked positions of sound sources and receivers

Generation and optimization of the Buddhist main hall models with SU

The advantage of simplicity of Sketchup was used to build the temple models in a more evocative manner. Abstract evolution process of the four models of Buddhist main halls were shown in

	Initial Sketchup models	Ultimate Comsol models

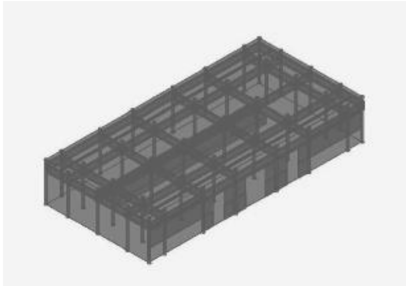
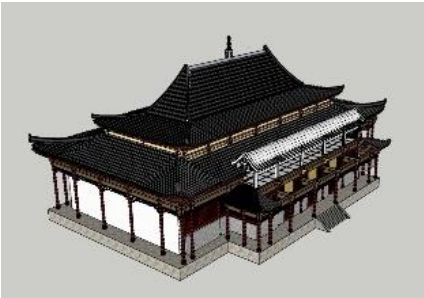
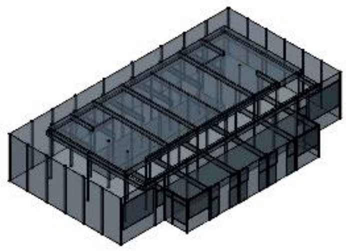
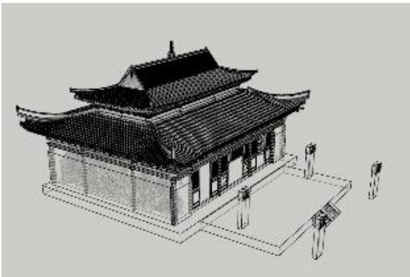
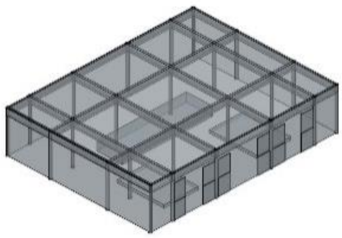
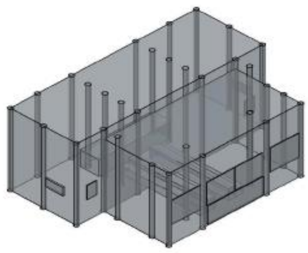
CTH		
XTH		
STMH		
PPH		

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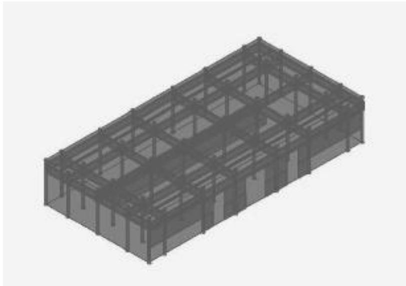
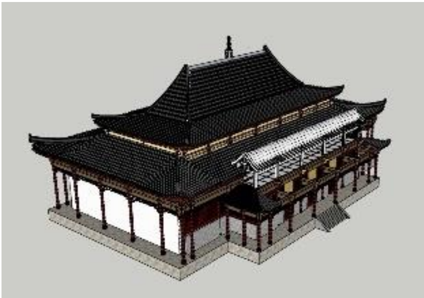
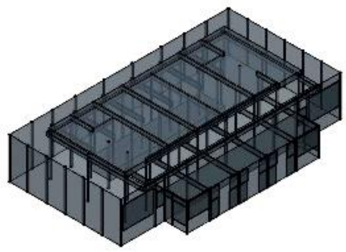
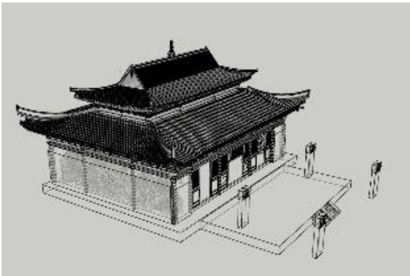
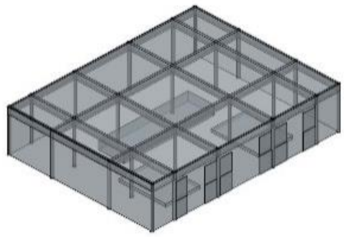
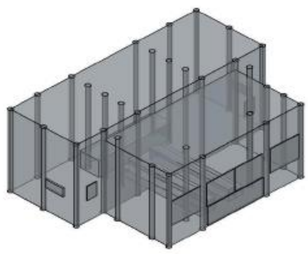
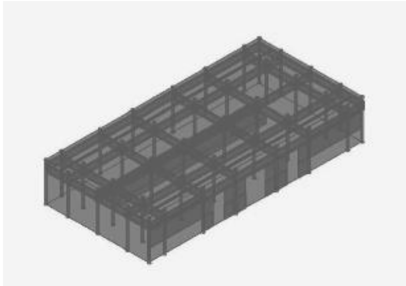
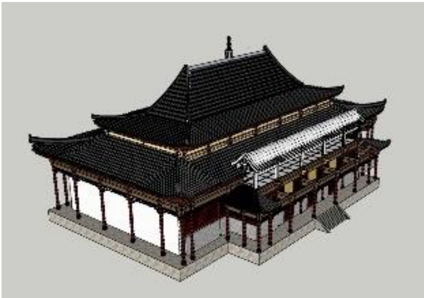
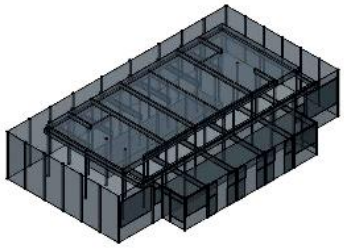
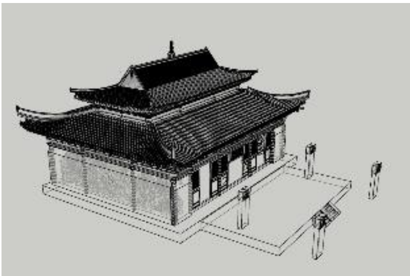
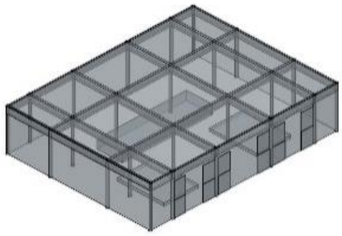
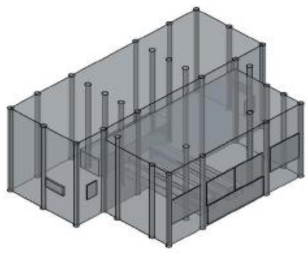
Table 1 comparison of the abstract evolution process of the four palace models

