Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

# Sound Propagation and Scattering in Performance Halls with Balconies

**L.Y. Cheung and S.K. Tang**

Department of Building Services Engineering, the Hong Kong Polytechnic University, Hong Kong, China

**PACS:** 43.55Gx, 43.55Fw

## ABSTRACT

Numerous concert halls and auditoria in Hong Kong has been built and used for decades. Most of the halls in this congested city are designed for multi-purpose use and built with balconies for maximizing the space use. While objective and subjective evaluations on acoustical properties of performance halls have been done around the world, it is time for Hong Kong to have her own systematic research. In the present study, measurements have been done in two fan-shaped multipurpose performance halls. The conditions with and without the acoustic enclosure were also studied. Dual channel dummy head was used as the receiver, while a omni-directional sound source with room acoustics DIRAC were used for MLS production and computing. Measurement points were located throughout the halls.

## INTRODUCTION

Starting from the 19th century, a number of acoustical parameters have been developed to evaluate hall performance. They include the reverberation time (RT), early decay time (EDT), strength G, bass ratio BR, Interaural cross correlation IACC, apparent source width (ASW) and the degree of listener envelopment (LEV) [1-3] .

While most of the architectural features in the hall have been extensively studied in the past around the world, the effects of balcony and overhang have received very limited attention.

However, no comprehensive analysis and measurement has been done in local halls. Although Beranek has included the concert hall in the Hong Kong Cultural Centre in his publication [1], no acoustics data can be found.

### Hall acoustics and balconies

Balconies are usually added into concert halls, opera houses and especially modern multi-purpose hall to increase the hall capacity while maintaining a relatively short distance between the stage and the audience.

Barron [2] has found that the overhangs reduce the late sound more than the early one and that the local reflections from back walls and soffits in the overhung section of the hall help maintain sound level. The overhangs create subjective effects of a reduction in the sense of reverberation, a reduction in loudness and reduced perceived solid angle for arriving sound.

According to the principle of acoustics, when a sound reaches a solid boundary, it will be diffracted and pass over other barriers and propagate until it reaches another reflecting surface. Therefore, by observing the architectural design of halls and opera houses with balconies, one can suggest that a portion of the sound energy will be reflected back and diffracted from the balcony front to the stage and the hall main floor. Opinions of musicians and acousticians [3] also reflect such phenomenon. This would be a positive effect of the balcony to the performers on the stage and to the audience on the main floor instead of just degrading the acoustics performance at seats under the overhangs.

Currently, scaled models and ray-tracing based computer simulation are used for concert halls and opera houses design and modelling. The most commonly used one is the ray-tracing model. The situation with the presence of a balcony or similar structure makes the computation complicated. The multiple scattering or diffraction at the balcony edges is not easy to model. Edwards and Kahn [4] reported that there is inaccuracy in such modelling. In their European horse shoe shaped opera house modelling, simulation results showed that sound focusing or the lack of reflected sound when the wall and balcony surfaces were too absorptive were problems for such halls. In real experience, these opera houses function well acoustically. Even modern ray-tracing based programs include an approximation for surface scattering and edge diffraction [5].

According to Lam [5] and Hodgson [6], a sound hitting a wall will be scattered at angles other than the specular reflection angle because of the imperfectly smooth surface in practice as well as the edge effects created by the finite size of the wall. They introduced the diffuse-reflections into different tracing models to approximate some of the scattering and diffracting properties of reflecting surfaces.

Chan and To [7] used computer simulation and ripple tank experiment to model the back scattering of the balconies. Their results indicated that the lower corner of the balcony front close to the sound source acts as a virtual source. Hence, they suggested that computer models incorporating such considerations can be constructed to evaluate the back-scattering effect in a concert hall and a horseshoe shaped opera house. Meanwhile, the cross-coupling effect between different panels should also be considered.

Full scale measurement can provide statistics and real situation when errors occur in modelling and simulation. Correlation and improvement can be developed by comparing real measurement results with modelling and simulation results. Factors being neglected in modelling and simulation can also be observed and recorded in real measurement.

## MEASUREMENT VENUES

Two different halls were picked for the present investigation. They are represented by Hall A and B. All of the halls are designed as medium size halls in the community.

