QUANTITATIVE AND QUALITATIVE ANALYSES OF UNDER-BALCONY ACOUSTICS WITH REAL AND SIMULATED ARRAYS OF MULTIPLE SOURCES

By

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by

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The objective of this study was to quantitatively and qualitatively identify the acoustics of the under-balcony areas in music performance halls under realistic conditions that are close to an orchestral performance in consideration of multiple music instrumental sources and their diverse sound propagation patterns. The study executed monaural and binaural impulse response measurements with an array of sixteen directional sources (loudspeakers) for acoustical assessments. Actual measurements in a performance hall as well as computer simulations were conducted for the quantitative assessments. Psycho-acoustical listening tests were conducted for the qualitative assessments using the music signals binaurally recorded in the hall with the same source array.

The results obtained from the multiple directional source tests were analyzed by comparing them to those obtained from the tests performed with a single omni-directional
source. These two sets of results obtained in the under-balcony area were also compared to those obtained in the main orchestra area.

The quantitative results showed that the use of a single source conforming to conventional measurement protocol seems to be competent for measurements of the room acoustical parameters such as $\text{EDT}_{\text{mid}}$, $\text{RT}_{\text{mid}}$, $C80_{500-2k}$, $\text{IACC}_{E3}$ and $\text{IACC}_{L3}$. These quantitative measures, however, did not always agree with the results of the qualitative assessments. The primary reason is that, in many other acoustical analysis respects, the acoustical phenomena shown from the multiple source measurements were not similar to those shown from the single source measurements. Remarkable differences were observed in time-domain impulse responses, frequency content, spectral distribution, directional distribution of the early reflections, and in sound energy density over time. Therefore, the room acoustical parameters alone should not be the acoustical representative characterizing a performance hall or a specific area such as the under-balcony area.

The under-balcony acoustics measured with multiple sources showed that 1) reduction in sound energy occurs across frequencies; 2) there are a number of strong early reflections mostly coming laterally and few reflections coming from upside; 3) this contributes to shorter EDTs, shorter $t_s^\prime$, higher $C80$s, higher LFs and lower $\text{IACC}_E$ coefficients; 4) the sound qualities are perceived with more clarity but less reverberance, spaciousness and envelopment relative to the main orchestra area.
CHAPTER 1
INTRODUCTION

Designing a balcony is a critical issue in a large auditorium both architecturally and acoustically. A balcony has been a prerequisite in auditoria to increase the seating capacity within a certain distance from the stage. The balcony contributes to a sensation of both visual and acoustic intimacy perceived by the audience seated on it. The audience seated on the balcony has the advantage that the direct sound arrives without grazing incidence\(^1\) (Cremer, 1975). However, the acoustics to the audience seated under the balcony overhang are sometimes questionable. The geometrical features of a balcony overhang are shown in Figure 1.1.

\[D: \text{Depth of balcony overhang, } H: \text{Opening height, } \theta: \text{Vertical angle of view}\]

Few studies have thus far been conducted on acoustics under the balcony overhang. According to Barron (1995), the balcony overhang reduces the late reverberant energy

\(^1\) Grazing incidence is the phenomenon indicating sound attenuation by seats occurring particularly at low frequencies. This phenomenon is also called seat dip effect.
more than the early. Fujimoto and Furuya (1996) indicated that the under-balcony area is
deficient in early energy coming from above. Kwon (2002) argued that the energy change
(reduction) in the under-balcony area is primarily dependent upon the height (H) of the
overhang at the opening aperture but independent of the depth (D) of the overhang unless
too deep with a D/H ratio over 1.5. Through a scale-model experiment and listening tests,
Kwon studied the effects of sound energy changes in the vertical dimension caused by the
balcony overhangs with different dimensions of H and D on perceived listener
envelopment. He suggested that the D/H ratio should maintain the maximum of 0.7 or the
vertical angle of view (θ) should maintain the minimum of 40 degrees under the balcony
overhang at 3 m high and the D/H ratio should maintain the maximum of 1.3 or the θ
should maintain the minimum of 30 degrees under the balcony overhang at 5 m high.

All of the previous studies used an omni-directional receiver (microphone) with a
single sound source radiating omni-directionally for their measurements, computer
simulations or experiments such as scale-model experiment. The use of only one single
omni-directional sound source may be unrealistic in investigation of the acoustics of a
concert hall because the actual music performances mostly consist of multiple sources
except for a soloist. Furthermore, sound radiation from the sources are not omni-
directional but merely directional. Therefore, the conventional measurement protocol
using such a single omni-directional sound source may have limits or uncertainty in
objective acoustical analysis of a concert hall.

This study executed monaural and binaural impulse response measurements with
real and simulated arrays of sixteen multiple directional sources for quantitative
acoustical assessment of the under-balcony area. Actual measurements in a performance
hall (Phillips Center for the Performing Arts) as well as computer simulations were conducted for this quantitative assessment. Psycho-acoustical listening tests were followed to qualitatively assess acoustics of the under-balcony area using the music signals recorded in the hall with multiple directional sources. The results obtained with multiple directional sources were compared to the results obtained with a single omni-directional source. These two sets of results obtained in the under-balcony seating area were also compared to those obtained in the main orchestra seating area.

**Research Objectives**

This study attempted to identify the under-balcony acoustics in concert halls more precisely under a realistic acoustic field measurement condition that is close to an orchestral symphony performance with a number of diverse sound source types and radiation patterns. The results would yield a better understanding of under-balcony acoustics and make it possible to improve design of the under-balcony area. Further, the current field measurement standard is reviewed for possible revision in correspondence to multiple source conditions, or an alternative standard guiding multiple source measurements may be necessary.

**Phillips Center for the Performing Arts (PCPA)**

The Phillips Center for the Performing Arts (PCPA) as shown in Figure 1-2 is located in the city of Gainesville, FL. The PCPA is a shoebox style multi-purpose hall with 1,754 seats and a volume of 15,320 cu. m (541,000 cu. ft). Its room dimensions are 45.7 m (150 ft) deep from the proscenium, 24.4 m (80 ft) wide and 19.8 m (65 ft) high. This hall has two stories of box seating area on both sides and two balconies at the back: a lower balcony, which is overhung, and an upper balcony, which is not overhung. The lower balcony overhang has a view angle of 19 degrees from the middle of the deepest
seating row and a depth to height ratio (D/H) of 2.0 with dimensions of 9.5 m (31 ft) deep and 4.8 m (15 ft 6 in) high at its opening aperture.

Figure 1-2. Interior and longitudinal section views of the Phillips Center for the Performing Arts (PCPA).

The configuration of the balcony overhang exceeds both overall overhang geometrical data on average from a typology survey of a total of 71 halls for music and the overall overhang geometrical data for the 23 shoebox style halls among the data (Kwon, 2004). Kwon found that the balcony overhangs on average from 71 halls yield a $\theta$ of approximately 31 degrees and a D/H ratio of 1.75 with dimensions of 6.7 m (22.1 ft) deep and 3.8 m (12.6 ft) high at the opening. Additionally, the balcony overhangs in the 23 shoebox style halls tend to have on average a $\theta$ of approximately 33 degrees and a D/H ratio of 1.7 with dimensions of 6.5 m (21.5 ft) deep and 3.9 m (12.8 ft) high.
Summary of Room Acoustic Technical Terms

The following table summarizes the terms of room acoustical parameters and qualities with their abbreviations used in this study. Definitions of each of those are included in Chapter 2 – Literature Review and Theoretical Background.

Table 1-1. Room acoustical parameters and qualities used in the study.

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<td>RT</td>
<td>Initial time delay gap</td>
<td>ITDG</td>
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<td>Sound strength or loudness</td>
<td>G</td>
<td>Lateral energy fraction</td>
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CHAPTER 2
LITERATURE REVIEW & THEORETICAL BACKGROUND

Under-Balcony Acoustics

Under-balcony acoustics can be characterized by the balcony overhang in the vertical dimension. In general, a balcony overhang influences little the lateral energy received by audience seated in the under-balcony area, whereas it diminishes the late reverberant energy as well as the early energy from above (Barron, 1995; Furuya & Fujimoto, 1996). Therefore, the overall sound energy lessens in the under-balcony area compared to the main room volume. The lack of the vertical energy in the overall early energy spectrum is, however, compensated by strong early reflections from surfaces located near to the under-balcony seats such as the balcony soffit (under-balcony ceiling) or rear wall (Barron, 1995). These local reflections can someway maintain the overall early energy level from the loss of early energy from upside. Kwon (2002) argued that the sound energy change (reduction) varies not by how deep the listener position is (or how deep the overhang is), but by how high the balcony overhang opening is. Under an overhang at a certain height, the degree of sound energy reduction changes little as the receiver positions deeper unless the overhang was critically deep with a D/H ratio larger than 1.5.

Figure 2-1 shows ray diagrams illustrating early reflections in a simple shoebox room configuration and their directional distributions within 150 ms. CATT-Acoustic, room acoustics prediction software, was used to model this imaginary room and to simulate the directional distribution of the early reflections from an omni-directional
source. A deep under-balcony position is compared to a position in the middle of the main orchestra area. As shown in the figure, the under-balcony position has comparable early reflections in the horizontal plane. However, not many early reflections are found at the under-balcony position in the vertical median plane except for a few reflections from nearby surfaces underneath the overhang and a reflection from the stage ceiling. This finding is also visually clarified through the directional distribution plots, which are named \textit{sound roses}\textsuperscript{2}, displayed in the middle of Figure 2-1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2-1.png}
\caption{Ray diagrams with early reflections in a computer modeled simple shoebox style configuration. Room dimensions: 24 m (W) x 30 m (L) x 18 m (H). A) a receiver (11) is in the middle of the main orchestra area. B) receiver (01) is deep under the balcony overhang. Middle on both sides: relative energy levels and directional distributions of early reflections. A0: source position.}
\end{figure}

\textsuperscript{2} Such plots of sound roses are sometimes called \textit{hedgehogs}. 

Barron (1995) studied the acoustic behavior under the balconies in several British halls and found that balcony overhangs reduce the late sound more than the early. The early lateral energy coming in the horizontal plane was, however, verified to be similar at the positions between main orchestra seats and under-balcony ones. Barron also found that the early local reflections progressively curtail early decay time (EDT) at seating locations toward the rear of the under-balcony area. Furuya and Fujimoto (1996) indicated that there is a lack of early reflections from the ceiling above the main orchestra toward the under-balcony space with the results of their measurements in several existing halls. An early acoustical study of Phillips Center for the Performing Arts (PCPA), Gainesville, FL conducted by Kwon (2003) confirms Barron’s finding and Furuya and Fujimoto’s findings. Some details from Kwon’s early study of PCPA are discussed in the following section.

**Case Study of PCPA**

![Figure 2-2. Source and measurement positions at level 1 in the PCPA (not to scale).](image)

The case study of PCPA involved both actual room acoustical measurements in the hall and computer modeling using *CATT-Acoustic* program. Both were conducted under
unoccupied condition with the fully extended stage enclosure. Note that the actual measurement data at lower and higher frequencies may not be reliable due to some technical troubles and therefore, the results from the measurements are discussed at frequencies from 250 through 2k Hz only. The measurement positions in the first seating level with the source position are shown in Figure 2-2.

Figure 2-3. Sound roses: directional sound energy distributions. A) At a main orchestra position (position 2). B) At an under-balcony position (position 6). Refer to the footnote for general description of each sound rose.

First of all, the early directional sound energy distributions simulated by CATT-Acoustic are discussed. The directional sound energy distributions simulated in the under-balcony area (position 6) are compared with those simulated in the main orchestra area

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3 Within each time range the incident ray vectors are projected onto the horizontal plane, the vertical plane and the ear-to-ear vertical plane. At each rose a % value is given calculated as the ratio of the energy projected to the plane to the total energy in the time-range. – Excerpted from CATT-Acoustic 8.0v manual.
As shown in Figure 2-3, the distributions of the incident reflections at 1k Hz and their strength are compared at time intervals of 0-80, 80-200, and 200-500 ms. The distributions in the vertical median plane or the ear-to-ear vertical plane in the under-balcony area indicate that there is a lack of energy in the vertical dimension all the way through the given time intervals.

Next, the measurement results of some room acoustical parameters are discussed. First, the reverberation times (RT) vary little through all the seating areas including the under-balcony area. The RTs measured at 5 seating areas across frequencies are presented in Table 2-1. These RTs representing each seating area average the RTs measured at 2 or 3 measurement positions in each area. For example, the RTs in the main orchestra area are the average values at positions 2, 7 and 8, and the RTs in the under-balcony are the average values at positions 6 and 10. The measurement positions 1, 3 and 5 added later are for identification of room acoustical phenomena longitudinally where the receiver position moves toward the under-balcony area.

| Table 2-1. Reverberation times in the Phillips Center for the Performing Arts (PCPA) (in second). |
|-----------------------------------------------|---------------|---------------|---------------|---------------|---------------|
| Seating Area                      | 250           | 500           | 1k            | 2k            | (500-1k)      |
| Main orchestra                    | 2.19          | 2.27          | 2.11          | 1.89          | 2.19          |
| Under-balcony                     | 2.15          | 2.39          | 2.10          | 1.83          | 2.25          |
| Under side boxes                  | 2.22          | 2.37          | 2.18          | 1.83          | 2.28          |
| Lower balcony                     | 2.32          | 2.26          | 1.99          | 1.78          | 2.13          |
| Lower side boxes                  | 2.21          | 2.32          | 2.06          | 1.76          | 2.19          |
| Average                          | 2.22          | 2.32          | 2.09          | 1.82          | 2.21          |
| Standard deviation                | 0.06          | 0.06          | 0.07          | 0.05          | 0.06          |

Second, the early decay times (EDT) tend to decrease gradually as the receiver position moves back from the main orchestra area into deep the under-balcony area.
(every third seat from position 1 through position 6). The EDTs measured at these 6 back-to-back positions across frequencies are shown in Figure A-1 included in Appendix A. The average EDTs at mid-frequencies and at frequencies of 250 through 2k Hz are shown in Table 2-2. The EDT trend is more clearly observed in average EDT obtained from each of 3 major areas as shown in Figure 2-4.

Table 2-2. Average early decay times in the PCPA as the position moves back toward the under-balcony area (in second).

<table>
<thead>
<tr>
<th>Positions</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT at mid (500-1k Hz)</td>
<td>2.62</td>
<td>2.27</td>
<td>2.12</td>
<td>2.06</td>
<td>1.71</td>
<td>1.81</td>
</tr>
<tr>
<td>EDT at 250-2k Hz</td>
<td>2.41</td>
<td>2.19</td>
<td>2.02</td>
<td>1.87</td>
<td>1.59</td>
<td>1.53</td>
</tr>
</tbody>
</table>

Figure 2-4. Early decay times (EDT) in the PCPA as the seating area moves back toward the under-balcony area. The EDTs in the main orchestra area are the average values at positions 2, 7 and 8, and the EDTs at the opening of the under-balcony area are the average values at positions 4 and 9, and the EDTs in the under-balcony are the average values at positions 6 and 10.
Third, the values of early-to-late sound energy index (C80) across frequencies tend to increase as the receiver position moves back from the main orchestra area into deep the under-balcony area except for position 1, which is in the front of the main orchestra area. The C80s at the six back-to-back positions across frequencies are shown in Figure A-2 in Appendix A. The average C80s at frequencies of 500 through 2k Hz are shown in Table 2-3. This C80 trend is more clearly observed in average C80s obtained from each of three major areas as shown in Figure 2-5.