	Initial Sketchup models	Ultimate Comsol models
CTH		
XTH		
STMH		
PPH		

As can be seen from the

	Initial Sketchup models	Ultimate Comsol models

CTH		
XTH		
STMH		
PPH		

, the highest internal space in the four temples is the Pusa Peak main hall, and hall with the largest square area is the Manjusri main hall. The Chongshan temple main hall is close to the Xiantong temple main hall, and the latter has additional entrance hall in comparison with the former. The final model sizes and scales of the four halls were shown in

Table 2.

Table 2 Final models' size and scale of the four main halls

		Hall width (m)	Hall depth (m)	Hall height (m)	Three proportions of halls (length: width: height)
CTH		39.116	19.044	7.481	5.2： 2.6： 1
XTH	The former Bao Sha	20.596	3.5	4.389	5.9： 1： 1.3
	The latter hall	34.339	17.457	6.356	5.4： 2.8： 1
STMH		25.215	19.569	6.145	4.1： 3.2： 1
PPH (front and back rooms)	The former Bao Sha	9.14	4.252	4.667	2.15： 1： 1.1
	The latter hall	12.07	4.46	5.3	2.7： 1： 1.2

Method

Research context

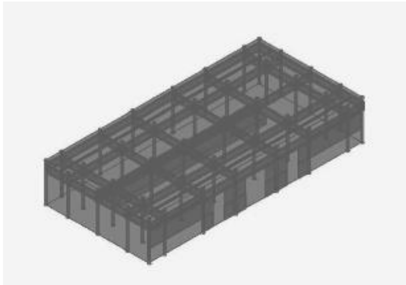
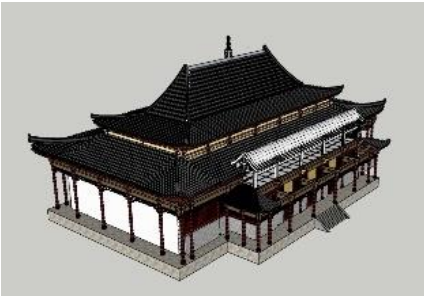
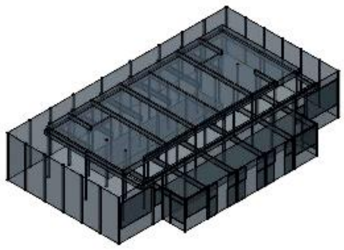
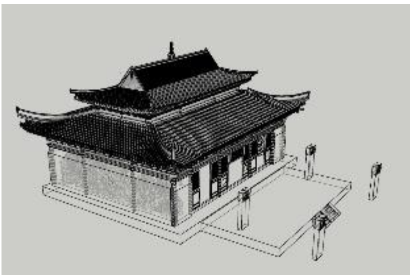
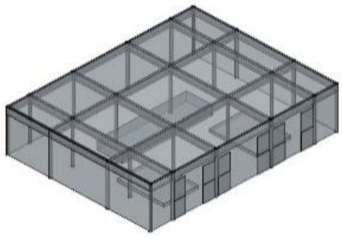
With the help of interpolation function, the advantage of RAC9Ray Tracing Method (Krokstad, Strom, & Sørsdal, 1968) embodies in that the research results could accurately analyze and reflect a series of key indicators, such as reverberation time (Sabine, 1900), (Bistafa & Bradley, 2000), surface received sound pressure level and the time of first arrival of sound line received at the receiving point (Barron, 1971) etc, because those are critical parameters for evaluating a heritage architecture. The method- comparing the energy from accurate direct and early reflections with the late reflections and reverberations to predict speech articulation- has been used for many years. The most common measurement index is C50, which calculates the ratio of the first 50ms sound energy to the entire impulse response sound energy (Bradley, Reich, & Norcross, 1999).

