The Effect of Orchestra Pit Diffusion on the Auditorium Acoustics of Opera House

Chen Yian¹*, Zhao Yuezhe²

¹State Key Laboratory of Subtropical Building Science, South China University of Technology, China
²State Key Laboratory of Subtropical Building Science, South China University of Technology, China
*Corresponding author’s e-mail: 201820104459@mail.scut.edu.cn

Abstract. A scale model of the Zhuhai Opera House, with 7 kinds of simulated orchestra pits, was made and analyzed in an experiment. The pulse response of the auditorium of the opera house was measured and analyzed. The results show that diffusion treatments for the orchestra pit can affect the sound transmission of stage source, increasing C80 and D50 in the rear part of the auditorium and can also affect the sound transmission of pit source, making the average value of G in the auditorium rise. As well, no significant changes were found on EDT and T20 under the diffusion treatment of the orchestra pit.

1. Introduction
In recent research related to the orchestra pit, scholars have put forward suggestions on the design of orchestra form. However, some of these suggestions came from experience and remain unverified. Most of the scientific experiments about orchestra pit design and sound quality in theater are carried out by computer simulation methods, which can provide a certain theoretical basis but cannot exactly show the actual situation because it is impossible to simulate low-frequency diffraction.

When conducting such acoustic research, scale model technology can also be used for research, which can well circumvent the defects of computer simulation research methods. It can simulate the linear propagation and diffraction of sound waves in reality, and it can also simulate different cases of the orchestra pit in the model at low cost. Yet, the scale model technology has not been applied to the exploration of orchestra pit design.

This paper takes the Zhuhai Opera House as an example, uses scale model technology to simulate 7 different forms of orchestra in the model, records the impulse response of sound field in the scale model, and analyzes important objective acoustic parameters of theater in the model such as early decay time EDT, reverberation time T20, clarity C80, Definition D50, Strength G, balance B, to explore the influence of different orchestra pit forms on the propagation of orchestra sound sources, and on the sound quality of the auditorium.

2. The Scale Model Experiment Theory
The scale model experiment is a technique contains 4 steps. First, reduce the actual hall in a certain scale. Second, select interface material according to the law of similarity. Third, use high-frequency sound source and record the impulse response in the model. At last, analyze the impulse response, find the acoustic defects and predict the acoustic parameters.
In order to ensure the corresponding relationship between the size of the construction and sound wavelengths in the model is the same as in the actual hall, so as to correctly reflect the diffraction, scattering, and other acoustic phenomenon, when the hall is reduced according to the scale ratio \( n \) (the size of the construction in the model is reduced by \( n \) times), the sound wavelength \( \lambda \) in the model should be reduced by \( n \) times as well, and the frequency \( f_m \) tested in the scale model should be correspondingly increased by \( n \) times, namely

\[
\frac{l_m}{l} = \frac{1}{n} \quad (1)
\]
\[
\frac{t_m}{t} = \frac{1}{n} \quad (2)
\]
\[
c_m = c \quad (3)
\]
\[
\frac{\lambda_m}{\lambda} = \frac{1}{n} \quad (4)
\]
\[
\frac{f_m}{f} = n \quad (5)
\]

where \( l, t, c, \lambda, f \) respectively means the size of the building component, the propagation time of sound, the speed of sound, wavelength and frequency. The subscript \( m \) represents the quantity in the scale model. Correspondingly, the acoustic characteristics of the interface material in the scale model at \( n \) times \( f \) frequency should be consistent with the acoustic characteristics of the interface material in the real hall at \( f \) frequency.

3. The Scale Model Of The Opera House

3.1 The Opera House Surveyed
The 1:20 scale model of Zhuhai Opera House was analyzed in detail during the present acoustic survey. This hall is a typical modern opera house with a horseshoe-shaped auditorium plan, a huge stage house, an adjustable proscenium opening, a vertically movable orchestra pit, and upholstered seats. The distance from the curtain to the edge of apron stage is 3.2 meters. The area of the orchestra pit is about 104 square meters.

The auditorium of Zhuhai Opera House has three storeys, namely main floor, upper main floor and balcony, which can accommodate up to 1550 seats. The smooth curved interior surface of the auditorium is molded by glass fibre reinforced gypsum (GFRG), without extra absorption area other than side light apertures, loudspeaker cabinets and the upholstered seats. Four reflection panels are hung under the ceiling of the auditorium, including one in front of the proscenium and three over the balcony.

3.2 Making The 1:20 Scale Model Of The Zhuhai Opera House
In order to correctly reflect the absorption characteristics of the full-scale material, the materials used in different parts of the 1:20 scale model of the Zhuhai Opera House have been carefully selected. The auditorium is made of GFRG material, and the auditorium simulates an empty seat state, using 9mm thick polyester fiberboard as the cushion sound absorption material. The wall of the stage is 8mm thick composite fiber reinforced cement board (FRC) with 50mm cavity. The stage curtain and sound-absorbing materials on the side and back walls of the stage are simulated using 9mm thick polyester fiberboard.