<table>
<thead>
<tr>
<th>Positions</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>C80 at 500-2k Hz</td>
<td>3.4</td>
<td>1.8</td>
<td>2.8</td>
<td>3.7</td>
<td>4.6</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Figure 2-5. Early-to-late sound energy index (C80) in the PCPA as the seating area moves back toward the under-balcony area. The C80s at the main orchestra area are the average values at positions 2, 7 and 8, and the C80s at the opening of the under-balcony area are the average values at positions 4 and 9, and the C80s at the under-balcony are the average values at positions 6 and 10.
Fourth, early lateral energy fraction (LF or LFC\textsuperscript{4}) is analyzed on the basis of the data obtained through the \textit{CATT-Acoustic} computer modeling and simulations of the PCPA. It is not surprising that the LFCs measured in the under-balcony area are much higher than those measured in the main orchestra area. The LFCs in these two areas are compared in Figure 2-6. Due to a lack of vertical energy as discussed earlier, sounds coming laterally below the balcony overhang may contribute largely toward the overall sound energy in this area. The LFCs at the six back-to-back positions across frequencies are shown in Figure A-3 in \textit{Appendix A}.

![Figure 2-6. \textit{CATT-Acoustic} simulated LFCs at the main orchestra area and the under-balcony area in the PCPA.](image)

\textsuperscript{4} The \textit{CATT-Acoustic} computes a numerical value of LFC in percentage using an element of $\cos\theta$ in the integral function instead of $\cos^2\theta$, which is used to compute a value of LF.
Representation of Impulse Response

Response of a room at a position to a measurement noise excitation, which is called impulse response or echogram, implies wide acoustical information about a given space. The acoustical information contained in an impulse response as shown in Figure 2-7, however, does not seem to be clearly readable at a first look but rather complicated to be extracted. Therefore, a delicate analysis process is needed to characterize its pattern and acoustical meaning. This would be a major reason why so many specific structural analyses on impulse responses have been followed since Wallace C. Sabine, a legendary room acoustician, tried to understand and characterize sound decay of a room in terms of reverberation (Cremer & Müller, 1978).

![Figure 2-7](image)

Figure 2-7. An example of measured broad-band room impulse response in a function of time.

The impulse response is comprised of numerous single impulses including the direct sound with reflections coming from the various room surfaces. The impulse response varies with frequency because the intensity of the source and the absorption and diffusion coefficients of the room boundaries differ over frequencies. It is also measured differently according to receiver and source locations.
Structural analysis methods of an impulse response have been developed largely on the basis of integrating the energies in specific time periods hypothesized to relate to perceived quality of sounds or plotting its rise or decay process. Among room acoustical representations resulted from the structural analyses on an impulse response in the manner of functional contributions of a specific part in the whole response system, the following are discussed in the next sections to evaluate the acoustics of under-balcony area: frequency responses; early sound decay with early decay time (EDT); reverberant energy with reverberation time (RT); early and late portions of the response with early-to-late sound energy index (C80); contributions of the early energy to the whole and to the late energy with C and D indices; arrival time period of the first reflection after the direct sound with initial time delay gap (ITDG); center of gravity of the squared impulse response area with center time ($t_s$); and directional distribution of sound.

**Room Acoustical Qualities**

The room acoustical qualities are firstly described in this section and all the technical terms of room acoustical parameters, their quantitative measures, such as reverberation time (RT), etc. mentioned in this section are described in the next section.

**Reverberance (Liveness)**

Reverberance or reverberation indicates the persistence of sounds in the room after the sound source stops. When a room is stimulated by a sound, a multitude of audible reflections fill the room and create reverberance. This perception of reverberance provides fullness of tone (Beranek, 1996) or sense of liveness to music as opposed to sense of “dryness”. With too much reverberance, the sound becomes muddy.

The reverberation time (RT) and the early decay time (EDT) are used to
quantitatively measure the reverberance of a room. Beranek (1996) observed from his surveys on concert hall acoustical qualities that the EDTs for unoccupied halls indicate acoustical quality better than the RTs for occupied halls does.

**Clarity**

Clarity indicates the degree to which sounds are distinguished in an ensemble (Reichardt, *et al.*, 1974; Beranek, 1996). In other words, clarity indicates how clearly an individual musical note is heard in the blending of sounds. The sense of clarity is determined by contribution of the early sound energy, which can perceptually build up the direct sound, relative to the reverberant energy. For example, an increase in early sound energy provides more transparency and clearness to music, resulting in an increase in sense of clarity.

The clarity index or early-to-late sound energy index (C80) is used to quantitatively measure the clarity and used, in general, to characterize the sound quality of music played in a hall. The sense of clarity depends on tempo or speed of music, number of notes in a musical passage (Reichardt, *et al.*, 1974) and on relative loudness of successive musical tones (Beranek, 1996).

**Loudness**

Loudness is acoustically defined as the subjective perception of the overall strength of sound. Loudness is the combined perception of the strength of the direct sound with the strength of the early sound and the strength of the reverberant sound. Particularly, early sound reflections shortly following the direct sound combine with the direct sound to increase perceived loudness (Thiele, 1953). The quantitative measure of loudness is the strength factor (G).
Loudness in a hall is affected by four architectural features: 1) distance of the listener from the stage; 2) surfaces that reflect early sound energy to the audience; 3) acoustically high absorption area (audience area and orchestra area) and room volume; 4) finish materials and conditions (Beranek, 2004). Beranek (1996) also found earlier from his survey on concert hall acoustics that the G is proportional to the reverberation time.
(EDT) and inversely proportional to the room volume (V). From the statistical straight line fit presenting their physical relationship that was drawn by Beranek as shown in Figure 2-8, Mehta, et al. (1999) derived its logarithmic mathematical expression as described in Equation 2.1.

\[ G_{mid} = 10 \log \left( \frac{EDT_{mid}}{V} \right) + 44 \text{ dB} \]  \hspace{1cm} (2.1)

**Warmth**

Warmth indicates the richness of bass tones. Extended reverberation at low frequencies relative to reverberation at mid-frequencies contributes to perception of warmth (Beranek, 1962). Based on this concept, Beranek developed bass ratio (BR) as now the conventional measure of the degree of warmth.

Recently, the perception of warmth is more likely determined by the strength of bass tones (Bradley, et al., 1997). In this case, the strength of sound at low frequencies \( (G_{low}) \) or particularly at 125 Hz \( (G_{125}) \) becomes a quantitative measure of warmth. A discussion on perceived warmth is extended further in the section of room acoustical parameters.

**Intimacy**

The room acoustical quality concept of intimacy was formalized by Beranek (1962). According to Beranek, acoustical intimacy is closely related to the time delay gap between the direct sound and the first reflection perceived by a listener, which is called initial time delay gap (ITDG). The shorter the ITDG is, the more intimacy a listener perceives. Beranek (1996) extended the definition of intimacy as the subjective impression of listening to music in a large room and its sounding as if the room were
small.

On the other hand, Barron (1988) argued that intimacy is related to proximity to the performers and defines intimacy as a listener’s degree of identification with the performance whether or not the listener feels acoustically involved. Barron’s concept would have the audience seated closely to the performers perceiving intimacy greater than the audience seated remotely. Beranek’s concept related to ITDG would have listeners seated remotely in a hall perceiving more intimacy because the arrival period between the direct sound and the first reflection is shorter as a listener is positioned farther from the source.

**Spaciousness (Apparent Source Width) and Envelopment**

It was not long before the sense of “spaciousness” took a solid position as a major room subjective quality in the field of concert hall acoustics. Spaciousness also denotes “spatial impression” or “auditory spaciousness.”

The conventional concept on spaciousness is that spaciousness indicates apparent source width (ASW) that is perceived and determined predominantly by the early lateral energy: early lateral fraction, shortly LF (Reichardt & Schmidt, 1967; Barron, 1971 & 1981; Marshall, 1981). The perception of ASW also depends on the incoherence of sounds (Damaske, 1968), listening level and degree of incoherence of lateral energy fraction (Keet, 1968), sound strength (G) at the listener and dynamic level of music being played such as pianissimo and fortissimo (Kuhl, 1978), overall sound pressure level (Barron & Marshall, 1981), and on early sound level (Morimoto and Iida, 1994). The ASW is defined as a sense of broadening of the sound source, that is, a kind of initial room acoustical impression sensed from the impact of early sound. The perception of ASW is closely related to the scale and type of the sound source and to the strong lateral
reflections at low through mid frequencies below 4k Hz (Barron and Marshall, 1981).

Now, the current idea on spaciousness is that overall spaciousness consists of two perceptual elements: ASW and envelopment or listener envelopment (LEV). However, spaciousness means to be more likely ASW and therefore, the concept of envelopment can be discussed separately. While spaciousness depends on the early lateral energy, envelopment depends on the late reverberant energy with the support of relatively strong late lateral energy. Envelopment indicates the sense of presence in the surrounding and diffusive sound field that can be perceived as soon as one encounters the feeling of ASW. The perception of envelopment is highly related to the low frequency components (Morimoto & Maekawa, 1988) or the strong lateral energy at low frequencies (Barron & Marshall, 1981).

Hidaka, et al. (1991 and 1992) suggested that the perceived ASW is determined primarily by IACC early at 500-4k Hz, whereas the perceived envelopment is determined by IACC late at 500-4k Hz. They further added that G at low frequencies, which is called $G_{\text{low}}$ or $G_L$, contributes to ASW. On the other hand, the frequency content at 4k Hz contributes little to spaciousness in concert-hall music performance environments (Blauert, et al., 1986a and 1986b), leaving IACC early and IACC late at 500-2k Hz to be suggested as measures of ASW and envelopment, respectively (Hidaka, et al., 1995; Beranek, 1996).

\[
LG_{80}^{\infty} = 10 \log \left( \int \int \int p_F^2(t) dt \int p_F^2(t) dt \int p_A^2(t) dt \right) \text{dB} \tag{2.2}
\]

$p_F(t)$: the instantaneous lateral sound pressure measured with a figure-of-eight microphone

$p_A(t)$: the response of the same source at a distance of 10 m in a free field
Bradley (1995) showed that envelopment is influenced by the relative level of the late lateral sound energy ($LG_{80}$ or $G_{LL}$) measured after 80ms over the octave-band center frequencies from 125 to 1k Hz. The $LG_{80}$ is expressed in Equation 2.2.

Furuya and Fujimoto (1996) added that the late vertical sound energy also has an influence on the perception of envelopment. As a general psycho-acoustical study of the reflections from upside by Furuya and Fujimoto (1995), the reflections from frontal upside within 200ms were found to contribute to the perception of envelopment. In other words, the increase of the vertical component of energy within 200ms enhances envelopment as well as that of lateral energy. This effect was confirmed by Furuya and Fujimoto’s recent study (2001) on the effects of directional energy on listener envelopment. Their study also showed that the late sound from other directions such as overhead or back contributes to envelopment.

Griesinger (1997) argued that spatial impression (spaciousness and envelopment) depends on the type of music that one is actually listening to. Griesinger considered the capability of human ears to extract spatial information from continuous music or speech using rise times, fall times and the spaces between musical notes. Griesinger then suggested that different spatial impression can be perceived by the nature of music: solo, chamber, lightly or thickly scored orchestral production.

The perceptions of ASW and envelopment are compared in Figure 2-9 on the basis of some of the above mentioned concepts. The figures simply show that both ASW and envelopment are dependent on the scale and type of music performance to some degree. The figures also potentially show that the ASW is more closely related to the sound source than envelopment.
Figure 2-9. Perceived ASW and envelopment (LEV).  A) Recital condition with a small listening size.  B) Orchestra condition with a large listening size.

Room Acoustical Parameters

Reverberation Time (RT)

A century ago, Sabine (1922) empirically derived a legendary formula predicting a reverberation time (RT) of a room, which became the most fundamental parameter used for room acoustical analysis. The Sabine formula expressed in Equation 2.3 can be used best for relatively large and uniform live spaces where sound decays smoothly (Kuttruff, 1976; Hodgson, 1996).

\[
T = \frac{kV}{A}
\]  

(2.3)

A: total room absorption power
\(k\): constant (0.163 in SI unit and 0.05 in English unit)
V: room volume

For relatively small and uniform dead spaces where sound decays abruptly and exponentially, the Eyring formula expressed in Equation 2.4 can be used (Hodgson,
1996). This Eyring formula predicts better an RT of a room where an average room absorption coefficient is larger than 0.5 (Eyring, 1930).

\[
T = -\frac{kV}{S \ln(1 - \bar{\alpha})}
\]  \hspace{1cm} (2.4)

\(\bar{\alpha}\): average room absorption coefficient  
S: total surface area of the room  
k: constant (0.163 in SI unit and 0.05 in English unit)  
V: room volume

In actual field measurements using modern equipment and software, an RT is measured as the time taken for the sound to decay by 60 dB. This is sometimes called T60. In many cases, this T60 is hard to be achieved due to the background noise against the measurement noise signal. Therefore, the RT is measured on the basis of the initial decay rate for a range of 30, 20 or 15 dB and extrapolated for the entire 60 dB decay. These RT terms are named T30, T20 and T15, respectively and T30 is most commonly used.

**Early Decay Time (EDT)**

Early decay time (EDT) was defined by Jordan (1970) as a measure of RT corresponding to the slope of the first 10 dB decay. There is a similar concept defined earlier. It is ‘initial reverberation time’ that was developed by Atal, *et al.* (1965) as a measure of RT corresponding to the first 160 ms or the first 15 dB of the decay. The EDT is commonly used nowadays to investigate the early energy behavior from a sound decay of a room particularly where its decay is non-exponential (Kuttruff, 1991).

The RT does not substantially vary with room shape because its measurement concept represents the sound decay process of a room as a whole. On the contrary, the
EDT depends on the measurement position because the early portion of a sound decay is strongly influenced by early reflections and therefore, it contains some information of the room geometry (Kuttruff, 1991).