### Hall A

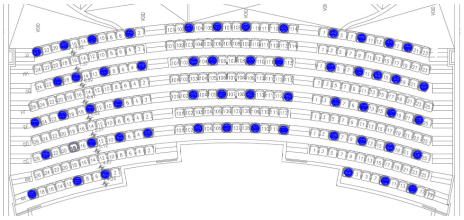

**Figure 1a**. Measurement points on the balcony for Hall A. All the shaded seats are the measurement locations.

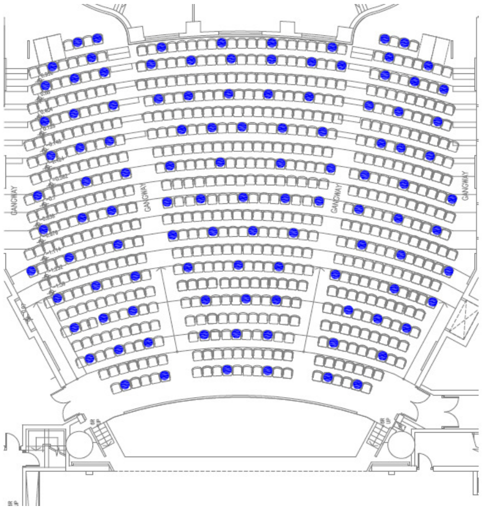

**Figure 1b.** Measurement points in the stall for Hall A. All the shaded seats are the measurement locations.

Hall A is a modern multi-purpose hall with classical interior design. It was completed and has come into operation in 2000. It is designed as a multi-purpose hall for musical performance, dramas, dance, and other cultural activities as well as for conferences and ceremonies.

Figure 1 shows the layout of Hall A. The hall has a symmetraical layout. All the seats are fully upholstered with armrest Instead of a smooth balcony edge, this balcony is designed with a zig-zag edge and it covers approximately 8 to 9 rows of seats in the stall. The two sides of the balcony are extended to the side wall of the stage's proscenium. The side walls in the stall are fitted with wooden boards and heavily upholstered panels while those on the balcony are plaster on concrete. Plaster board are used on the ceiling above the stall area with plaster on concrete is used for ceiling above and under the balcony. The floor of the stall and the balcony are not carpeted.

A demountable orchestra shell is used for its concert setting.

### Hall B

Hall B was also built in late-90s and opened in 2000. The hall is a modern fan-shaped hall with symmetrical design (Figure 2). All the seats are fully upholstered with armrest. The floors of the seating area in the stall and on the balcony are not carpeted. Its balcony cotains four rows of seats and has two additional wings on both sides. It covers 6 rows of seat underneath it.

The technical balconies on both sides besides the stage opening are of three different levels. They appeared as small void with timbre walls. On the side walls in the stall area and on the balcony, there are grids of acoustics boxes at low to mid-level and with motorised velour curtains covering the plastered walls at mid to high level. There are catwalks and lighting bars hoisted over the seating area. Nearly all the electrical and mechanical services installed at the ceiling are exposed. There are ceiling mounted acoustics boxes installed on top of them. The ceiling under the balcony is with false ceiling.

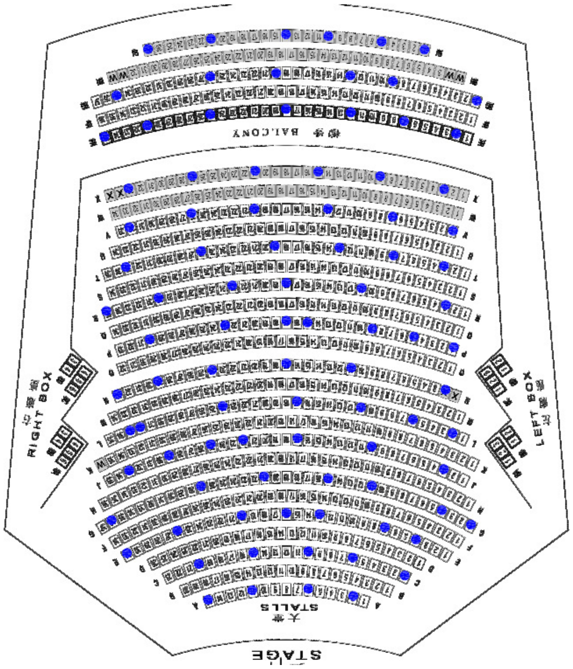

**Figure 2.** Measurement points for Hall B. All the shaded seats are the measurement locations.

## MEASUREMENT PROCEDURES

All the halls were measured in unoccupied conditions in accordance with ISO 3382. Measurements are conducted in both with and without acoustic enclosure conditions.