3.3 Selected Cases Of Orchestra Pit
Base on original design of the orchestra of the Zhuhai Opera House, this study transform the boundary surfaces of the orchestra, forming 7 cases of orchestra shapes with linden boards. The 7 cases of orchestra shapes are as follows.

Case 1: The original orchestra pit of Zhuhai Opera House in scale;
Case 2: Outward inclined the side wall of the orchestra pit by 7.5°;
Case 3: Outward inclined the side wall of the orchestra pit by 15°;
Case 4: Inward inclined the side wall of the orchestra pit by 7.5°;
Case 5: Inward inclined the side wall of the orchestra pit by 15°;
Case 6: The outward inclination angle of the back wall of the orchestra is 15°;
Case 7: The outward inclination angle of the back wall of the orchestra is 22.5°;
Among them, Case 2 to 5 are to explore the effect of different side wall inclination treatments on the sound energy diffusion; Case 6 and 7 are to explore the effect of back wall inclination treatment on the sound energy diffusion of the orchestra. The specific cases are shown in Figure 1 below.

4. Measurement Technique

4.1 Sources and receivers
The change in form of the orchestra may affect the propagation path of sound source on the stage and in the orchestra, when studying the sound quality effects of the change in the orchestra form, it is necessary to consider the mutual influence and balance between the sound source on the stage and in the pit. Therefore, in this experiment, two sound source points are set: stage sound source S1 and orchestra sound source S2. The stage sound source S1 is located on the longitudinal center line of the stage, 1m behind the curtain line and the orchestra sound source S2 is located in the center of the orchestra, which is usually the position of the woodwind in the orchestra.

The Zhuhai Opera House is symmetrical in size. According to ISO3382 [1], it is possible to arrange receiving points in half of the auditorium. Each seat area is equipped with 1 measuring point, a total of 6 measuring points, which are the reception point R1 in the front row side area of the pool seat, R2 in the front row middle area of the pool seat, R3 in the middle row middle area of the pool seat, and the middle row side of the pool seat. Area R4, the rear compartment of the pool seat R5, and the middle area of the building R6. The measuring point layout is shown in Figure 2 below.
The experiment is conducted in two rounds of testing. The first round is for the stage sound source S1. When S1 is sounding, the impulse responses of 6 measuring points under 7 cases are recorded, and each measuring point is recorded 3 times for each cases. When S2 is sounding, it is the second round, and the impulse response is recorded repeatedly as in round 1. As well, the temperature and humidity during each measurement is recorded.

In the full-scale experiment, the excitation end of the stage sound source and the orchestra sound source is 1.5m away from the ground, while in the scaled model experiment, the height of the sound source from the ground is scaled by 1:20 to 75mm, which simulates the performance of an actor singing or playing height. In the full-scale experiment, the receiving point should be kept 1.2m from the ground. In the scaled model, the height of the receiving point from the ground is 60mm, which simulates the height of ears when the audience sits in the auditorium.

4.2 Measurement
BDMSI-040528 electric spark source and B&K 4138 1/8 inch microphones with B&K UA-0355 nose cones were used as the source and receivers respectively. The electric-spark source radiates up to around 160 kHz, with the average impulse width of 0.189 ms. Impulse responses generated by the spark source were recorded using a B&K PULSE 3052A. The impulse responses recorded in the 1:20 scale model hall were transformed to full scale via the B&K 7841 DIRAC 4.0 software, with air absorption considered.

5. Experimental Results And Discussion
5.1 Strength G
Comparing the average G values of the two sound sources in the auditorium under different orchestra cases, it can be found that overall the G of the orchestra sound source S2 is greater than the G of the stage sound source S1. As shown in Figure 3 and 4, the G of S1 and S2 in the auditorium has a small difference at low frequency 125 Hz, and a large difference at 500 Hz and 1000 Hz. In addition, the G of S1 in the auditorium is less affected by the orchestra diffusion treatment, and only slightly increases at 1000 Hz. Among them, the inward side wall inclination treatment (Case 4, Case 5) makes the G value increase relatively large, at about 1dB; while G of S2 in the auditorium is greatly affected by the orchestra diffusion treatment, and the effect of the back wall tilting treatment is obvious, which increases the intermediate frequency G value of the auditorium by 2dB on average.
From Figure 5 and Figure 6 below, it can be found that when the S2 sounds, at R5, Case 6 causes a significant increase in $G$ value, and under the influence of Case 7, the $G$ value decreases; at R6, Case 6 and 7 lead to obvious $G$ value increase. The difference in the effects of Case 6 and 7 in R5 may be due to the large inclination angle of the back wall of Case 7, which reflects more sound energy to the balcony area, resulting in a decrease in the sound energy obtained in the rear area of the main floor.