**Early-to-Late Sound Energy Index (C80)**

The clarity index \( C \) (Klarheitsmaß C) was defined by Reichardt, *et al.* (1974) as the logarithmic ratio of the early energy within 80 ms to the late reverberant energy after 80 ms. This index is usually called C80 nowadays and physically expressed in Equation 2.5. The clarity index is derived from the impulse response and measured in dB.

\[
C80 = 10 \log \left( \frac{\int_{80\text{ms}}^{\infty} p^2(t)dt}{\int_{0}^{80\text{ms}} p^2(t)dt} \right) \text{ dB} \quad (2.5)
\]

\( p(t) \): impulse response

The C80 is inversely related to the RT. As the RT decreases and so does the reverberant energy, the early energy increases. As a result, the C80 becomes larger. According to Reichardt, *et al.* (1974), 0 dB of C80 may be acceptable for the Baroque period music that usually consists of densely textured musical notes and -6 to -3 dB may be required for the Romantic period music. According to Beranek (1996) with his survey results, the concert halls with the average C80s at octave-band center frequencies of 500 through 2k Hz between -1 and -5 dB were judged the best.

The definition index \( D \) (Deutlichkeit D), a similar concept to the clarity index \( C \), was defined earlier by Thiele (1953) as the ratio of the early energy within 50 ms to the total energy. This index is usually called D50 nowadays and physically expressed in
Equation 2.6. The definition index is a measure of distinctness of sound and used rather for speech intelligibility analysis as a basic objective parameter. It is also derived from the impulse response and measured in percentage.

\[
D50 = \frac{\int_{0}^{50\text{ms}} p^2(t)\,dt}{\int_{0}^{\infty} p^2(t)\,dt} \times 100\%
\]

\[p(t): \text{impulse response}\]

**Sound Strength (G)**

The sound strength (G) is defined as the logarithmic ratio of the sound pressure of the measured impulse response at a listener position in a room to that of the impulse response obtained at a distance of 10 m from the same sound source generating the same power in a free field or in an anechoic chamber (Gade & Rindel, 1985). In other words, the G indicates the difference in sound pressure level from the level measured under the latter reference condition. The sound source is assumed to be omni-directional. The G is physically expressed in Equation 2.7 and measured in dB.

\[
G = 10\log\left\{\frac{\int_{0}^{\infty} p^2(t)\,dt}{\int_{0}^{\infty} p_A^2(t)\,dt}\right\} \text{ dB}
\]

\[p(t): \text{impulse response}\]

\[p_A(t): \text{impulse response measured with the same sound source in an anechoic chamber at a distance of 10 m}\]

Kuttruff (2000) cited that Gade and Rindel (1985) found from their measurements
in 21 Danish concert halls that the sound strength shows a linear decrease by 1.2 to 3.3 dB per distance doubling from the front to the rear of any hall.

**Bass Ratio (BR) and Bass Strength ($G_{125}$)**

The bass ratio (BR) is defined as the ratio of the RTs at low frequencies of 125 and 250 Hz to those at mid-frequencies of 500 and 1k Hz. The BR is expressed in Equation 2.8. Beranek (1996) addressed that the BR is meaningful for a hall only when fully occupied because the audience absorbs the high frequency sounds more than the low frequency sounds.

\[
BR = \frac{RT_{125} + RT_{250}}{RT_{500} + RT_{1k}}
\]  

(2.8)

RT: reverberation time at a given frequency

The BR had been an objective measure of the subjective perception of warmth of sound for a long time until Bradley, *et al.* (1997) found from subjective tests that the low frequency reverberation time is not significantly related to the measure of warmth. They found that the sound strength at low frequencies, particularly at 125 Hz, is related to perceived warmth and proposed the bass strength, $G_{low}$ or $G_{125}$, as an objective measure of warmth.

**Initial Time Delay Gap (ITDG)**

The initial time delay gap (ITDG) was defined by Beranek (1962) as the time interval between the direct sound and the first reflection at a listener position. The ITDG is generally measured in the center of the main orchestra seating level. As expressed in Equation 2.9, this concept can also be determined by geometrical measurements of the difference in length between the traveling path of the direct sound and that of the first
arriving reflection at a position.

\[ ITDG = \frac{[\text{length of the first reflection path} - \text{length of the direct sound path}]}{c} \]  
\[
(2.9)
\]
c: speed of sound in air

The ITDG is dependent upon the size of the room, the location of reflecting surfaces and the locations of source and receiver. According to Beranek (1996) with his survey on acoustics of the concert halls, a shorter ITDG is preferred. The measurements in ITDG of the so-called best ranked concert halls resulted in 25 ms or below (Beranek, 1996). The reflections arriving within 40 ms after the direct sound contribute to perception of intimacy (Siebein & Gold, 1997).

**Center Time \((t_s)\)**

The center time (Schwerpunktszeit \(t_s\)) was initially developed by Kürer (1969) and refined by Cremer (1978). As expressed in Equation 2.10, the center time is defined as the time indicating the center of gravity of the squared impulse response. The center time is measured in milliseconds.

\[
 t_s = \left\{ \frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p^2(t)dt} \right\} \text{ ms} \]  
\[
(2.10)
\]
p(t): impulse response

According to Cremer (1978), Kürer showed that the parameter of center time can be used to characterize a specific position in a room with regard to the distinctness and clarity of the sound. Kürer also demonstrated the negative relationship between center
time and speech intelligibility. For example, the shorter center times yield the higher
clearness of the sound and the higher speech intelligibility. Cremer (1978) added that in
general the center time increases as G increases.

**Lateral Energy Fraction (LF or LEF)**

There have been many discussions on importance of lateral energy and on its
contribution particularly to the perception of spaciousness. Among them, Barron and
Marshall (1981) developed the physical concept of lateral energy fraction (LF) as an
objective measure of spaciousness. Its refined form is given in Equation 2.11. The LF is
defined as the ratio of the early lateral energy to the total early energy arriving through all
directions.

$$
LF = \frac{\int_{5ms}^{80ms} \int_{0}^{80ms} p^2(t) \cos^2 \theta dt}{\int_{0}^{80ms} p^2(t) dt}
$$

(2.11)

p(t): impulse response

The element of \(\cos^2 \theta\) in the numerator of the above equation is sometimes replaced
by \(\cos \theta\). Where a figure-of-eight microphone is used in measurements, the estimation of
LF is given by Equation 2.12.

$$
LF = \frac{\int_{5ms}^{80ms} \int_{0}^{80ms} p_8^2(t) dt}{\int_{0}^{80ms} p^2(t) dt}
$$

(2.12)

\(p_8(t)\): impulse response through figure-of-eight microphone
\(p(t)\): impulse response through omni-directional microphone
Interaural Cross-Correlation (IACC)

The degree of the similarity or coherence between two signals received at the two ears of a listener is measured by the interaural cross-correlation function as expressed in Equation 2.13. The $\tau$ indicates the interaural time difference (ITD) between the two ears with regard to the time taken for a sound wave to travel one side to the other and it ranges within $\pm 1$ ms.

\[
\rho_{rl} = \frac{\int_{t_1}^{t_2} p_r(t) p_l(t + \tau) dt}{\left[ \int_{t_1}^{t_2} p_r^2(t) dt \int_{t_1}^{t_2} p_l^2(t) dt \right]^{1/2}}
\]  

(2.13)

$p_r(t)$: impulse response at right ear  
$p_l(t)$: impulse response at left ear  
$\tau$: time integration limit between two ears (varied within $\pm 1$ms)  
t_1: lower time limit  
t_2: upper time limit

The maximum value is chosen from the absolute values of the above function measured within the range of $\tau$ from -1 to +1 ms as shown in Equation 2.14. This value is specifically called the interaural cross-correlation (IACC) (Damaske & Ando, 1972).

\[
IACC = \max |\rho_{rl}(\tau)| \text{ for } |\tau| \leq 1\text{ms}
\]  

(2.14)

There are several kinds of IACC used nowadays that differ according to the lower and upper time limits of $t_1$ and $t_2$ in Equation 2.13. The integration from 0 to 1000 ms ($t_1 = 0$, $t_2 = 1000$ ms) yields IACC total ($IACC_A$). This $IACC_A$ is divided into two components: first, the integration within 80 ms ($t_1 = 0$, $t_2 = 80$ ms) yields IACC early ($IACC_E$); second, the integration from 80 ms to 1000 ms ($t_1 = 80$ ms, $t_2 = 1000$ ms) yields
IACC late (IACC_L). Note that IACC_{A3}, IACC_{E3} or IACC_{L3} is denoted where the average of IACC coefficients measured at the three octave-band center frequencies of 500, 1k and 2k Hz is taken.

**Binaural Quality Index (BQI)**

The binaural quality index (BQI) was defined by Beranek (2004) as 1-IACC_{E3}. The BQI may be conveniently used to measure the perceived ASW. In addition, the BQI can be effectively used to estimate the acoustical quality of a fully occupied hall with its value measured in the unoccupied room condition (Beranek, 2004).

\[
BQI = \left[ 1 - IACC_{E3} \right]
\]  

(2.15)
CHAPTER 3
RESEARCH METHOD AND TOOLS

In general, this study involved orchestral impulse response measurements and in-room music playback recordings for quantitative and qualitative acoustical assessments of under-balcony areas in performance halls. A total of sixteen directional sound sources arrayed on the stage in a performance hall were used for the multiple source acoustical tests and analysis. These sources represented a large orchestral group, which consists of a variety of instruments whose source directivities vary. In the under-balcony area, the acoustical results obtained from the multiple source tests were analyzed by comparing them to those from the single omni-directional source tests. These two sets of the results obtained in the under-balcony area were furthermore investigated by comparison to those obtained in the main orchestra seating area.

Quantitative Assessment Method

Acoustical measurements in an actual hall as well as computer modeling and simulations were executed. The real hall acoustical measurements were monaurally and binaurally conducted at the Phillips Center for the Performing Arts (PCPA) in Gainesville, Florida. Five approaches were involved in the quantitative assessment. First, time-domain impulse responses were analyzed. Second, frequency spectra were analyzed. Third, trends or characteristics in room acoustical parameters were identified. The parameters included early decay time (EDT), reverberation time (RT), sound strength or loudness (G), bass strength (G_{125}), early-to-late sound energy index (C80), and center time (t_s). Fourth, trends or characteristics in binaural room acoustical parameters were
identified. These parameters included interaural cross-correlation (IACC) and binaural quality index (BQI). Lastly, acoustical behavior in early sound energy was specifically examined. For this examination, C index (early-to-late sound energy ratio) and D index (early-to-total sound energy ratio) were introduced. In addition, the computer modeling and simulation technique was used for analysis particularly of early arriving sounds and their directionalities.

**Qualitative Assessment Method**

A psycho-acoustic experiment was executed for qualitative assessment of the sounds as well. The psycho-acoustic experiment involved a listening comparison test, which is a way to subjectively evaluate room acoustical qualities. Music playback was binaurally recorded in the performance hall and the recorded music signals were reproduced through stereo headphones in the laboratory for the listening test. The listening test required one to compare and evaluate the music signals in eight acoustical quality categories including loudness, reverberance (liveness), clarity, warmth, intimacy, spaciousness (source width), envelopment, and overall impression. The results from the qualitative assessment were further compared to those from the quantitative measurements.
CHAPTER 4
ROOM ACOUSTICAL MEASUREMENTS AND QUANTITATIVE ANALYSIS

This chapter discusses room acoustics of the under-balcony area measured monaurally and binaurally with a single omni-directional sound source as well as with an array of multiple directional sound sources.

Apparatus and Setup for Measurements

Measurement Apparatus and Module

The equipment used for the measurements are listed below.

- IVIE PC 40 real time analyzer
- Dodecahedron omni-directional loudspeaker: Norsonic Type 223
- Directional loudspeakers: 12 units of EV FM-1202ER and 4 units of Peavey SP115M
- Subwoofer: RADIAN RCS-118
- Omni-directional microphone: Earthworks M30BX, ½”
- Dummy head binaural system: Brüel & Kjær Type 4100
- Mixer: Whirlwind MIX5s
- Cross-over unit: Ashly XR1001
- Power amplifier: Crown MICRO-TECH 1202 (2 units for directional loudspeakers), Crown COM-TECH 200 (for dodecahedron loudspeaker), GRAS Power Module Type 12AA (for dummy head binaural system)
- Soundcard: Digigram VXPocket v2 Professional Soundcard
- Laptop computer with WinMLS program

WinMLS, acoustical measurement software, was used as a host measurement module and a built-in pseudo random noise signal of Maximum Length Sequence (MLS)\(^5\) was used as a stimulus signal. A measurement block diagram with the equipment used is shown in Figure 4-1, and the receiver systems are shown in Figure 4-2.

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\(^5\) A Maximum Length Sequence (MLS) is a pseudo random noise sequence used for measurements of room impulse responses or for spectral analyses.
Figure 4-1. Block diagrams of the measurement setup. A) Measurements with single omni-directional source. B) Measurements with multiple directional sources.
Loudspeaker Setup

A dodecahedron omni-directional loudspeaker with a subwoofer next to it for the single source measurements (Measurement 1), which is described later, was placed at 1.5 m high in the middle of the stage just ahead of the proscenium as shown in Figure 4-3. On the other hand, 16 directional loudspeakers also with a subwoofer for the multiple source measurements (Measurement 2) were placed according to the positions of each musical instrument group: 7 speakers for the string group (3 for first and second violins, 2 for violas and cellos, and 2 for double basses), 2 speakers for the woodwind group (1 for clarinets and oboes, and 1 for bassoons), 5 speakers for the brass group (1 for French horns, 3 for trumpets and trombones, and 1 for tubas), and 2 speakers for the percussion group. These loudspeakers were allocated in consideration of composition and formation of a large symphony orchestra and of power output from each of the instrument groups. The subwoofer was positioned with the brass group because a great deal of orchestra low frequency energy is produced from this group and nearby double basses.
Figure 4-3. Layout of loudspeakers. A) Positions of an omni-directional loudspeaker and 16 directional loudspeakers. B) Positions of 16 directional loudspeakers in a perspective stage view of the 3D computer model. S1–S3: string group (first and second violins), S4–S5: string group (violas and cellos), S6–S7: string group (double basses), W1: woodwind group (clarinets and oboes), W2: woodwind group (bassoons), B1: brass group (French horns), B2–B4: brass group (trumpets and trombones), B5: brass group (tubas), P1–P2: percussion group, SW: subwoofer.

Figure 4-4. Loudspeaker source directions in the CATT-Acoustic 3D model.
Setup of Loudspeaker Source Directions

As shown Figure 4-4, the face directions of the 16 loudspeakers were adjusted according to main directions of sound radiation of each instrument, which was studied by Meyer (1978, 1993). The directions of the performers’ seat of each instrument group were also taken into account. For example, the directions of the loudspeakers representing either the first and second violin groups or the viola group were horizontally adjusted toward the conductor position and vertically tilted upward similar to the main sound propagation pattern of the violin or viola. The directions for the cello and double bass group faced the conductor position. The direction for the woodwind group of clarinets and oboes was adjusted downward, whereas the direction for the woodwind group of bassoons was tilted upward. The directions for the brass group of trumpets and trombones faced the conductor position, whereas the direction for the brass group of tubas was tilted about 70 degrees upward and the one for the brass group of French horns was horizontally adjusted about 110 degrees toward the stage right against the conductor position in the front-back axis of the hall. The directions for the percussion group faced upward.