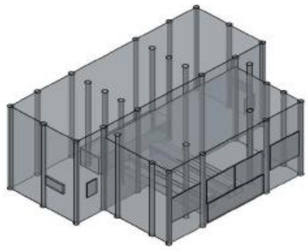
Instrument and data collection

Seven different coupling variables were selected for each of the four models, and sound absorption coefficients were defined for each variable, then Octave frequency spectrum was selected for the sound source in no particular order. Therefore, the RAC method could resolve the problem that ADE (Acoustic Diffusion Equation) method can only evaluate the acoustic energy diffusion of high-frequency sound waves (Vorländer, 1989), while RAC method can evaluate the acoustic field of spectral sound sources, which is closer to the actual acoustic performance of the Buddhist temple. What's more, because of the analysis process occupies more computer resources, which affects the calculation time, it generally requires a higher degree of simplification of the models.

Data analysis

The ceilings inside of the halls are either inner flat or flat, and the mesh divisions of the finite element models are very complicated with too many free degrees in calculation and have long simulation time, which occupy a lot of time for optimizing and adjusting the models. Therefore, the flat decoration ceilings were used to play the role of sound absorption (Campbell, Nilsson, & Svensson, 2015), as shown at the right row on

	Initial Sketchup models	Ultimate Comsol models
CTH		
XTH		
STMH		

PPH		

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(2) The windows are round or prismatic pattern wood lattice with a pane size of 8cm ~ 10cm and a radius of 3.5cm ~ 6cm and the sound wavelength of 10 kHz high frequency sound is equivalent to this size. It is known that the windows has little influence on high frequency sound in these sizes.

(3) In order to reduce and eliminate errors, we omitted or hidden some parts in the construction of the models, especially in the construction of the brackets, crossbeams, beams and other structures of the roof, according to the logic rules. The analyzed form could still be geometrically divided and combined, which were relatively complete ideal models.

Preparation of simulation calculation

It is necessary to give the boundary conditions (Kawai, 2007), (Zeng, Chen, & Sun, 2003), (Korany, Blauert, & Alim, 2001) by of values and parameters to conduct ball-surface sound source and receiver(Figure 3) transmission simulation in the pre-calculation periods (Appendix **Error! Reference source not found.**). Although d irectional sound sources is commonly used in monaural measurement of acoustic impulse response, we have considered and decided to use such ball-surface sound source that emit sound energy in the real halls in order to establish stronger correlation with the chanting, as sound source are primarily human voices in a direction-changing way. The sound source was placed at the regular seated height of 110 cm on a cushion (about 25cm height) (assumed to be the average person's height 170 cm). In addition, all the parameters were set under the condition that when the meditation (chanting) areas were full in order to get largest degree, which is effective for various sound receivers. The RAC method was used to simulate the equation of acoustic density and acoustic pressure. The acoustic pressure received by the acoustic receiver are expressed by p_{rms}(pressure of receiver model sound), the acoustic line density is expressed as I and I_n is the density of the n ray detected by the acoustic receiver. The specific RAC method equations are shown below:

(1) $I_n = \frac{L_r Q_n}{V_r}$ (2) $(P_{rms}^2)_n = \rho c I_n$

Where, V_r is the volume of the receiver, L_r is the distance that the sound ray passes through inside the receiver, Q_n is the energy carried by the n sound ray, ρ is the sound particle density, and c is the sound velocity at room temperature. The two equations determines the simulation rules of the ray tracing method and reflects acoustic density and pressure from energy carried by the n sound ray.