5.2 Balance B
Barron in 1993 proposed the definition of balance B: The ratio of sound energy from the stage singing sound to the sound energy from a band's sound in the orchestra, both received by a certain seat in the hall. [2] The B value can be used to measure the dominance of the stage sound source and the orchestra sound source. In later research, Gustavo Basso pointed out that when both sound sources are non-directional sound sources, the balance B value of a certain auditorium position is equal to the difference between the $G$ value of the stage sound source and the orchestra sound source at its position. [3] Studies have shown that the audience are most satisfied when the balance B value is between -2.0dBA and 2.3dBA. When B is greater than 4.5dBA, the listener will feel that the singing voice is too loud [4].

From Figure 7, it can be found that the orchestra diffusion treatment reduces the average B value in the auditorium, indicating that the orchestra diffusion treatment will spread more sound energy of band instruments into the auditorium. Among them, Cases 6 and 7 can greatly reduce the B value of the mid-frequency band, but may cause the band's sound energy to be too large and exceed the appropriate
In this experiment, Case 6 and 7 greatly support the orchestra sound source, which is probably because the orchestra sound source is provided with more reflective surfaces, and the sound energy is transmitted to the auditorium. John O'Keefe’s research has pointed out that the reflected sound supports the orchestra sound source more than the stage sound, and most of the orchestra sound energy received in the auditorium comes from the reflected sound energy. [5]

5.3 Clarity C80
On the whole, the clarity C80 of the S1 in the auditorium is greater than the clarity C80 of the S2. The diffusion treatment of the orchestra has little effect on the overall C80 average value of both the S1 and S2.

However, in the view of the position of measurement points, the diffusion treatment has different effects on the C80 at different positions, showing a trend of C80 dropping in the near area and increasing in the distance. As shown in Figure 8 and Figure 9, when the S1 is sounding, in R4, R5, and R6 that are far away from S1, the orchestra diffusion treatment can slightly increase the C80 in these positions; while in the R1, R2 and R3 that are closer to the sound source S1, C80 is reduced under the diffusion treatment. In addition, when S2 sounds, the tilting of the back wall (Case 6, 7) has a slight increase of about 1dB in the mid-range of the remote R5 and R6 positions.
5.4 Definition D50
Similar to the C80, the average D50 of the auditorium of S1 is greater than that of S2. Orchestra diffusion treatment has little effect on the D50 of the two sound sources in the auditorium. The trend in C80 can also be found in D50, showing that D50 drops in the near area and increase in the distance.

5.5 Early Decay Time EDT, Reverberation Time T20
The orchestra diffusion treatment has little effect on the EDT and T20 of the measuring point in the auditorium. EDT and T20 are mainly affected by the sound absorption of the auditorium, and the impact of the diffusion treatment is small. A comparative analysis of multiple cases for each measuring point shows that there is no obvious regularity in the change of EDT, and there is no obvious difference in T20.

6. Conclusion
This experiment tested the impulse responses of 6 measuring points in 7 cases when the sound source was on the stage (S1) and on the orchestra (S2). By analyzed the G, B, C80, D50, and other acoustic parameters, conclusions can be draw as below:

The G of the stage sound source S1 is less affected by the orchestra diffusion treatment, while the orchestra sound source S2 is greatly affected. The effect of tilted back wall is is the most obvious, which can greatly increase the G of S2. It can be seen that the orchestra diffusion treatment is more beneficial to the orchestra sound source at most of the measuring points, resulting in a decrease in the B value.

The C80 and D50 of the stage sound source S1 at each measuring point are more susceptible to the influence of the orchestra diffusion treatment. Orchestra diffusion treatment increases the C80 and D50 of positions that are far away from the sound source, while lowering the C80 of positions that are closer to the sound source.

EDT is affected by orchestra diffusion to a certain extent, but the impact has no obvious regularity. T20 has little or almost no impact by diffusion treatment.

Reference
[1] ISO 3382-1, Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces[S]. 2009.
[2] Barron.M. Auditorium acoustics and architectural design[M]. London: E&F Spon, 1993: 330-335
[3] Basso G. Acoustical balance between the stage and the pit in the Teatro Colón of Buenos Aires[J]. Journal of the Acoustical Society of America, 2018.
[4] O'Keefe.J. Measurement of stage to pit balance in four proscenium arch theatres[C]. Proceedings of IOA - Auditorium Design at the Millennium, Belfast: 1997
[5] O'Keefe.J. Small scale modelling of stage to pit balance- a pilot study[C]. ICA - ASA Conference. Seattle, Washington: 1998