Stimulus Noise Signal Calibration

The output level of the omni-directional loudspeaker was calibrated at 110 dB at 1 m. On the other hand, the overall output level of the 16 directional loudspeakers was calibrated, under the steady-state noise condition, to the level of the omni-directional loudspeaker measured at 10 m away from the place where the omni-directional loudspeaker was located. It was assumed that the power output of the sound sources produces the stationary energy density from this distance as in the reverberant sound field where the sound level is optimally independent of the distance from the source.
Measurement Room Conditions

The measurements were conducted with unoccupied audience seating. The stage enclosure was fully extended as it is when used for large orchestra concerts. About 70 performers’ chairs with music stands were placed in the typical seating patterns used on stage by a symphony orchestra. Refer to Figure 4-3 (A).

Measurement Locations

A total of 6 measurement positions in the room were selected as shown in Figure 4-5. The positions included 1 position (position A) from the main central orchestra seating area, 3 (positions B, C and D) from the under-balcony area, 1 (position E) from the lower central balcony area, and 1 (position F) from the upper central balcony area. Position A is 15 m (49 ft) away from the proscenium where the single omni-directional source was located. The positions under the balcony overhang included 1 position (position B) from the middle of the overhang opening, 1 (position C) from the inner central seating area, and 1 (position D) from the inside corner seating area. Position C is 25 m (82 ft) away from the proscenium and 5.5 m (18 ft) from the overhang opening. Positions A, B, C, E, and F are off-center of the room but are almost in the same longitudinal sectional plane. Positions C and D are in the same transverse section. The detailed distances of the receiver positions are shown in Table 4-1.

| Table 4-1. Receiver distance from omni-directional source at proscenium. |
|---------------------------------|-----|-----|-----|-----|-----|-----|
| From proscenium axis           | A   | B   | C   | D   | E   | F   |
| From longitudinal center axis  | 15.0| 19.5| 25.0| 24.8| 23.8| 34.1|
| From longitudinal center axis  | 1.5 | 1.5 | 1.5 | 10.4| 1.6 | 1.8 |
| 3-D Euclidean                  | 15.1| 19.6| 25.1| 26.9| 24.7| 35.7|

* 3-D Euclidean distance is measured from the omni-directional source at 1.5 m high above the stage floor.
Measurement positions. The positions are shown in the main floor seating chart (top) and in a longitudinal section (bottom).

**Measurement 1**

In this series of measurements, the room acoustical impulse response measurements with a single omni-directional source were repeatedly taken monaurally and binaurally at the positions indicated above. The objective of these measurements was to record data in accordance with the current ISO 3382\(^6\) standard measurement protocol using a single omni-directional source.

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\(^6\) ISO 3382 is an international standard in acoustics specifying measurement of reverberation time of rooms with reference to other acoustical parameters.
Measurement 2

In this second series of measurements, the room acoustical impulse response measurements with 16 directional sources were monaurally and binaurally taken at the same receiving positions. The results are compared to those from Measurement 1 in the following discussion.

Results and Discussions

Two notes should be stated in advance of discussions. First, as mentioned earlier, position C (a deep under-balcony seat) is primarily discussed with position A (a main orchestra seat) in this study. Second, the results obtained from the monaural receivers are primarily discussed or a note is given otherwise.

Impulse Responses

The time-domain broad-band impulse responses within 3 s and 500 ms measured at position C were shown in Figure 4-6 and 4-7 respectively. As shown in the impulse responses measured with a single source, the direct sound was distinctively observed from the succession of reflections after the direct sound. The time delay between the direct sound and the first reflection was also clearly seen. On the contrary, a number of large spikes were observed over an early time window of tens of milliseconds as shown in the impulse responses measured with 16 multiple sources. It seems that multiple direct sounds arrived one after another and began to mingle with room reflections. Consequently, it does not seem possible for one to read or identify an initial time delay gap (ITDG) from these impulse responses. This discussion will be extended in the next section.
Figure 4-6. Broad-band impulse responses within 3 s at position C. A) Measured with a single omni-directional source. B) Measured with multiple directional sources.
Figure 4-7. Broad-band impulse responses within 500 ms at position C. A) Measured with a single omni-directional source. B) Measured with multiple directional sources.

When compared to the impulse responses measured at position A, relatively larger spikes were observed at position C over the early time window of 100 ms in the impulse
responses either measured with a single source or with multiple sources. The impulse responses at position A were shown in Figures B-1 and B-2 in Appendix B. This under-balcony acoustical phenomenon may be due to strong early reflections coming from the nearby surfaces such as rear wall and under-balcony ceiling as indicated by Barron (1995). This discussion will also be extended in the following section.

**Early Impulse Responses**

Computer modeling and simulations were conducted to clearly identify the early sound energy distribution. The computer simulated early impulse responses at 1k Hz within 100 ms of the direct sound at position C were shown in Figure 4-8. A clear difference in the early sound energy component between the impulse response simulated with a single source and the one simulated with multiple sources was observed. As shown in Figure 4-8 (A), the first reflection following the direct sound arrived from the rear wall at position C after a 24 ms delay. As shown in Figure 4-8 (B), on the contrary, a group of direct sounds arrived over a 30 ms time period and began to mix with early arriving reflections. This finding implies two things. One is that the direct sounds from the orchestral performers do not arrive at a listener simultaneously. The other is that some late arriving direct sounds from the performers located upstage are perceived with some early arriving reflections at the same time. At this point, it is implicit to say that the definition of the room acoustical parameter of ITDG should be revised when evaluating rooms where multiple sources are typically used. Another finding from the impulse response simulated with multiple sources is that the direct sounds and reflections were densely spaced over time.

The above findings are also true with the computer simulated early impulse responses obtained at position A. Refer to Figure 4-9 in this section and Figure B-3 in
Appendix B. From Figure 4-9, it was observed that the first reflection perceived at position A came from a side wall after 30 ms.

Figure 4-8. Early impulse responses simulated at 1k Hz within 100 ms at position C. A) With a single omni-directional source. B) With multiple directional sources. 1\textsuperscript{st} order reflections: sounds that reflect off one surface before arriving at the receiver position, 2\textsuperscript{nd} and 3\textsuperscript{rd} order reflections: sounds that reflect off two or three surfaces before arriving at the receiver position. Direct sounds in (B) in order from the earliest: S1, S4, S2, S5, S3, S6, S7, W1, W2, B2, B1, B4, B3, B5, P2, and P1 (these tag numbers are defined in Figure 4-3).
Figure 4-9. Early impulse response at 1k Hz within 100 ms at position A simulated with a single omni-directional source.

Directions of the reflections found in the impulse response at position C simulated with a single source indicated that most of the early reflections come within a maximum incidence angle of 33 degrees limited by the balcony overhang in the vertical dimension. Refer to Figure 4-10. All of the early reflections shown in Figure 4-8 (A) came from the rear wall, the side walls, or from the upfront stage enclosure. No reflection coming from the main ceiling or under-balcony ceiling was observed within 100 ms. Only one reflection was found to come from the ceiling above the stage as shown in Figure 4-11. However, the vertical incidence angle of this reflection path is only about 15 degrees. On the other hand, the early reflections perceived at position A came through variable directions in both vertical and horizontal dimensions. Some reflections came from the side walls, some came from the rear wall, and some came from the upfront stage enclosure. Refer to Figure 4-9. In addition, many reflections were also found to come from the main ceiling or ceiling reflector or from the ceiling above the stage as identified in Figure 4-9 and Figure B-4 in Appendix B.
Figure 4-10. Examples of the early reflection paths to position C from the rear or side walls in longitudinal section views (not to scale).

Figure 4-11. Early reflection path to position C from the ceiling above the stage in a longitudinal section view (not to scale).

**Frequency Responses**

The frequency response measured with multiple directional sources at position A was compared to the one measured with a single omni-directional source in Figure 4-12. The amplitude of the frequency response measured with multiple sources was found to be much higher than the one measured with a single source by 5 to 10 dB at low frequencies.
and by 5 to 20 dB at high frequencies. At mid-frequencies, however, the phenomenon was not clearly readable between these frequency responses. On the other hand, the phenomenon was not clearly identifiable over almost all frequencies from the frequency response measured with multiple sources at position C when compared to the one measured with a single source. Refer to Figure 4-13.

Figure 4-12. Frequency responses measured at position A.

Figure 4-13. Frequency responses measured at position C.

Next, the frequency responses measured with multiple sources at positions A and C were compared with each other. As shown in Figure 4-14, the difference in amplitude is not clearly identifiable at mid-frequencies between position C and position A. However, the frequency response at position C was much lower in amplitude by 5 to 20 dB at high
frequencies over 1k Hz and lower by 3 to 10 dB at low frequencies above 50 Hz. This phenomenon particularly at high frequencies is similarly observed in the frequency responses measured with a single source. The amplitude at position C was 5 to 10 dB lower at high frequencies in this case. Refer to Figure B-5 in Appendix B. The variations at very low frequencies observed in this particular hall seem to be due to frequency filtering by the balcony overhang opening aperture in relation with wave length to the dimension of the opening height as indicated by Kwon (2002). The opening height of the balcony overhang in the PCPA is 4.8 m and its corresponding cut-off frequency is about 70 Hz. The cut-off frequency becomes about 90 Hz if excluding the chair height. Barron (1995) also indicated that reduction in bass frequencies appears to be due to additive effects of both grazing incidence and the overhang barrier. In addition, as discussed above, reduction in sound energy at high frequencies also appears to be significant.

Figure 4-14. Frequency responses measured at positions A and C with multiple directional sources.

To summarize, it was argued that first, sound energy decreases in the under-balcony area; second, the decrease in sound energy occurs significantly at high frequencies as well as at low frequencies; and third, this decrease in sound energy is possibly caused by balcony overhang barriers to some degree.
Room Acoustical Parameters

This section discusses under-balcony acoustics with regard to general room acoustical parameters based on the measurements with multiple directional sources. The parameters include early decay time (EDT), reverberation time (RT), sound strength or loudness index (G), bass strength ($G_{125}$), early-to-late sound energy index ($C_{80}$), and center time ($t_c$).

Early decay time (EDT)

As presented in Table C-1 in Appendix C and Figure 4-15, some variations in the EDT measured with multiple directional sources were observed at position C over low frequencies when compared to the EDTs measured with a single omni-directional source. However, the EDTs at position A varied marginally within 0.1 second across most of the octave-band center frequencies from 125 through 4k Hz. The typical EDTs at mid-frequencies ($EDT_{mid}$) either at position A or C measured with multiple sources did not significantly vary from the $EDT_{mid}$ at the same position but measured with a single source. The overall difference at mid-frequencies was only 0.1 second or so either at position A or C. Also refer to Figure B-6 in Appendix B.

On the other hand, the EDTs measured with multiple sources at position C as shown in Figure 4-16 were found to be shorter than the EDTs at position A over most of the octave-band center frequencies. The overall EDTs at position C over mid-frequencies were shorter than those at position A by approximately 0.35 and 0.3 seconds when measured with multiple sources and a single source, respectively. This tendency in EDT agrees to Barron’s (1995) finding that the EDT decreases as a listener’s position moves back under a balcony overhang.
Figure 4-15. Early decay times (EDT) measured at position C.

Figure 4-16. Early decay times (EDT) at positions A and C measured with multiple directional sources.
Reverberation time (RT)

The RTs at positions A and C measured with a single omni-directional source or multiple directional sources are presented in Table C-2 in Appendix C. Interestingly, the RTs at position C measured with multiple sources varied little within 0.15 seconds in octave-band center frequencies from 125 through 4k Hz compared to the RTs measured with a single omni-directional source. This overall RT tendency was also true for the RT data obtained at position A. As shown in Figure B-8 included in Appendix B, the RTs measured with multiple sources varied also little within 0.15 seconds in most of the octave-band center frequencies from 125 through 4k Hz compared to the ones measured with a single source. At position either A or C, the average mid-frequency RT ($RT_{\text{mid}}$) measured with multiple sources was approximately 0.1 second different from the $RT_{\text{mid}}$ measured with a single source.

![Figure 4-17. Reverberation times (RT) measured at position C.](image-url)
Next, the RTs at positions A and C measured with multiple sources are compared with each other in Figure 4-18. It was found that the RTs varied little through listener positions. The RT$_{\text{mid}}$ measured at position C was 2.14 sec and the one measured at position A was 2.22 sec, which means that the difference is less than 0.1 sec. In addition, the RTs are little different from the hall average RTs. A similar tendency was observed in the RTs measured with a single source as well. Refer to Figure B-9 in Appendix B.

It was observed from this study that the RTs did not significantly vary at each octave-band center frequency regardless either of listener position or of sound source array. Refer to Table 4-2, which shows the average RTs and standard deviations by sound source array measured at six positions throughout the hall. The RTs at mid-frequencies measured at these positions are shown in Figure 4-19. From the measurements with multiple directional sources throughout the hall, the average RT at mid-frequencies and
the standard deviation are 2.18 sec and 0.04 sec, respectively. From the measurements with a single omni-directional source, those are 2.13 sec and 0.03 sec, respectively.

Table 4-2. Average RTs and standard deviations by sound source array measured at six positions throughout the hall.

<table>
<thead>
<tr>
<th>Octave band center frequencies (Hz)</th>
<th>At mid (500-1k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>2.13</td>
</tr>
<tr>
<td>250</td>
<td>2.13</td>
</tr>
<tr>
<td>500</td>
<td>2.13</td>
</tr>
<tr>
<td>1k</td>
<td>2.19</td>
</tr>
<tr>
<td>2k</td>
<td>2.19</td>
</tr>
<tr>
<td>4k</td>
<td>2.19</td>
</tr>
<tr>
<td>(500-1k)</td>
<td>2.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Single omni-directional source</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.95</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multiple directional sources</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>2.05</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Figure 4-19. Average mid-frequency reverberation times (RT_{mid}) throughout the hall.

The above RT tendency in a hall suggests that the acoustics in the under-balcony area may not be distinctively characterized by numerical measurements of RT. It is also possible to argue that the parameter of RT does not seem to be an appropriate room acoustical index to allow one to objectively assess acoustical field conditions of any specific areas in a hall such as the area under a balcony overhang because the RT is
almost independent on measurement position. One final note that should be addressed is that the conventional measurement method in use of a single omni-directional sound source would consequently be competent for identification of the RT characteristic of a hall as a whole.

**Early-to-late sound energy index (C80)**

Examining the characteristic of C80 observed at position A, the results clearly showed that the C80 values measured with multiple directional sources were 1 to 3 dB lower over each of the octave-bands than those measured with a single omni-directional source. Refer to Table C-3 in *Appendix C* and Figure B-10 in *Appendix B*. Over octave-band center frequencies from 500 to 2k Hz, the overall C80 (typically named C80\(_{500-2k}\)) measured with multiple sources was found to be approximately 1.5 dB lower than the one measured with a single source.