Only one source point was employed. Onmipower type 4292 was used. It was positioned at centre stage, 1m from the stage edge and 1.5m above the stage floor.

The room acoutcis software B&K DIRAC Room Acoustics Software Type 784 was used. Its built-in maximum length sequence (MLS) sound source was used as the sound source for all the measurements. The software was used for conducting measurements at each receiver point and extracting data.

The MLS signal generated was measured and recorded at random positions throughout the audience area in the stall and on the balcony. The B&K head and torso simulator Type 4128C was used as a dual channel dummy head receiver. The microphones are embedded at its eardrum positions. The measurement duration was set as 2.73 sec. There are at least 80 measurement points in each hall and the points for with and without the acoustic canopy condition are the same.

## RESULTS AND DISCUSSIONS

The impulse response measured at each receiver's position in the hall is recorded in a .wav file. The wave was then analysised using Dirac and the octave band results for all parameters are exported as text files.

All the seats are classified into 4 receiver zones: front stall, middle stall, under-balcony and balcony. They are represented with the following legends in all the plots: △- front stall, ✳- mid stall, □-underbalcony and ○- balcony respectively.

All the values used in table and plots are the average of the two channels measured. In all the following tables, the mean values of the parameters are given with their standard deviation in italic form. The roman number I, II, III, IV represents the 4 receiver zones, nearly the front stall, the middle stall, the under-balcony and balcony respectively.

### RT, Reverberation time

Table 1 summarizes the mean of the RT measured at 500Hz in the 2 halls. 'Y' and 'N' indicate with and without acoustic enclosure on the stage.

**Table 1**. The mean RT measured at 500Hz

| | Acoustics Enclosure | I | II | III | IV |
|---|---|---|---|---|---|
| Hall A | N | 1.00 | 0.99 | 0.98 | 0.99 |
| | | *0.05* | *0.05* | *0.06* | *0.06* |
| | Y | 0.95 | 0.96 | 0.94 | 0.97 |
| | | *0.03* | *0.03* | *0.09* | *0.04* |
| Hall B | N | 1.32 | 1.32 | 1.34 | 1.39 |
| | | *0.07* | *0.06* | *0.10* | *0.07* |
| | Y | 1.47 | 1.46 | 1.45 | 1.47 |
| | | *0.03* | *0.04* | *0.03* | *0.02* |

It is reasonable to have the measured RTs of hall setting with acoustic enclosures higher than those of the settings without the enclosures. When comparing the results in different seating zones for the measurement with acoutics enclosure, the measured RTs at the mid-stall, which is in front of the balcony, increase slightly.

**Table 2**. The mean D50 measured at 500Hz

| | Acoustics Enclosure | I | II | III | IV |
|---|---|---|---|---|---|
| Hall A | N | 0.70 | 0.68 | 0.64 | 0.70 |
| | | *0.04* | *0.03* | *0.05* | *0.07* |
| | Y | 0.65 | 0.60 | 0.56 | 0.65 |
| | | *0.07* | *0.06* | *0.06* | *0.06* |
| Hall B | N | 0.59 | 0.46 | 0.54 | 0.44 |
| | | *0.10* | *0.05* | *0.03* | *0.05* |
| | Y | 0.40 | 0.35 | 0.41 | 0.37 |
| | | *0.10* | *0.05* | *0.03* | *0.06* |

### Definition, D50

D50 is the ratio of the early to total sound energy for the first 50msec. Table 2 shows the mean D50 measured at 500Hz in the 2 halls. The trends for the change of the values are the same within the hall with and without acoustic enclosure. However, the values for the balcony are the lowest among 4 zones in Hall B.