Findings

RT comparison

Before simulation, we had collected the data from previous research materials (Schröder, 1954), (Embrechts, 2000), summarized the sizes and structures of typical objects, and established the models in Comsol. Since we had considered the realistic materials decoration in the halls, the material parameters of the models were defined (Appendix **Error! Reference source not found.**). The f inite element mesh were divided for the four models through manual accuracy, then the reverberation time inside the halls were calculated (**Error! Reference source n ot found.Error! Reference source not found.**

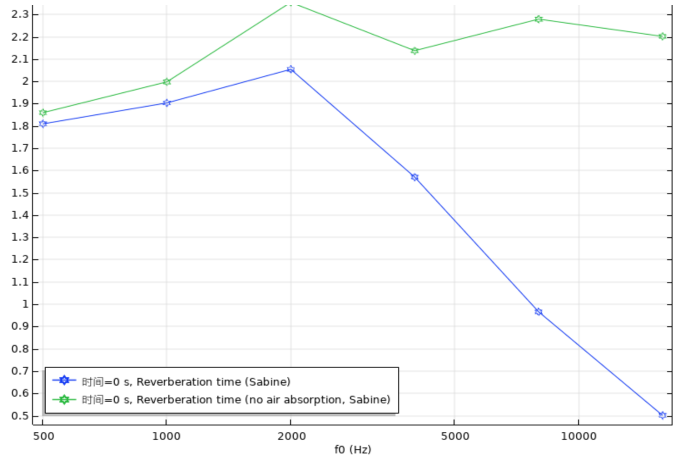

Figure 5 Reverberation of T60 and Tn60 in the PPH

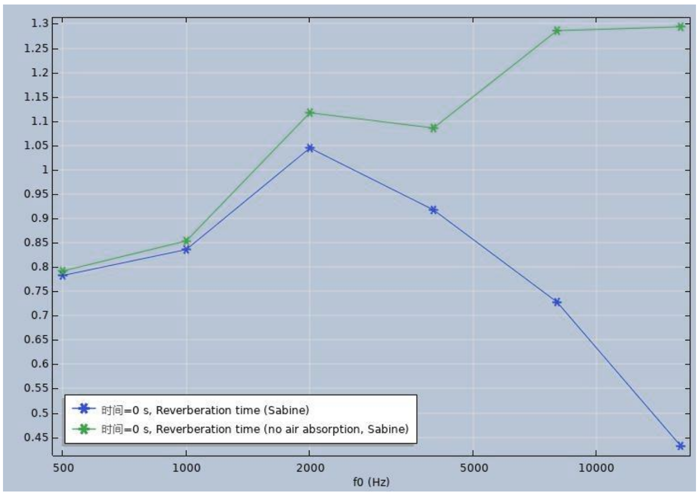

Figure 6 Reverberations of T60 and Tn60 inside the STMH

Figure 7) and a series of conclusions were proposed and interpretations were discussed.