![Graph of C80 dB vs Octave-band Center Frequency](image)

Figure 4-20. Early-to-late sound energy index (C80) measured at position C.
As shown in Figure 4-20, on the other hand, the C80 values at position C measured with multiple sources tended to gradually increase with higher frequencies, indicating that the early energy is stronger relative to the late reverberant energy at higher frequencies. When compared to the C80 values measured with a single source, however, the behavior of C80 from the measurements with multiple sources did not seem to be distinctively characterized at position C. At the octave-band center frequencies from 500 to 2k Hz, the C80\textsubscript{500-2k} value measured with multiple sources and the one measured with a single source were 1.1 and 0.8 dB, respectively, which are approximately the same.

![Figure 4-21. Early-to-late sound energy index (C80) at positions A and C measured with multiple directional sources.](image)

Next, the C80 values at positions A and C measured with multiple sources are compared with each other in Figure 4-21. This comparison suggests that the C80 values at position C were 1 to 4 dB higher at octave-band center frequencies from 125 Hz than those at position A. Also refer to Figure 4-22. In case of the measurements with a single
source, the C80 tendency was not very clear compared to the tendency observed in Figure 4-21 but the C80 values at position C also tended to be higher at most of the octave-band center frequencies. At the octave-band center frequencies from 500 to 2k Hz, the C80\textsubscript{500-2k} at position C was found to be about 1 dB higher than the one at position A.

![Graph showing comparison of early-to-late sound energy index (C80) at position C relative to the one at position A.](image)

Figure 4-22. Comparison of the early-to-late sound energy index (C80) at position C relative to the one at position A.

**Center time (t\textsubscript{s})**

The results of t\textsubscript{s} obtained at position A showed that the t\textsubscript{s} measured with multiple directional sources was approximately 25 ms longer on average over each of the octave band center frequencies than those measured with a single omni-directional source. Refer to Table C-4 in Appendix C and Figure B-12 in Appendix B. As shown in Figure 4-23, on the other hand, the behavior in t\textsubscript{s} at position C was not observed in the same or even similar way as above in t\textsubscript{s} at position A. The behavior in t\textsubscript{s} at position C measured with multiple sources did not seem to be distinctively characterized when compared to the t\textsubscript{s} at
the same position measured with a single source. One note on $t_s$ at position C measured with multiple sources can, however, be added. It is that the $t_s$ in this study tended to gradually decrease with higher frequencies contrary to the C80 tendency.

![Diagram of center times ($t_s$) measured at position C.](image)

**Figure 4-23.** Center times ($t_s$) measured at position C.

The $t_s$' at positions A and C measured with multiple sources are compared with each other in Figure 4-24. This comparison suggests that the $t_s$' at position C were shorter by as much as 30 ms on average at each octave band center frequency from 250 Hz than those at position A. In the case of measurements with a single source, the $t_s$ behavior was not clearly differentiated between these two positions from this study but the $t_s$' at position C tended to be shorter at mid-frequencies than those at position A. Refer to Figure B-13 in *Appendix B*. 
To summarize the behaviors in C80 and $t_s$ identified in the under-balcony area, first, the behavior in C80 or $t_s$ resulted from the measurements with multiple sources may not be clearly differentiated from the measurements with a single source, contrary to the behavior of C80 or $t_s$ observed in the main orchestra area. Second, the behaviors in C80 and $t_s$ suggest that early sound energy is relatively stronger than late sound energy in the under-balcony area (position C) when compared to those in the main orchestra area (position A). Barron (1995) similarly indicated earlier that balcony overhangs reduce the late (reverberant) sound more than the early. Discussion on early sound energy will be further extended in a later section.

**Sound strength (G)**

The G values at position C measured with multiple directional sources were found
to be lower at 250 through 2k Hz but higher at frequencies below 250 or above 2k Hz than those at the same position but measured with a single omni-directional source. Refer to Figure 4-25. A similar overall tendency was also observed at position A as shown in Figure B-14 in Appendix B, but the G values measured with multiple sources tended to be lower only at 250 and 500 Hz. At mid-frequencies as presented in Table 4-3, the G values at positions A and C measured with multiple sources were lower by 0.2 and 2.7 dB respectively on average compared to those at the same positions measured with a single source. It is not yet clear but this result argues that sound energy coming from an array of multiple directional sources at mid-frequencies is reduced in the under-balcony area more than the one coming from a single omni-directional source. This phenomenon will be clarified in the following discussion and the sound strength at a bass frequency, 125 Hz, will be discussed in the next section.

Figure 4-25. Relative sound strength (G) at position C measured with multiple directional sources.
Table 4-3. Relative sound strength (G) at bass (125 Hz) and mid-frequencies (in dB).

<table>
<thead>
<tr>
<th>Position or source array</th>
<th>Category of comparison</th>
<th>At 125 Hz</th>
<th>At mid (500-1k Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main orchestra area (Position A)</td>
<td>Multiple directional sources relative to single omni-source</td>
<td>6.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Under-balcony area (Position C)</td>
<td>Multiple directional sources relative to single omni-source</td>
<td>5.4</td>
<td>-2.7</td>
</tr>
<tr>
<td>Single omni-directional source</td>
<td>Under-balcony area (position C) relative to main orchestra area (position A)</td>
<td>-3.2</td>
<td>-1.4</td>
</tr>
<tr>
<td>Multiple directional sources</td>
<td>Under-balcony area (position C) relative to main orchestra area (position A)</td>
<td>-3.9</td>
<td>-3.8</td>
</tr>
</tbody>
</table>

Next, comparing the measurements of G at position C to those at position A measured with the same source array, it was found that more reductions occurred in G when measured with multiple directional sources than a single omni-directional source. As shown in Figure 4-25 and Table 4-3 above and Figure B-15 in Appendix B, the relative G values at position C to those at position A measured with multiple sources yielded approximately -4 dB on average over all the octave-band center frequencies and also approximately -4 dB at mid-frequencies. Gade and Rindel (1985) indicated based on their measurements in 21 Danish concert halls that the sound strength decreases linearly by 1.2 to 3.3 dB per distance doubling in the halls. According to their argument, the above reduction in sound strength in the under-balcony area of the PCPA is excessive because the distance of position C is 5 m shorter than double the distance of position A. On the other hand, the relative G values at position C measured with a single source yielded approximately -2 dB on average over all octave-band center frequencies and approximately -1.5 dB at mid-frequencies when compared to those at position A. Refer to Table 4-1 and Figure 4-5 with regard to distances of the receiver positions. When measuring distances from the omni-directional source and from the 16 directional
sources, the increases in distance at position C compared to position A are 10 m and on average 9.7 m, respectively. The increases in distance from the same source array are similar.

These findings can clearly argue that sound energy coming from an array of multiple directional sources lessens in the under-balcony area more than the sound energy coming from a single omni-directional source does. Additionally, this argument expends a discussion that sound energy regardless of frequencies may decrease more and more in the under-balcony area as the number of sound sources, i.e., music performers, increases when compared to sound energy in the main orchestra area for some reasons.

**Bass strength (G\(_{125}\))**

Sound strength at a bass frequency of 125 Hz, which is called G\(_{125}\), is discussed in this section. As shown in Figure 4-26, the G\(_{125}\) values measured with multiple directional sources either at position A or C were found to be much higher than those at the same position measured with a single omni-directional source. One should note again here the location of the subwoofer for the measurements. For the measurements with a single omni-directional source, the subwoofer was positioned next to it, whereas the subwoofer was positioned at the inner corner around the brass instrument group for the measurements with multiple directional sources. At the corner of the stage enclosure, the bass sound from the subwoofer may build up with the help of the nearby surfaces and spread effectively toward the main volume. Another finding is that, as also generally observed in G over frequencies, comparing the G\(_{125}\) values at position C to those at position A measured with the same source array, more reduction occurred in G\(_{125}\) when measured with multiple directional sources than a single omni-directional source.
Figure 4-26. Relative bass strength ($G_{125}$) at positions A and C.

To summarize, first, bass sound energy at 125 Hz either in the main orchestra area or in the under-balcony area was found to be much higher when measured with multiple directional sources than a single omni-directional source. Second, bass sound energy at 125 Hz coming from an array of multiple sources decreased in the under-balcony area more than bass sound energy coming from a single omni-directional source did.

**Early Sound Energy**

Early sound energy derived from impulse response measurements in the under-balcony area is examined further through this section in addition to some discussions made through the previous sections about $C_{80}$ and $t_s$. Two approaches were involved in this extension of examination. One is that the early sound energy over specified time
windows was examined relative to the late sound energy. This concept was designated as
the C index. The other is that the early sound energy over specified time windows was
examined relative to the total sound energy. This second concept was designated as the D
index. The specified time windows in both C and D indices included seven early time
limits of acoustically interest, which are first 10, 20, 50, 80, 100, 150, and 200 ms.

**Early-to-late sound energy (C index)**

The early-to-late energy ratios over 500 to 2k Hz at position C measured with
multiple directional sources were found to be similar to those measured with a single
omni-directional source as presented in Figure 4-27. This result may argue with regard to
the structure of the measured impulse responses that the decay rates in sound energy over
time between these two source arrays are similar or that the integrations of sound energy
over time decrease at a similar rate in the under-balcony area. In other words, the squared
area of the impulses decrease in the under-balcony area at a similar rate over time periods
specified above. On the other hand, at position A, it was found that the early-to-late
energy ratios measured with multiple sources were lower to some degree than those
measured with a single source. Refer to Figure B-16 in *Appendix B*.

Another interesting finding is that the sound energy center of gravity shifted at
around 75 ms in the under-balcony area (position C) when measured with either multiple
directional sources or a single omni-directional source, whereas the center of gravity
shifted at around 100 ms in the main orchestra area (position A). In other words, the
center of sound energy gravity in the under-balcony area is ahead of the one in the main
orchestra area. This finding indicates that early sound energy in the under-balcony area is
relatively stronger when compared to the main orchestra area.
Figure 4-27. Early-to-late sound energy over 500 through 2k Hz at position C.

Figure 4-28. Early-to-late sound energy over 500 through 2k Hz at positions A and C measured with multiple directional sources.
Next, the early-to-late energy ratios at positions A and C measured with multiple sources are compared with each other in Figure 4-28. This presentation shows that the early-to-late energy ratios at position C were approximately 2 to 3 dB higher than those at position A. In case of the measurements with a single source, it was also generally observed that the early-to-late energy ratios at position C tended to be higher than those at position A except for two time windows of 10 and 20 ms. Refer to Figure B-17 in Appendix B. These results confirm that early sound energy in the under-balcony area is relatively stronger when compared to the main orchestra area, regardless of sound source types or arrays used for measurements.

**Early-to-total sound energy (D index)**

![Diagram](image)

Figure 4-29. Early-to-total sound energy over 500 through 2k Hz at position C.

In general, the trends found in the D index are similar to those found in the C index at 500 through 2k Hz over the time windows specified earlier. At position C, the early-to-
total energy ratios measured with multiple directional sources were found to be similar to those measured with a single omni-directional source as shown in Figure 4-29. On the other hand, at position A as shown in Figure B-18 in Appendix B, the early-to-total energy ratios measured with multiple sources tended to be lower to some degree than those measured with a single source. This is because the direct sound predominates in the early spectrum at position A when measured with a single source, resulting in higher early-to-total energy ratios than those measured with multiple sources.

Figure 4-30. Early-to-total sound energy over 500 through 2k Hz at positions A and C measured with multiple directional sources.

Next, the early-to-total energy ratios at positions A and C measured with the same sound source array were compared with each other. Either measured with multiple sources or a single source, the early-to-total energy ratios at position C tended to be higher than those at position A except for two very early time windows of 10 and 20 ms. Refer to Figure 4-30 and Figure B-19 in Appendix B. These results also suggest that the
early sound energy in the under-balcony area is relatively stronger when compared to the main orchestra area, regardless of sound source types or arrays used for measurements. As discussed earlier, early arriving strong local reflections contribute to a degree toward composition of the early sound energy in the under-balcony area.

**Binaural Room Acoustical Parameters**

Up to now, the data measured through a monaural receiver were discussed in assessments of impulse responses, frequency spectra, room acoustical parameters, and early sound energy. In this section, the binaural measurements taken through a dummy head system with built-in two channel microphones are discussed. The following discussions are made on two primary binaural room acoustical parameters of interaural cross-correlation (IACC) and binaural quality index (BQI).

**IACC total (IACC_A)**

At position C as in Table C-5 in *Appendix C* and Figure 4-32, the coefficients in IACC_A over mid- through high-frequencies measured with multiple directional sources varied within 0.09 compared to those measured with a single omni-directional source. However, the average coefficients (IACC_{A3}) at frequencies of 500 through 2k Hz resulted alike. The binaural impulse responses within 1000 ms measured at position C are compared with each other in Figure 4-31. On the other hand, it was found at position A that the IACC_A coefficients measured with multiple sources were approximately 0.1 lower at mid- through high-frequencies than those measured with a single source. The IACC_{A3} at position A measured with multiple sources were approximately 0.08 lower than the one measured with a single source. That is to say, correlation between two signals at both ears measured with multiple sources in the main orchestra area (position
A) seems to be a bit lower compared to the one measured with a single source. Note that lower in correlation or IACC is actually more preferred. The binaural impulse responses within 1000 ms measured at position A are shown in Figure B-20 in Appendix B.

The coefficient in $IACC_{A3}$ at position C averaged over 500 through 2k Hz tended to be lower than the one at position A when measured either with a single source or multiple sources. Particularly when measured with a single source, the $IACC_{A3}$ coefficient at position C resulted approximately 0.15 lower than the one at position A. Refer to Figure 4-33, Table C-5 in Appendix C and Figure B-22 in Appendix B.

![Figure 4-31. Comparison of broad band binaural impulse responses within 1000 ms measured at position C. A) Left channel impulse response measured with a single omni-directional source. B) Right channel impulse response measured with a single omni-directional source. C) Left channel impulse response measured with multiple directional sources. D) Right channel impulse response measured with multiple directional sources.](image-url)
Figure 4-32. IACC total (IACC_A) at position C.

Figure 4-33. IACC total (IACC_A) at positions A and C measured with multiple directional sources.
IACC early (IACC_E)

In case of IACC_E either at position A or C, the coefficients measured with multiple sources tended to be lower at high frequencies than those measured with a single source. However, the average coefficients at 500 through 2k Hz (which is IACC_E3) measured with multiple sources were similar to the one measured with a single source at the same position, which are approximately 0.5 at position A and 0.3 at position C. Refer to Table C-6 in Appendix C, Figure 4-35 and Figure B-24 in Appendix B.

Figure 4-34. Comparison of broad band binaural impulse responses within 100 ms measured at position C. A) Left channel impulse response measured with a single omni-directional source. B) Right channel impulse response measured with a single omni-directional source. C) Left channel impulse response measured with multiple directional sources. D) Right channel impulse response measured with multiple directional sources.
Figure 4-35. IACC early (IACC\(_{E}\)) at position C.