### Clarity, C80

The clarity factor C80 is a measure, in dB, of the strength of the early sound to the reverberant sound. The larger the value, the larger the intelligibility of the music and vocal sound is.

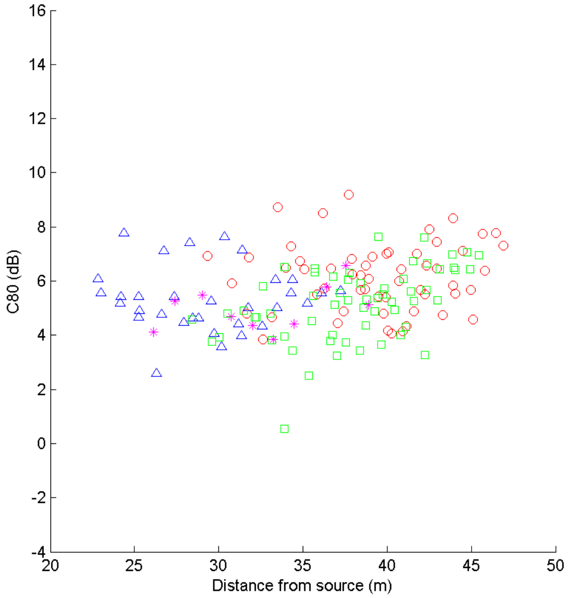

**Figure 3.** The plot of C80 against distance for Hall A with acoustics enclosure

Figure 3 shows the results for Hall A with acoustic enclosure: the values for all the points vary within each zone.

From Table 3, the measured C80s without acoustic enclosures are larger than those with the enclosures in both halls while they have the same characteristcs within the same hall. Contrastingly, values on the balcony in Hall A are larger than those in the stall and under-balcony while they are similar to those in the stall but smaller than those under balcony in Hall B.

**Table 3**. The mean C80 measured at 500Hz

| | Acoustics Enclosure | I | II | III | IV |
|---|---|---|---|---|---|
| Hall A | N | 6.52 | 5.64 | 5.59 | 6.97 |
| | | *1.04* | *0.83* | *0.93* | *1.34* |
| | Y | 5.33 | 4.97 | 4.47 | 6.16 |
| | | *1.17* | *0.84* | *1.16* | *1.25* |
| Hall B | N | 4.44 | 2.85 | 4.37 | 2.94 |
| | | *1.45* | *0.96* | *0.82* | *0.96* |
| | Y | 1.04 | 0.14 | 1.31 | 0.45 |
| | | *1.61* | *0.69* | *0.62* | *1.13* |

### Strength Factor, G

The G values used are the relative values. Figure 4 shows that the measured relative G values decrease with the distance between the source point and the receiver point.

In Figure 4, the sound strength decreases with increasing distance from source in Hall A. The G values of each zone are approximately the same. The balcony and the underbalcony points have similar distances from the source but the underbalcony is having a higher G value, ie. it receivers more energy than a point with the same distance from the source on the balcony.

In Hall B, there are some points with sudden drops of G in the front stall with and without the acoustic enclosure. This happened around the sixth to eighth rows of seat in the stall. Such decreases occur not only in 500Hz, also in all other frequency bands.

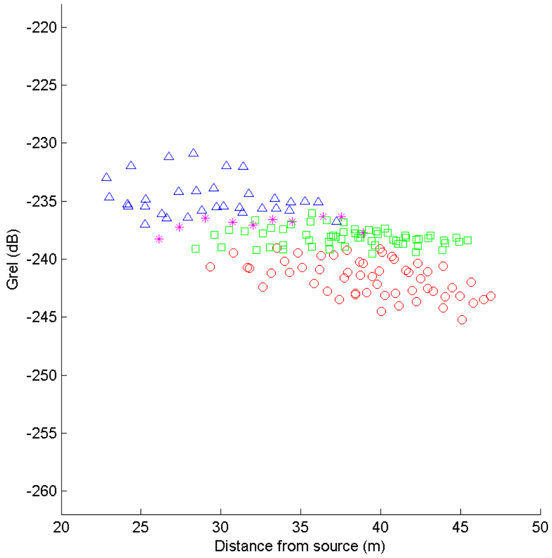

Figure 4. The plot of relative G against distance for Hall A with acoustic enclosure

## BASS RATIO

The bass ratio BR is calculated from the measured RT values at 125Hz and 250Hz with respect to the mid-frequencies values.