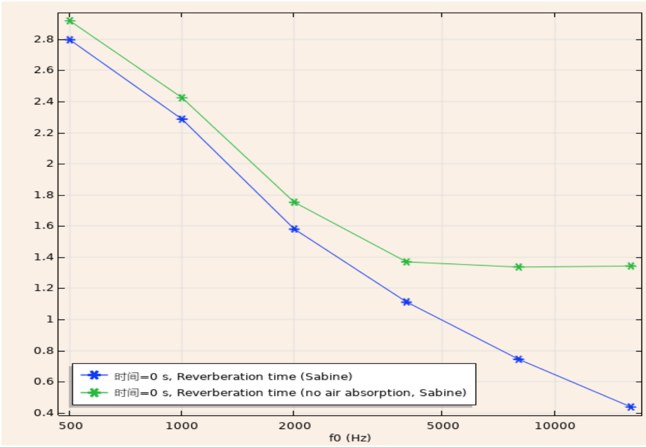

Figure 4 Reverberation of T60 and Tn60 in the CTH

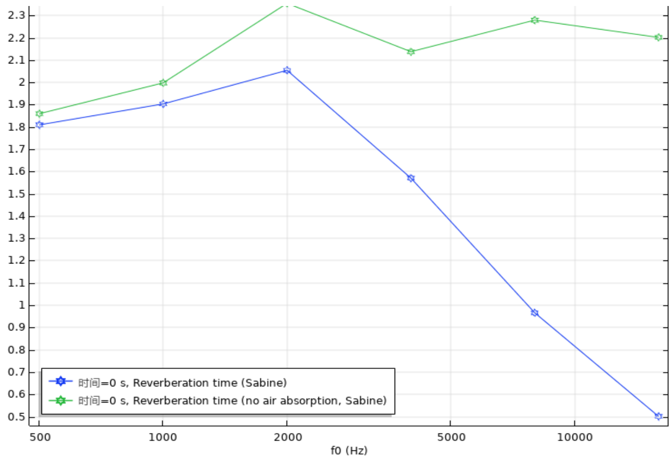

Figure 5 Reverberation of T60 and Tn60 in the PPH

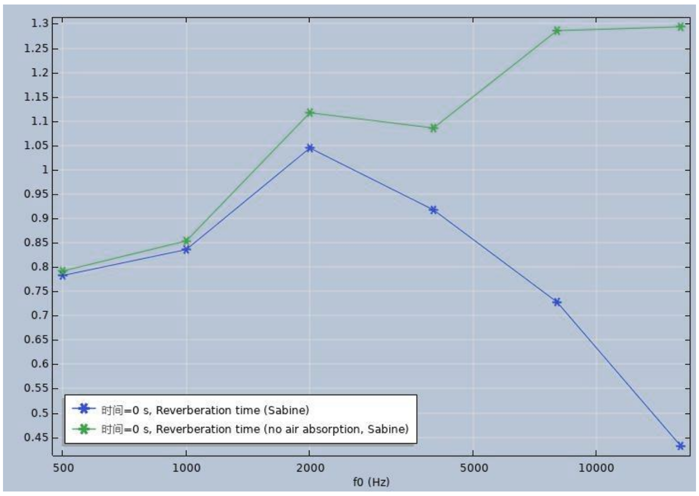

Figure 6 Reverberations of T60 and Tn60 inside the STMH

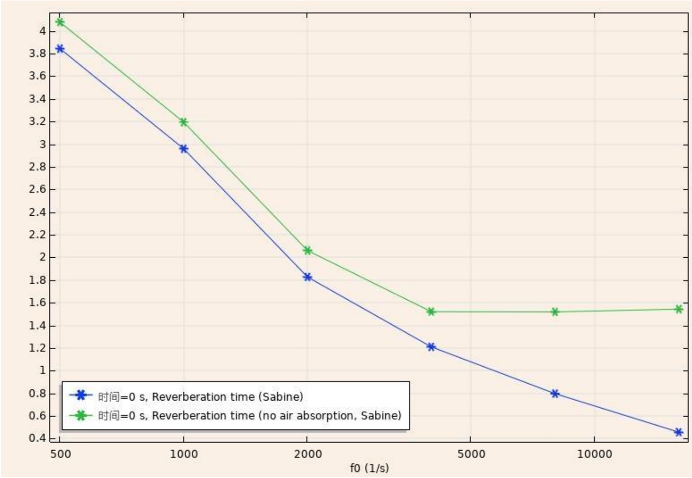

Figure 7 Reverberation of T60 and Tn60 in the XTH

Observing the four figures, we could proposed conclusions as follows:

(1) In the Chongshan temple main hall, T_{n60} had an inflection point at the frequency of 4300Hz, after which the value remained in the same level, indicating that the air had obvious absorption performance to the high-frequency sound above 4300Hz.

(2) In the hall of Bodhisattva, T_{60} whose sound frequency was less than 2000Hz raised with the increase of frequency, which was about 1.16s at 500Hz and 1.22s at 1kHz.The time was the largest at 2000Hz (about 1.3s), and then it decreased with a large slope to 0s at the frequency of 14000Hz.It proves that the hall had a great influence on the reverberation of high frequency and medium high frequency.

(3) The result in the Shuxiang temple Manjusri main hall was divided into two stages. With 2000Hz as the node, T_{60} whose sound frequency was less than 2000Hz increased with the increase of frequency, which was about 0.83s at 1000Hz.The maximum time was at 2000Hz, about 1.04s. After that, the slope decreased significantly. It shows that the hall had a great influence on the reverberation performance of high frequency and medium high frequency.

(4) In the main hall of Xiantong temple, before the sound frequency of 4000Hz, the two were in good agreement. After 4000Hz, T_{60} gradually declined in a straight line, and T_{60} was 0.4s at a frequency of about 18000Hz. After 4000Hz, T_{n60} showed a slight upward trend, with a T_{n60} rate of 1.6s at 18000Hz. For 500Hz voice, T_{60} even reached 4s, and T_{n60} reached 3.82s.The simulation result indicates that reverberation time was very large.

Comparison of the first ray arrival time (Re1first)

Calculation results

In 2000, the acoustic method was used to simulate the primary and secondary reflected rays on rough surface**Error! Bookmark not defined.**, and the ray method w as theoretically effective in simulating the arrival time of the first ray (Barron, 1971).