Figure 4-36. IACC early (IACC\(_{E}\)) at positions A and C measured with multiple directional sources.
The coefficient in $IACC_E$ at position C averaged over 500 through 2k Hz tended to be explicitly lower than the one at the position A when measured either with a single source or with multiple sources. The difference in $IACC_{E3}$ between these two positions is approximately 0.2 regardless of measurement source types or arrays. Refer to Figure 4-36 and Table C-6 in Appendix C and Figure B-25 in Appendix B. The broad band early binaural impulse responses within 100 ms measured at position C are compared with each other in Figure 4-34 and those measured at position A are shown in Figure B-23 in Appendix B.

Madaras (1996) indicated that the IACC within 80 ms – which is $IACC_E$ here – for front seats is primarily determined by the level of the direct sound relative to that of the reflections. According to Madaras’ scale-model study, the $IACC_E$ for front seats increases as the level of the direct sound relative to that of the reflections increases. On the other hand, $IACC_E$ for rear seats is less influenced by the level of the direct sound but greatly influenced by the arrival direction of the reflections. Madaras showed that the reflections from the sides generally contribute to producing lower $IACC_E$ and the reflections from the ceiling and front/back walls contribute to producing higher $IACC_E$ for rear seats. Then, the $IACC_E$ at position A in the middle of the main orchestra area in this study may be characterized by both the level of the direct sound relative to that of the reflections and the arrival direction of the reflections. On the contrary, the $IACC_E$ at position C may be largely affected by the reflections horizontally from the sides, resulting in possibly lower $IACC_E$. As shown earlier, at position C, few reflections came from upside. Many reflections were also found to come from behind but most of these reflections came horizontally within 20 degrees from the ear-to-ear axis of a listener at this position.
To summarize the IACC\textsubscript{E3} identified in the under-balcony area when measured with multiple sources, the correlation between two signals at both ears was found to be similar to the one measured with a single source but to be much lower by 0.2 compared to the one in the main orchestra area measured with the same sources.

**IACC late (IACC\textsubscript{L})**

The coefficients in IACC\textsubscript{L} at positions A and C measured with a single omni-directional source as well as multiple directional sources are compared in Table C-7 in Appendix C. As shown in the table, the coefficients over frequencies at position C measured with multiple sources were found to be generally similar to those at the same position measured with a single source and also similar to those at position A measured with multiple sources. At position C, the overall coefficient at 500 through 2k Hz (which is IACC\textsubscript{L3}) measured with multiple sources and the one measured with a single source were 0.13 and 0.14, respectively, which are similar. At position A, the coefficient of IACC\textsubscript{L3} measured with multiple sources and the one measured with a single source were 0.13 and 0.17, respectively. Refer also to the binaural impulse responses within 1000 ms as shown in Figure 4-31 and Figure B-20.

As far as a discussion expands on the basis of the above finding, it can be argued that the IACC\textsubscript{L} identified in the under-balcony area does not seem to be affected by a balcony overhang, a barrier in the vertical dimension. The fact is that, as shown in Figure 4-37, the coefficients in IACC\textsubscript{L3} averaged over 500 through 2k Hz did not significantly vary at six measurement positions throughout the hall. The average and the standard deviation for the single source measurements are approximately 0.155 and 0.025, respectively, and those for the multiple source measurements are approximately 0.13 and
0.023, respectively. Since the arrival direction of the reflections greatly affects IACC early (IACC_E) for rear seats (Madaras, 1996), it is possible to suggest that the nearby geometrical element of a balcony overhang in the vertical dimension contributes to characterizing substantially the IACC early behavior in the under-balcony area rather than the IACC late behavior.

Figure 4-37. IACC_L3 measured throughout the hall.

**Binaural quality index (BQI)**

Lastly, Binaural Quality Index (BQI), which is derived from the coefficient in 1-IACC_E3, is discussed. As shown in Figure 4-38, the BQI value at position C tended to be slightly higher than those obtained at any other measurement positions in the hall and to be about 0.2 higher than the one at position A when measured either with a single omni-directional source or multiple directional sources. The average and the standard deviation for the single source measurements at six positions throughout the hall are approximately
0.62 and 0.077, respectively, and those for the multiple source measurements are approximately 0.58 and 0.075, respectively.

![Figure 4-38. BQI [1-IACC_E3] by measurement position throughout the hall.](image)

As discussed earlier, since IACC_E or BQI is largely determined by arrival direction of the reflections for rear seats and since many early local reflections arrive through narrow incidence angles from a horizontal plane in the under-balcony area, which means that these reflections arrive laterally, these reflections would particularly contribute toward weakening degree of coherence of sounds and hence resulting in lower IACC_E and in higher BQI. Another possible reason is that few high incidence angled reflections coming from above the under-balcony area due to the balcony overhang barrier would consequently yield lower IACC_E or IACC_A for the under-balcony area. The directionality of the reflections in the under-balcony area is further discussed in the later section.
Summary of Typical Room Acoustical Parameters

Single omni-directional source versus multiple directional sources

The results of the typical room acoustical parameters measured in the main orchestra area and in the under-balcony area are summarized in Tables 4-4 and 4-5, respectively. As shown in both tables, the results from the multiple directional source measurements are, in most of the room acoustical parameters, similar to those from the single omni-directional source measurements. Only $C_{80}$ values disagree with each other in the main orchestra area and the $G_{\text{mid}}$ values disagree with each other in the under-balcony area. The features identified in the room acoustical parameters between these source arrays are clarified in the next section with statistical analysis.

Table 4-4. Summary of room acoustical parameters measured in the main orchestra area.

<table>
<thead>
<tr>
<th>Source array</th>
<th>EDT$_{\text{mid}}$ (sec)</th>
<th>RT$_{\text{mid}}$ (sec)</th>
<th>$C_{80}$ (dB)</th>
<th>$G_{\text{mid}}$ (dB)</th>
<th>IACC$_{E3}$</th>
<th>IACC$_{L3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single omni-directional</td>
<td>2.3</td>
<td>2.1</td>
<td>-0.2</td>
<td>-</td>
<td>0.53</td>
<td>0.17</td>
</tr>
<tr>
<td>Multiple directional</td>
<td>2.2</td>
<td>2.2</td>
<td>-1.9</td>
<td>-0.2$^*$</td>
<td>0.50</td>
<td>0.13</td>
</tr>
</tbody>
</table>

$^*$ This value indicates the $G_{\text{mid}}$ relative to the one measured with a single omni-directional source.

Table 4-5. Summary of room acoustical parameters measured in the under-balcony area.

<table>
<thead>
<tr>
<th>Source array</th>
<th>EDT$_{\text{mid}}$ (sec)</th>
<th>RT$_{\text{mid}}$ (sec)</th>
<th>$C_{80}$ (dB)</th>
<th>$G_{\text{mid}}$ (dB)</th>
<th>IACC$_{E3}$</th>
<th>IACC$_{L3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single omni-directional</td>
<td>2.0</td>
<td>2.1</td>
<td>0.8</td>
<td>-</td>
<td>0.30</td>
<td>0.14</td>
</tr>
<tr>
<td>Multiple directional</td>
<td>1.9</td>
<td>2.1</td>
<td>1.1</td>
<td>-2.7$^*$</td>
<td>0.31</td>
<td>0.13</td>
</tr>
</tbody>
</table>

$^*$ This value indicates the $G_{\text{mid}}$ relative to the one measured with a single omni-directional source.

Room averages

The results of the typical room acoustical parameters measured through six positions in the hall are averaged and summarized in this section. The room average values obtained from the single omni-directional source measurements and from the multiple directional source measurements are shown in Table 4-6 and 4-7, respectively,
with their standard deviations. The results of the multiple directional source measurements were found to be similar to those of the single omni-directional source measurements in the room acoustical parameters except $G_{\text{mid}}$. The average $G_{\text{mid}}$ value of the hall measured with multiple directional sources relative to the one measured with a single omni-directional source is 2.1 dB lower. The standard deviation is 0.7 dB. The above summary from this study can argue that the use of a single omni-directional source seems to be effective in measurements of the typical room acoustical parameters such as $\text{EDT}_{\text{mid}}$, $\text{RT}_{\text{mid}}$, $C_{80_{500-2k}}$, $IACC_{E3}$ and $IACC_{L3}$.

Table 4-6. Summary of room acoustical parameters measured with a single omni-directional source in the hall.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\text{EDT}_{\text{mid}}$ (sec)</th>
<th>$\text{RT}_{\text{mid}}$ (sec)</th>
<th>$C_{80_{500-2k}}$ (dB)</th>
<th>$G_{\text{mid}}$ (dB)</th>
<th>$IACC_{E3}$</th>
<th>$IACC_{L3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>2.0</td>
<td>2.1</td>
<td>-0.1</td>
<td>-</td>
<td>0.38</td>
<td>0.16</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.16</td>
<td>0.03</td>
<td>1.0</td>
<td>-</td>
<td>0.08</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 4-7. Summary of room acoustical parameters measured with multiple directional sources in the hall.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\text{EDT}_{\text{mid}}$ (sec)</th>
<th>$\text{RT}_{\text{mid}}$ (sec)</th>
<th>$C_{80_{500-2k}}$ (dB)</th>
<th>$G_{\text{mid}}$ (dB)</th>
<th>$IACC_{E3}$</th>
<th>$IACC_{L3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.9</td>
<td>2.2</td>
<td>0.2</td>
<td>-2.1*</td>
<td>0.42</td>
<td>0.13</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.17</td>
<td>0.04</td>
<td>1.2</td>
<td>0.7</td>
<td>0.08</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* This value indicates the average $G_{\text{mid}}$ relative to the one measured with a single omni-directional source.

**Under-balcony area versus main orchestra area**

The results of the typical room acoustical parameters measured with a single omni-directional source and with multiple directional sources are compared between the main orchestra area and the under-balcony area in Table 4-8 and 4-9, respectively. Regardless of the source array, the results of the typical room acoustical parameters measured in the under-balcony area showed shorter in $\text{EDT}_{\text{mid}}$, higher in $C_{80_{500-2k}}$, lower in $G_{\text{mid}}$ and lower in $IACC_{E3}$. When measured with multiple directional sources, the under-balcony
area was measured with approximately 0.35 sec shorter in EDT_{mid}, 3 dB higher in C80_{500-2k}, 4 dB lower in G_{mid} and 0.2 lower in IACC_{E3}.

Table 4-8. Summary of room acoustical parameters measured with a single omni-directional source in the main orchestra and under-balcony areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>EDT_{mid} (sec)</th>
<th>RT_{mid} (sec)</th>
<th>C80_{500-2k} (dB)</th>
<th>G_{mid} (dB)</th>
<th>IACC_{E3}</th>
<th>IACC_{L3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main orchestra area</td>
<td>2.3</td>
<td>2.1</td>
<td>-0.2</td>
<td>-</td>
<td>0.53</td>
<td>0.17</td>
</tr>
<tr>
<td>Under-balcony area</td>
<td>2.0</td>
<td>2.1</td>
<td>0.8</td>
<td>-1.4*</td>
<td>0.30</td>
<td>0.14</td>
</tr>
</tbody>
</table>

* This value indicates the G_{mid} relative to the one measured with a single omni-directional source.

Table 4-9. Summary of room acoustical parameters measured with multiple directional sources in the main orchestra and under-balcony areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>EDT_{mid} (sec)</th>
<th>RT_{mid} (sec)</th>
<th>C80_{500-2k} (dB)</th>
<th>G_{mid} (dB)</th>
<th>IACC_{E3}</th>
<th>IACC_{L3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main orchestra area</td>
<td>2.2</td>
<td>2.2</td>
<td>-1.9</td>
<td>-</td>
<td>0.50</td>
<td>0.13</td>
</tr>
<tr>
<td>Under-balcony area</td>
<td>1.9</td>
<td>2.1</td>
<td>1.1</td>
<td>-3.8*</td>
<td>0.31</td>
<td>0.13</td>
</tr>
</tbody>
</table>

* This value indicates the G_{mid} relative to the one measured with a single omni-directional source.

**Directional Early Sound Energy Distribution**

Some general ideas on the arrival direction of the early reflections in the under-balcony area can be found in the earlier section of this chapter discussing on the impulse responses at 1k Hz within 100 ms identified through the CATT-Acoustic simulations with a single omni-directional source. See Figure 4-8 through 4-11. As also discussed earlier in Chapter 2, a pilot study of the under-balcony area attempted to identify the directional sound energy distribution with the sound roses. See Figure 2-3. In this section, the directional distribution of the early sound within 100 ms is further discussed with visual inspections on the hedgehogs as well as the sound roses. CATT-Acoustic allows one to produce hedgehog or sound rose plots only with a single source. Therefore, the simulations with a single omni-directional source is discussed here. For better understanding of the directional behavior of the early energy, surface diffusion was not
included in the *hedgehogs* and *sound roses*, which means that only specular reflections were simulated.

The *sound roses* and the *hedgehogs* indicating the directions and strengths of the early specular reflections simulated in the main orchestra area (position A) and in the under-balcony area (position C) within 100 ms are compared with each other in Figures 4-39 and 4-40. The *hedgehogs* are displayed over time at intervals of 20 ms. It is particularly interesting that a great number of early reflections are seen in the *hedgehog* simulated in the under-balcony compared to the one simulated in the main orchestra area. According to a visual inspection of the *sound rose* as well as the *hedgehog*, many of these reflections were found to come from the rear left or right. This finding is also supported by the reflection direction identified from the early impulse response as shown in Figure 4-8.

Figure 4-39. Comparison of sound roses\(^7\): directional early sound energy distribution within 100 ms at 1k Hz only with specular reflections simulated with a single omni-directional source. No surface diffusion is included. A) In main orchestra area (position A). B) In under-balcony area (position C).

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\(^7\) A description on how to read a *sound rose* diagram can be found on page 9.
Figure 4-40. Comparison of hedgehogs\(^8\): directional early sound energy distribution within 100 ms at 1k Hz only with specular reflections simulated with a single omni-directional source. No surface diffusion is included. A) In main orchestra area (position A). B) In under-balcony area (position C).

Furthermore, the \textit{sound rose} in Figure 4-39 (B) suggests that many of the meaningful reflections arrive in the under-balcony area through low incidence angles around a horizontal plane. The sound energy of the reflections projected on the horizontal plane relative to the total energy within 100 ms reaches 94\%, which is much higher than the relative sound energy on the other planes. These early arriving strong horizontal reflections supported by the local geometrical elements such as balcony overhang ceiling (soffit) and rear wall and side walls below the balcony overhang would contribute to enhancing the early energy in the under-balcony area, resulting in a shorter EDT, a higher C80, a shorter \(t\_s\), and a lower IACC\(_E\).