From the plot of bass ratio against distance (Figure 5), not much correlation between the two parameters can be found. Although hall of the values fall into the same range, they vary about 10% in each zone. From Table 4, one can observe that the BRs in the presence of the acoustic enclosure are larger than those without the enclosure.

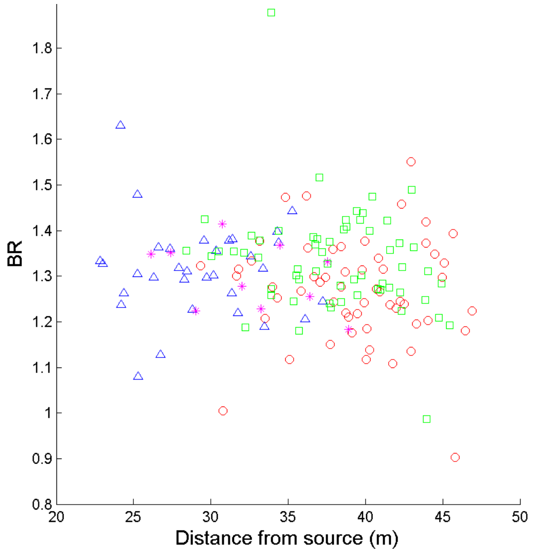

**Figure 5.** The plot of Bass Ratio against distance for Hall A with acoustic enclosure

**Table 4**. The mean of the Bass Ratio (BR) measured

| | Acoustics Enclosure | I | II | III | IV |
|---|---|---|---|---|---|
| Hall A | N | 1.42 | 1.37 | 1.40 | 1.41 |
| | | *0.12* | *0.12* | *0.09* | *0.13* |
| | Y | 1.31 | 1.31 | 1.36 | 1.27 |
| | | *0.10* | *0.06* | *0.11* | *0.12* |
| Hall B | N | 1.27 | 1.29 | 1.26 | 1.25 |
| | | *0.13* | *0.09* | *0.08* | *0.10* |
| | Y | 0.92 | 0.92 | 0.94 | 0.90 |
| | | *0.05* | *0.07* | *0.04* | *0.05* |

## CONCLUSION

The acoustical properties of two fan-shaped multi-purpose performance halls were measured in the present study.

The reverberation times with the acoustic enclosure are larger than those without the enclosure. Both the defitintion and clarity drop with increasing distance away from the sound source but the trend is reversed after the mid stall. The strength factor, G, decreases with distance and in some cases, it is minimum at the front stall near the source. The bass ratio does not have much correlation with the distance of the location.

## ACKNOWLEDGEMENT

LYC is supprted by a studentship from the Hong Kong Polytechnic Univertisy.

## REFERENCES

1 L.L. Beranek, *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*. (Springer, New York, 2004). pp.201-206, 503-526

2 M. Barron, "Balcony overhangs in concert auditoria" *J. Acoust. Soc. Am*. **98**, 2580-2589 (1995).

3 L.L. Beranek, *Concert and Opera Halls: How They Sound*. (Published for the Acoustical Society of America through the American Institute of Physics, Woodbury, N.Y., 1996). pp.22-26, 567-575

4 N. Edwards and D. Kahn, "Why do traditional opera houses work so well for opera?" *J. Acoust. Soc. Am*. **103**, 2784 (1998).

5 Y.W. Lam, "A comparison of three diffuse reflection modeling methods used in room acoustics computer models" *J. Acoust. Soc. Am*. **100**, 2181-2192 (1996).

6 M. Hodgson, "Evidence of diffuse surface reflections in rooms" *J. Acoust. Soc. Am*. **89**, 765-771 (1991).

7 T.M. Chan and W.M. To, "Modelling of Scattering from Balcony Fronts" *Building Acoustics*. **9**, 219-231 (2002).