Table 3 Comparison of arrival time of the first ray in the four main halls

First ray arrival time	CTH	XTH	STMH	PPH
Re1first (s)	0.0297	0.0271	0.0381	0.0105
Arrival order	3	2	4	1

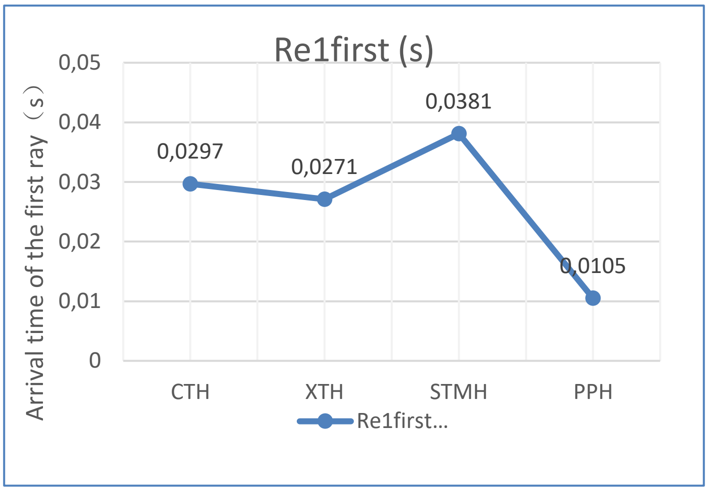

Figure 8 Comparison diagram of arrival time of the first ray in the four main halls

According to Table 3 and

Figure 8, the re1first value in the PPH was the smallest, the values in the CTH and XTH stood between the middle place, and the value in the PPH was 1/3 less to that in the STMH. The re1first values obviously had correlationship with the geometry shapes of the halls.

When the minimum interval between reflected sound and direct sound appears, for example when the time of language sound is more than 1/25s (0.04s) and music sound is more than 1/10s (0.1s), echo will occur. Therefore, the distance should correspond to less than 14m and 34m respectively, so as to ensure that there will be no echo problems when chanting, chanting and playing in the main halls.

Result analysis

The speed of acoustic wave transmission in the halls were related to the proportions of the geometric shapes of the halls, especially to the proportions of the halls' heights. It can be obtained that the speed of acoustic wave transmission in the hall space with a large proportion of the hall height to depth is higher, and the first arrival time is short. On the contrary, the speed of first sound line arrival time is long and the speed is low.The PPH has the highest ratio of height to depth in the four halls, and the height is very close to the depth, besides the first arrival time in it is also the shortest (0.0150s) in the four main halls, and the time of early reflection sound is the shortest.The ratio between the height and depth of the STMH is the smallest among the four sample halls, therefore, the first sound line takes the longest time to arrive (0.0381s), and the acoustic wave transmission rate is the smallest.What the arrival time of the first sound line placed in the middle level were the CTH and XTH.

Conclusions

The main hall of Pusa Peak tends to own the optimal reverberation effect in the shortest period most possibly because of the highest ratio of hall space height to depth, and the speed of acoustic wave transmission in it was the highest.

Characteristics of SPL at the spatial acoustic interface in the four main halls

In order to research the sound effect of stable sound field felt by monks during the chanting period in the main hall of Bodhisattva, Sound Pressure Level (SPL) Cross Sections were set as the seating areas (Marshall, 1967), (Sessler & West, 1964), as shown in

Figure 12**Error! Reference source not found.Error! Reference source not found.** .

Discussion

SPL value distribution at the interface surface in the XTH. The SPL values existed in the area where the sound source was located, but SPL values did not exist in the diagonal position of the sound source and the meditation area on the east side. The values on the west side were mainly distributed in 80dB, and the values on the east side were mainly distributed in 60-73dB, roughly showing a trend of low value in the east and high value in the west.

The SPL value distribution in the recitals area was not continuous, but in shape of intermittent sheets and blocks, and the value was mainly within the interval of 78-85dB.There was no SPL value on the surface and back of the Buddha table. The SPL value of the west side (73dB) was lower than that of the previous adjacent position. The eastern value was roughly the same as the previous value, about

68dB.There was no SPL value distribution on the surface of the eastern chanting area. In particular, the SPL value was still the lowest on the whole surface of the south side of the altar, about 60~65dB, at the place where the altar met the pillars on the east side of the Ming dynasty.