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\(^8\) The head direction is along the time axis. Reflection incidence direction and its strength are coded as the angle and the length of each line. Direct sound and 1\(^{st}\) order specular reflections are drawn with thick lines. – Excerpted from \textit{CATT-Acoustic v8.0} manual.
CHAPTER 5  
PSYCHO-ACOUSTICAL EXPERIMENT AND QUALITATIVE ANALYSIS

This chapter discusses qualitative acoustical assessments of the under-balcony area by means of psycho-acoustic listening tests of room acoustical quality criteria using music playback recordings.

Recording of Music Playback

The method for recording music signals followed similar procedures and techniques to those used in the impulse response measurements, which were discussed in the previous chapter. The same measurement equipment including loudspeakers was used, and the arrangement and system setup were similar to those used to measure the impulse responses except for a few equipment connections including connection of a compact disk player with a mixer. The music signals were binaurally recorded with a single omni-directional sound source as well as with an array of multiple directional sound sources.

Apparatus and Module

The additional equipment used for the music recording included a compact disk player and a program of *SIA-Smaart Acoustic Tools*\(^9\) on a laptop computer. *SIA-Smaart Acoustic Tools* was used for recording the music signals, which were reproduced on a compact disk player. A block diagram of this measurement and equipment setup is shown in Figure 5-1. The music signals were recorded only through the binaural system.

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\(^9\) *SIA-Smaart Acoustic Tools* is an acoustic software program for measurement and analysis of impulse response data or analysis of other audio data in wave file format.
Figure 5-1. Block diagrams of setup for music playback recording. A) Output equipment setup for recording with a single omni-directional loudspeaker. B) Output equipment setup for recording with multiple directional loudspeakers. C) Input equipment setup with 2-channel binaural system.

Music Signals

Three anechoic symphony music pieces obtained from the DENON Anechoic Orchestral Music Recording PG 6006 on a digital compact disk were used for recording in the hall. They are listed as follows:

- Handel’s Symphony No. 6 of “Water Music Suite”: bars 1–11, 21 seconds
- Mozart’s Overture of “Le Nozze di Figaro”: bars 1–18, 16 seconds
- Brahms’ Symphony No. 4 in e minor (Opus 98): bars 354–362 in the 1st movement, 17 seconds
**Recording Locations**

Recording of the music pieces was conducted at five positions of six positions where the impulse responses were measured. The five positions, which were labeled A through E, included one position (position A) in the main central orchestra seating area, three positions (positions B, C and D) in the under-balcony area, and one position (position E) in the lower central balcony area. The receiver locations and distances from the stage were described on pages 38–39 in the previous chapter.

**Recording of Music Signals**

One set of recordings was made for each sound source array. First, the music signals played through a single omni-directional source were binaurally recorded at the positions indicated above. Second, binaural recordings were made with an array of sixteen directional loudspeakers.

**Psycho-Acoustic Listening Test**

The music signals recorded in the performance hall were reproduced in the laboratory for the psycho-acoustic listening tests to qualitatively evaluate room acoustical qualities perceived in the under-balcony area compared to those perceived in the main orchestra area. The music signals recorded with multiple directional sources were, furthermore, evaluated by locations – under-balcony area and main orchestra area – compared to those recorded at the same location with a single omni-directional source.

**Apparatus**

The listening tests were conducted with music signal reproduction through stereo headphones. The equipment used for the tests included a RANE HC-6 headphone...
console; SONY MDR-V600 stereo headphones; and a laptop computer with digital audio player. A block diagram of equipment setup for the listening tests is shown in Figure 5-2.

![Block diagram of setup for listening tests](image)

**Listening Conditions**

The overall sound level at the ear was set at 62 dBA in consideration of comfortable listening level. This level was adjusted through two acoustical programs of *SIA-Smaart Acoustic Tools* and *SONY Sound Forge* with a music signal recorded through the dummy head binaural system wearing the same pair of stereo headphones. The level adjustment was done through two processes. First, the weak music signal in wave format obtained in the PCPA gained 15 dB through the *SONY Sound Forge*. Second, its level was then adjusted to the required level through the *Acoustic Tools*, which was also used for recording the music signal in the hall. Specifically, the level was adjusted to the required level compared to the amplitude of the music signal originally recorded in the hall.

**Test Music Signal**

A 21-second segment presenting the first 11 bars in Handel’s Symphony No. 6 of *Water Music Suite* was used as the test signal. Bech (1990) suggested from the study of methods for design and analysis for listening tests that the length of each stimulus should be in the range of 20 to 40 seconds. In addition, Bech suggested that the sections of the
stimuli should be selected such that the variations in loudness and timbre are minimal within a section. The lengths of the other two music pieces by Mozart and Brahms may be a bit short for one to perceive enough information at once with regard to room acoustical sound qualities. The variations in loudness and timbre are relatively consistent without a major rise or fall and the playing dynamics is also relatively consistent in the music piece by Handel rather than the other music pieces by Mozart and Brahms.

Test Subjects

A total of thirteen subjects with normal hearing sensitivity participated in the tests. Five acousticians and four musicians were among them. The subjects also included three persons who have some or a strong background in architectural acoustics.

Design of Listening Comparison Tests and Evaluation Questionnaire

The listening test involved comparison and evaluation of paired music recordings in terms of room acoustical criteria, which subjectively express qualities of perceived sounds. The test consisted of two major parts: the first part included the preliminary training session; and the second part included the main paired listening comparison test. The need for training sessions was suggested by Bech (1989, 1990). Olive (1994) as well as Bech showed that such preliminary training contributes to reducing different aspects of the subject’s performance and at the same time increasing the subject’s performance to a similar level, and hence maintaining the level of error variance low. The length of test time was designed to complete a test within 30 minutes maximum allotted due to mental fatigue. Bech (1990) suggested that the maximum time limit of a single listening session by a subject, without breaks, should be in the range of 30 minutes to 1 hour depending on the complexity of the test.
**Preliminary listening training**

This training session was designed particularly for lay persons who do not have enough experiences in listening to classical orchestral music or/and who do not have a fair knowledge about the content and vocabulary involved in the main test so that the decision process may be potentially affected while evaluating. The training session would help one to practically understand the meanings of the vocabulary used to assess room acoustical quality criteria in orchestral music and to become familiar with the testing environment. The training session also included a pre-test that provides an opportunity to listen to a few music samples that are also heard in the main test. This training session was given to three subjects including one musician who are not familiar with the vocabulary involved in the main test or have limited knowledge in architectural acoustics.

**Evaluation questionnaire**

The evaluation questionnaire was designed for a paired comparison test. The subjects listened to the paired music recordings and selected one that was perceived more, larger, or stronger in each of the room acoustical quality criteria. Three choices were given, including a choice of *No perceived difference*. Definitions of the room acoustical quality criteria were provided in the questionnaire and verbally explained further as required. The questionnaire format is found in *Appendix D*.

**Format and sequence of main test**

An evaluation questionnaire included one of three different test forms. Each test form consisted of four sets of paired music recordings but in different order. These four sets of parings are categorized in Table 5-1. Two sets of those were composed of a music signal recorded with multiple directional sources and a music signal recorded with a
single omni-directional source. One set was recorded in the main orchestra area (position A) and another set was recorded in the under-balcony area (position C). The other two sets were composed of a music signal recorded at the under-balcony area and a music signal recorded at the main orchestra area. One set was recorded with a single omni-directional source and another set was recorded with multiple directional sources.

Table 5-1. Categories of test sets.

<table>
<thead>
<tr>
<th>Test set</th>
<th>Category of music recording</th>
<th>Category of paired comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Music signals recorded in main orchestra area</td>
<td>Multiple directional sources versus Single omni-directional source</td>
</tr>
<tr>
<td>2</td>
<td>Music signals recorded in under-balcony area</td>
<td>Multiple directional sources versus Single omni-directional source</td>
</tr>
<tr>
<td>3</td>
<td>Music signals recorded with a single omni-directional source</td>
<td>Under-balcony area versus Main orchestra area</td>
</tr>
<tr>
<td>4</td>
<td>Music signals recorded with multiple directional source</td>
<td>Under-balcony area versus Main orchestra area</td>
</tr>
</tbody>
</table>

**Results and Discussions**

Each two music signals paired in each of the above four sets were subjectively compared with each other in order to identify room acoustical qualities perceived in the under-balcony area. In-depth discussions were made of the acoustical qualities identified in the under-balcony area particularly when simulated with music reproductions recorded with multiple directional sources. The results were further compared to those from the numerical measurements that were described in Chapter 4.

**Multiple Directional Sources versus Single Omni-Directional Source**

**Music signals recorded in main orchestra area**

This section discusses the result obtained from listening test set 1 as categorized in Table 5-1. Listening test set 1 compares the music signal from multiple directional
sources with the one from a single omni-directional source where both signals were
recorded in the main orchestra area. The results are summarized in Table 5-2.

<table>
<thead>
<tr>
<th>Room acoustical qualities</th>
<th>Responses, %</th>
<th>Room acoustical qualities</th>
<th>Responses, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single</td>
<td>Multiple</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>Loudness</td>
<td>23.1 (3)</td>
<td>46.2 (6)</td>
<td>30.8 (4)</td>
</tr>
<tr>
<td>Reverberance</td>
<td>23.1 (3)</td>
<td>69.2 (9)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Clarity</td>
<td>23.1 (3)</td>
<td>76.9 (10)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Warmth</td>
<td>84.6 (11)</td>
<td>15.4 (2)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Intimacy</td>
<td>38.5 (5)</td>
<td>53.8 (7)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Spaciousness</td>
<td>23.1 (3)</td>
<td>61.5 (8)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Envelopment</td>
<td>38.5 (5)</td>
<td>53.8 (7)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Overall impression</td>
<td>38.5 (5)</td>
<td>53.8 (7)</td>
<td>7.7 (1)</td>
</tr>
</tbody>
</table>

The numbers in parentheses indicate the number of subjects responded to the given category.

** The response category of Single indicates the music signal recorded with a single omni-directional source and that of Multiple indicates the music signal recorded with multiple directional sources.

At 95% ($p < 0.05$) significance level, the results argue that reverberance (or
liveness) and clarity were perceived more from the signal recorded with multiple sources
than the one recorded with a single source, whereas warmth was perceived more from the
signal recorded with a single source than the one recorded with multiple sources. As
shown in Table 5-2, about 70% (9 subjects) and 77% (10 subjects) responded to the
signal recorded with multiple sources with regard to perceived reverberance and clarity,
respectively. About 85% (11 subjects) responded to the signal recorded with a single
source with regard to perceived warmth.

Interestingly, the results of the above three room acoustical qualities were found to
contradict those of the quantitative measurements. First, the RT, an objective measure of
reverberance, varied little at each octave band regardless either of listener position or of
sound source array. Refer to the section discussing the results from the reverberation time
measurements included in Chapter 4 with Table 4-2 and Figure 4-19. In the main orchestra, the average RT at mid-frequencies measured with a single source was 2.13 sec and the one measured with a multiple sources was 2.22 sec, which means that the difference is only about 0.1 sec. In addition, these RTs are little different from the hall average RTs. Aside from the RT results, the late reverberant energy relative to the early energy or conversely the early energy relative to the late reverberant energy may explain the result from the qualitative evaluation of reverberance. The C80 at 500-2k Hz measured with multiple sources relative to a single source is approximately -2 dB and the $t_s$ across octave bands measured with multiple sources relative to a single source is approximately 25 ms on average.

Second, the numerical measure of clarity identified in the main orchestra showed that the C80s measured with a single source were 1.8 dB higher on average across octave band center frequencies from 125 through 4k Hz and 1.7 dB higher on average over 500 through 2k Hz than those measured with multiple sources. See Table C-3 in Appendix C. According to Reichardt, *et al.* (1974) and Beranek (1996), the sense of clarity depends on tempo or speed of music and number of notes in a musical passage. The tempo or speed of music and the number of notes are rather constant through the 21-second music signal used for the listening tests. Then, some other possibilities that explain this contradiction may be found from the measured impulse responses. A number of successive early sounds including both direct sounds and reflections without any delay longer than 10 ms, which are found in the impulse response measured with multiple sources, may contribute to perceived clarity.
Third, the numerical measure of warmth showed that the $G_{125}$ measured with multiple sources was as much as 6 dB higher than the one measured with a single source. Accordingly more warmth should be perceived from the music signal recorded with multiple sources. This issue is further discussed later in another section with some other possibilities to clarify this contradiction.

On the other hand, at 90% ($p < 0.1$) significance level, the result from the listening tests adds an argument that spaciousness (apparent source width) was perceived by about 62% (8 subjects) more from the music signal recorded with multiple sources. In fact, the $\text{IACC}_{E3}$ coefficients, a numerical measure of spaciousness, measured with multiple sources or a single source were about the same, which is about 0.5. See Table C-6 in Appendix C. Again, a number of successive early reflections with multiple direct sounds that are produced from the multiple sources may contribute to perceived spaciousness.

**Music signals recorded in under-balcony area**

This section discusses the result obtained from listening test set 2 as categorized in Table 5-1. Listening test set 2 compares the music signal from multiple directional sources with the one from a single omni-directional source where both signals were recorded in the under-balcony area. The results are summarized in Table 5-3.

At 95% significance level, the results argue that loudness, clarity and intimacy were perceived more from the signal recorded with multiple sources than the one recorded with a single source. On the contrary, as also observed in the results from test set 1, the signal recorded with a single source was perceived as warmer than the one recorded with multiple sources. As shown in Table 5-3, about 70% (9 subjects) and 77% (10 subjects) rated the signal recorded with multiple sources with regard to perceived
loudness and intimacy, respectively. All the subjects rated the signal recorded with multiple sources with regard to perceived clarity but rated the one recorded with a single source with regard to perceived warmth.

Table 5-3. Results from test set 2.

<table>
<thead>
<tr>
<th>Room acoustical qualities</th>
<th>Single</th>
<th>Multiple</th>
<th>No perceived difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness</td>
<td>15.4 (2)</td>
<td>69.2 (9)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Reverberance</td>
<td>46.2 (6)</td>
<td>38.5 (5)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Clarity</td>
<td>0.0 (0)</td>
<td>100.0 (13)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Warmth</td>
<td>100.0 (13)</td>
<td>0.0 (0)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Intimacy</td>
<td>23.1 (3)</td>
<td>76.9 (10)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Spaciousness</td>
<td>38.5 (5)</td>
<td>46.2 (6)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Envelopment</td>
<td>38.5 (5)</td>
<td>53.8 (7)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Overall impression</td>
<td>38.5 (5)</td>
<td>61.5 (8)</td>
<td>0.0 (0)</td>
</tr>
</tbody>
</table>

* The numbers in parentheses indicate the number of subjects responded to the given category.

** The response category of Single indicates the music signal recorded with a single omni-directional source and that of Multiple indicates the music signal recorded with multiple directional sources.

Contrary to expectations, the qualitative results of perceived clarity, warmth and loudness were not supported by the quantitative measurements. First, the average C80, a numerical measure of clarity, at 500 through 2k Hz measured with multiple sources in the under-balcony was only 0.3 dB higher than the one measured with a single source. See Table C-3 in Appendix C. A possibility that may support this qualitative result contradicting the quantitative result was discussed in the previous section.