There was no SPL value on the surface of the Buddha platform in the STMH, but there was SPL value distribution on the back side. The value of SPL increased intermittively from east to west within the range of 68-78dB. In the lower corner of the east side, the irregular SPL value was higher than the adjacent value (66dB) (about 70dB).Meanwhile, the meditation area 6.5m away on the east side did not receive SPL. In front of the Buddha altar facing the recitation area, SPL value increased gradually from east to west. Similarly, in the lower corner of the east side, the irregular SPL value was higher than that of the adjacent side. The SPL value distribution in the recumbence area was not continuous, and the value was the highest in the northwest corner, which reduced the transmission outward in a circular shape and presented a fracture in the southeast corner, indicating that the SPL value disappeared at this location, and the size was within the interval of 75-93dB.

The SPL values from the east and south side of the sound source were still distributed in the STMH, which was about 75~77dB. It should be pointed out that the SPL value of the east side of the main hall was 60~65dB, where the column in the direction of depth met the Buddha altar, which was the lowest value. The SPL of the left and right sides reached 70~75dB, which was 10dB higher. The highest SPL on the surface of the altar was at the southwest corner nearest to the sound source, which was about 80~82dB.

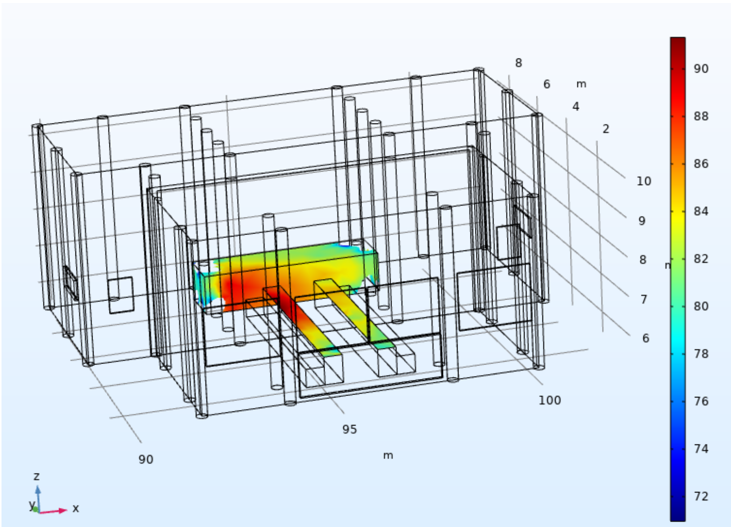

Figure 9 Distribution diagram of interface of SPL surface in the PPH

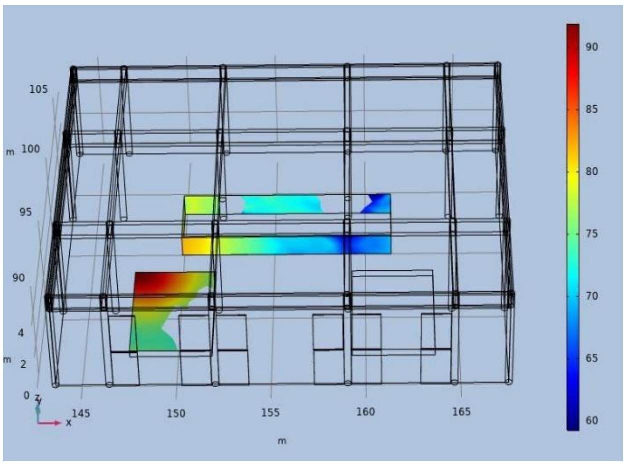

Figure 10 Distribution diagram of interface of SPL surface in the STMH

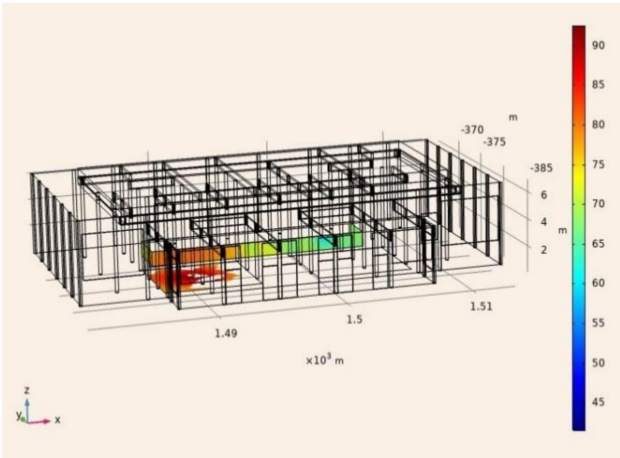

Figure 11 Distribution diagram of interface of SPL surface in the XTH

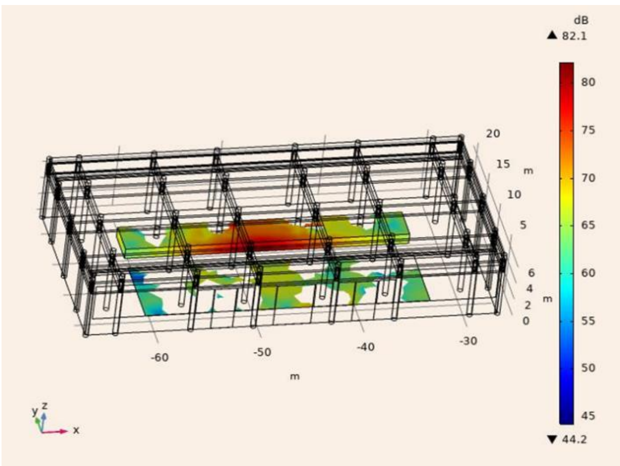

Figure 12 Distribution diagram of interface of SPL surface in the CTH

Distribution of sound pressure level at the interface surface in the CTH. SPL value was high in the middle region but low in the east and west. The overall appearance was a discontinuous color block, with two rows of secondary columns, no SPL value at the position where the sound source area met the column. The SPL value of the upper surface of the altar was about 73dB in the middle room, 63-68dB in the secondary room, and 62-66dB in the minor room. There was no SPL value distribution on the vertical surface of the north side of the altar. Compared with the Buddhist altar area, the blank area of SPL value in the chanting area was larger, showing the pattern of color spots in the range of 65-53dB, and local spots in the southwest position (SPL value was about 60-65dB).The difference between the two temples was that SPL value also run through the surface of the chanting area in the east.

On the west side of the altar, the SPL value was 65dB; on the south side, the SPL value was the largest(about 78~82dB)at the smallest position from the straight line of the sound source. As the distance between the east and the west was farther, the SPL value was smaller, and the SPL value decreased step by step from the center to both sides, and the minimum value decreased by 15dB. However, there was no distribution of SPL at the two pillars in the most central space connecting with the Buddhist altar, with the column as the center and extending outwardly in the area with a radius of 1m. There was also no SPL value on the vertical surface of the north side of the altar.

Distribution of surface SPL inside the PPH. When the reciting sounds from monks at the selected position were selected as the sound source, it can be observed that after the space is divided by the middle merit box, the two rows of meditation seats are separated by a wooden box slightly higher than 30cm. From the figure, SPL values were highest on the upper surface on the west side of the recitation areas (95dB).The sitting area on both sides showed a high SPL value in the middle, while the farther the two ends were toward the south and north, the lower the SPL value were. The SPL value was the smallest at the surface which is farthest from the sound source, which was about 82.4~83dB. In particular, SPL values were not distributed on the four vertical planes of the sitting area on both sides, and no SPL distribution was detected on the surface of the altar.

In the XTH and STMH, "acoustic shadow area" with blank SPL appeared in some parts of the sound field, and the distribution of sound energy was uneven, and the acoustic quality consistency of the meditation area in front of the Buddha statue in the hall was not good. It implicates the transmission of thoughts between Buddha and monks will be interfered badly when Buddhists are chanting from the usual acoustic feedback for the performer on the stage (Kahle, 2016). As the distance between the east and the west was farther, the SPL value was smaller, and the SPL value decreased to the minimum by approximately 15dB step by step from the center to both sides. Pillars in the middle space of the Daxiong main hall may have worst impact on the acoustic effect when monks are chanting.

Conclusion

As one of world religious heritage (D. X. Zhang, Liu, Wei, & Xiao, 2011) (Berardi, Iannace, & Ianniello, 2016), (Rafael Suárez, Alonso, & Sendra, 2016), (Zhao, 2017), Buddhist sound plays a critical role in creating the atmosphere of Chinese Buddhist temple, and various

Buddhist ceremonies and dojos in the Daxiong main hall constitute rich types of Buddhist temple sound, therefore it is necessary to research the inner sound field determined by the structure of the main hall. By simulating the sound field of the main halls in the typical Buddhist temples in China using RAC method in the software, the following conclusions are obtained: "acoustic shadow area" with blank SPL appeared in some parts of the sound field, and the distribution of sound energy was uneven, and the acoustic quality consistency of the meditation area in front of the Buddha statue in the hall was not good. It implicates the transmission of thoughts between Buddha and monks will be interfered badly when Buddhists are chanting from the usual acoustic feedback for the performer on the stage. As the distance between the east and the west was farther, the SPL value was smaller, and the SPL value decreased to the minimum by approximately 15dB step by step from the center to both sides. Pillars in the middle space of the Daxiong main hall may have worst impact on the acoustic effect when monks are chanting.

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