Second, G_{125}, a numerical measure of warmth, measured with multiple sources was in fact 5.4 dB higher than the one measured with a single source. Again, this contradiction issue in perceived warmth between the quantitative result and the qualitative result is further discussed in a later section.
Figure 5-3. Contours of perceived loudness in under-balcony area conceptually approximated following Zwicker and Fastl’s ideas. A) Contour of loudness perceived from the impulse response measured with a single omni-directional source. B) Contour of loudness perceived from the impulse response measured with multiple directional sources.

Third, the average G, a numerical measure of loudness, at mid-frequencies measured with multiple sources was actually about 3 dB lower than the one measured with a single source. See Table 4-3. Then, why did a majority of the subjects perceive the music signal recorded with multiple sources as louder? A possible answer can be found from Zwicker and Fastl (1999). Zwicker and Fastl described that 1) the initial peak in a level-time function impulse response does not produce the highest peak in its loudness-time function; 2) echoes (strong reflections) and reverberation contribute strongly to perceived loudness; 3) sound energy lower than $1/10^{th}$ of the previous sound does not add loudness. In addition, a strong following reflection within 30 ms is integrated by the ear.
and increases loudness (Hass, 1972). From the impulse response measured in the under-balcony area with multiple sources then, a number of successive strong early sounds including both direct sounds and reflections without any delay longer than 10 ms would contribute to increasing the perceived loudness. The contour of subjective loudness perceived from the impulse response measured with a single source is compared to the one perceived from the impulse response measured with multiple sources as shown in Figure 5-3. Both impulse responses were measured in the under-balcony area and the contours of perceived loudness were conceptually approximated following Zwicker and Fastl’s ideas specified.

The result of perceived intimacy can be discussed with the numerical measurements of ITDG. As defined earlier, the ITDG is the time interval between the direct sound and the first reflection and can be determined by geometrical measurements or from impulse responses. See Chapter 2 for the details. This conventional ITDG measurement is based on single source radiation. As also discussed in Chapter 4, now the question is how the ITDG can be determined from a measurement with multiple sources as opposed to a single source. Further, how can a correlation be defined between ITDG and perceived acoustical intimacy when multiple sound sources are present such as an orchestra group with various music instruments? Obviously, there will be multiple direct sounds and multiple first reflections at a listener position. It may not be reasonable to determine an ITDG based on the time interval between the very first direct sound of the multiple direct sounds and the very first reflection because they might not originate from the same source, meaning that those sounds may be totally different.
Table 5-4. Initial time delays in the main orchestra area (position A) obtained from the
*CATT-Acoustic* simulated multiple source impulse response. (in milliseconds)

<table>
<thead>
<tr>
<th>Source positions</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>W1</th>
<th>W2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26</td>
<td>37.5</td>
<td>31</td>
<td>19</td>
<td>18.5</td>
<td>44</td>
<td>42</td>
<td>30.5</td>
<td>37.5</td>
</tr>
</tbody>
</table>

continued

<table>
<thead>
<tr>
<th>Source positions</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>P1</th>
<th>P2</th>
<th>Average</th>
<th>Std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>36.5</td>
<td>17</td>
<td>24</td>
<td>5.5</td>
<td>8</td>
<td>14</td>
<td>25.1</td>
<td>12.4</td>
</tr>
</tbody>
</table>

* The tagged source positions are found in Figure 4-3 in Chapter 4.

Table 5-5. Initial time delays in the under-balcony area (position C) obtained from the
*CATT-Acoustic* simulated multiple source impulse response. (in milliseconds)

<table>
<thead>
<tr>
<th>Source positions</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>W1</th>
<th>W2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>21</td>
<td>11</td>
<td>17</td>
<td>15</td>
<td>15</td>
<td>22.5</td>
<td>23</td>
<td>23</td>
<td>21</td>
</tr>
</tbody>
</table>

continued

<table>
<thead>
<tr>
<th>Source positions</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>P1</th>
<th>P2</th>
<th>Average</th>
<th>Std dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8</td>
<td>23.5</td>
<td>22.5</td>
<td>23</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>15.5</td>
<td>8.7</td>
</tr>
</tbody>
</table>

* The tagged source positions are found in Figure 4-3 in Chapter 4.

An alternative way to determine a single number of ITDG from the multiple
sources then is to find an average value of the time intervals between each of the direct
sounds and its source corresponding first reflection. For example, from this study, the
ITDGs in the main orchestra area and in the under-balcony area obtained from the
multiple sources are shown in Table 5-4 and 5-5, respectively. The average ITDG in the
main orchestra area is 25.1 ms. The average ITDG in the under-balcony area is 15.5 ms,
which is shorter. On the other hand, when measured with a single source, the ITDG in the
main orchestra area is 30 ms, whereas the ITDG in the under-balcony area is 24 ms. This
result suggests that the average ITDG measured with multiple directional sources is
shorter than the ITDG measured with a single omni-directional source in either the main
orchestra area or the under-balcony area. This is true because many sound sources when
measured with multiple sources were positioned close to the nearby surfaces of the stage enclosure.

The ITDG obtained in an alternative way can support the qualitative result that sound from an array of multiple directional sources is perceived as being more intimate than in sound from a single omni-directional source particularly in the under-balcony area. However, this argument should be clarified. Some additional discussions are found in a later section.

**Under-Balcony Area versus Main Orchestra Area**

**Music signals recorded with a single omni-directional source**

This section discusses the result obtained from listening test set 3 as categorized in Table 5-1. Listening test set 3 compares the music signal obtained in the under-balcony area with the one obtained in the main orchestra area where both signals were recorded with a single omni-directional source. The results are summarized in Table 5-6.

At 95% significance level, the results argue that the music signal recorded in the main orchestra area is more preferable than the one recorded in the under-balcony area. As shown in Figure 5-7, about 70% (9 subjects) rated the signal recorded in the main orchestra area with regard to perceived overall impression. At 90% significance level, the results add an argument that reverberance was perceived by about 62% (8 subjects) more from the music signal recorded in the main orchestra area. In fact, the quantitative result of the RT does not support this qualitative result. As discussed earlier, the RT varied little at each octave band regardless either of listener position or of sound source array. See Table 4-2 and Table C-2 in *Appendix C*. The average RTs at mid-frequencies were approximately 2.1 sec in both the main orchestra area and the under-balcony area. Again,
regarding the early energy relative to the late reverberant energy, the C80 at 500-2k Hz measured in the under-balcony area is approximately 1 dB higher relative to the main orchestra area, meaning that the main orchestra area is relatively more reverberant.

Table 5-6. Results from test set 3.

<table>
<thead>
<tr>
<th>Room acoustical qualities</th>
<th>Main orchestra area</th>
<th>Under-balcony area</th>
<th>No perceived difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness</td>
<td>53.8 (7)</td>
<td>0.0 (0)</td>
<td>46.2 (6)</td>
</tr>
<tr>
<td>Reverberance</td>
<td>61.5 (8)</td>
<td>15.4 (2)</td>
<td>23.1 (3)</td>
</tr>
<tr>
<td>Clarity</td>
<td>30.8 (4)</td>
<td>53.8 (7)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Warmth</td>
<td>53.8 (7)</td>
<td>15.4 (2)</td>
<td>30.8 (4)</td>
</tr>
<tr>
<td>Intimacy</td>
<td>46.2 (6)</td>
<td>38.5 (5)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Spaciousness</td>
<td>38.5 (5)</td>
<td>53.8 (7)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Envelopment</td>
<td>61.5 (8)</td>
<td>30.8 (4)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Overall impression</td>
<td>69.2 (9)</td>
<td>15.4 (2)</td>
<td>15.4 (2)</td>
</tr>
</tbody>
</table>

* The numbers in parentheses indicate the number of subjects responded to the given category.
** The response category of Main orchestra area indicates the music signal recorded in the main orchestra area and that of Under-balcony area indicates the music signal recorded in the under-balcony area.

Music signals recorded with multiple directional sources

This section discusses the result obtained from listening test set 4 as categorized in Table 5-1. Listening test set 4 compares the music signal obtained in the under-balcony area with the one obtained in the main orchestra area where both signals were recorded with multiple directional sources. The results are summarized in Table 5-7.

At 95% significance level, the results argue that reverberance, spaciousness and envelopment were perceived more from the signal recorded in the main orchestra area than the one recorded in the under-balcony area. On the contrary, clarity was perceived more from the signal recorded in the under-balcony area. As shown in Table 5-7, all the subjects rated the signal recorded in the main orchestra area with regard to perceived reverberance and about 85% (11 subjects) rated the same signal with regard to
spaciousness (ASW) or envelopment. About 70% (9 subjects) sensed more clarity from the signal recorded in the under-balcony area.

Table 5-7. Results from test set 4.

<table>
<thead>
<tr>
<th>Room acoustical qualities</th>
<th>Main orchestra area</th>
<th>Under-balcony area</th>
<th>No perceived difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loudness</td>
<td>53.8 (7)</td>
<td>23.1 (3)</td>
<td>23.1 (3)</td>
</tr>
<tr>
<td>Reverberance</td>
<td>100.0 (13)</td>
<td>0.0 (0)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Clarity</td>
<td>23.1 (3)</td>
<td>69.2 (9)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Warmth</td>
<td>61.5 (8)</td>
<td>23.1 (3)</td>
<td>15.4 (2)</td>
</tr>
<tr>
<td>Intimacy</td>
<td>46.2 (6)</td>
<td>46.2 (6)</td>
<td>7.7 (1)</td>
</tr>
<tr>
<td>Spaciousness</td>
<td>84.6 (11)</td>
<td>15.4 (2)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Envelopment</td>
<td>84.6 (11)</td>
<td>15.4 (2)</td>
<td>0.0 (0)</td>
</tr>
<tr>
<td>Overall impression</td>
<td>61.5 (8)</td>
<td>38.5 (5)</td>
<td>0.0 (0)</td>
</tr>
</tbody>
</table>

The numbers in parentheses indicate the number of subjects responded to the given category.

The response category of Main orchestra area indicates the music signal recorded in the main orchestra area and that of Under-balcony area indicates the music signal recorded in the under-balcony area.

The qualitative result of perceived clarity was supported by the quantitative measurement, whereas the qualitative results of reverberance, spaciousness and envelopment contradicted their primary quantitative measurements. First, the result of perceived clarity is supported by the numerical measurement of the C80. The C80 at 500-2k Hz measured in the under-balcony area is 3 dB higher than the one measured in the main orchestra area, which means that reverberant energy is relatively less in the under-balcony area. See Table C-3 in Appendix C. This tendency in early-to-late sound energy also supports the result of perceived reverberance, though the numerical measurement of the RT is not supportive in this regard. The tendency in RT in the hall was described earlier. See Table 4-2.

Second, revisiting the quantitative measurements of IACC early, the coefficient of IACC_{E3} in the under-balcony area was about 0.2 lower than the one in the main orchestra
area regardless of the sound source array. See Table C-6 in Appendix C. As known, as the coefficient of IACC\textsubscript{E3} decreases or as the value of BQI (1-IACC\textsubscript{E3}) increases, sounds are perceived as more spacious (Berenek, 2004). In addition, the values of lateral energy fraction (LF) from the CATT-Acoustic simulations as shown in Table 5-8 are 6 to 12% higher across octave-band center frequencies in the under-balcony area than the main orchestra area. The LF\textsubscript{E4} in the under-balcony area is approximately 8% higher than the one in the main orchestra area. According to the above quantitative results, sounds in the under-balcony area should be perceived as more spacious than the main orchestra area.

On the other hand, the result of spaciousness gains some support from sound strength among the factors contributing to spaciousness, which were described in Chapter 2. The G values in the under-balcony area are approximately 4 dB lower on average across octave-band center frequencies than those in the main orchestra area.

Table 5-8. Lateral energy fraction (LF) from CATT-Acoustic simulations with multiple sources. (in percentage)

<table>
<thead>
<tr>
<th>Receiver location</th>
<th>Octave-band center frequencies (Hz)</th>
<th>LF\textsubscript{E4} (125-1k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main orchestra area (Position A)</td>
<td>125</td>
<td>250</td>
</tr>
<tr>
<td>Under-balcony area (Position C)</td>
<td>19.9</td>
<td>20.1</td>
</tr>
</tbody>
</table>

Third, comparison of the qualitative assessment on perceived envelopment with its possible quantitative measure of IACC late becomes a subtle issue to discuss. The reason is that the coefficients of IACC\textsubscript{L3} were measured almost consistently regardless of sound source array and measurement locations. See Figure 4-37. Among the factors affecting perceived envelopment as discussed in Chapter 2, the reverberant energy that is relatively lower in the under-balcony area may explain the reason why envelopment was perceived
less in the area compared to the main orchestra area. Some other issues involved in the qualitative assessments of spaciousness and envelopment are discussed in the next section.

At 90% significance level, the result can add an argument that the music signal recorded in the main orchestra area is perceived warmer than the one recorded in the under-balcony area. This result of perceived warmth is simply supported by the quantitative measurements of bass strength ($G_{125}$). The $G_{125}$ measured in the under-balcony area is about 4 dB lower relative to the one measured in the main orchestra area. See Table 4-3.

**Further Discussions**

**Issues in listening test method**

One note should be stated with regard to the listening test method involved in this study. The listening test using headphones might not be an effective way to qualitatively evaluate some of the room acoustical qualities, particularly spaciousness (ASW) and envelopment. From normal listening, a sound image is usually perceived around a listener’s head as external, whereas a sound image from listening through headphones is mostly situated in the middle of a listener’s head, which is called In-Head Localization, or IHL (Toole, 1970). The subjects might have difficulties to assess qualities of perceived spaciousness or envelopment due to this in-head localization resulting from headphone listening. The absence of room reverberation and visual information occurred by headphone reproduction may also affect psychological judgment (Toole, 1970). The absence of room reverberation, however, is not always the case nowadays because of advanced headphone technologies in that regard. Judgment on perceived intimacy might
also be affected by the sound that is reproduced through headphones.

**Assessment on perceived warmth**

An in-depth discussion on some other possibilities that may support the result from the room acoustical quality assessment of warmth is extended in this section. The discussion includes a few alternative quantitative measurements such as $G_{250}$ and $G_{\text{low}}$ and an analysis of the actual low frequency contents presented in the original anechoic music sample and its room playback recordings that were used for the listening test.

In addition to $G_{125}$, $G$ at low frequency bands of 125 and 250 Hz ($G_{\text{low}}$) and $G$ at 250 Hz ($G_{250}$) can be considered as the alternative measures of perceived warmth. As shown in Table 5-9, the $G_{\text{low}}$ measured with multiple directional sources in either the main orchestra area or the under-balcony area was approximately 1 dB higher than the one measured with a single omni-directional source. The results of $G_{\text{low}}$ from this study also contradicted the qualitative result that warmth was perceived more from the music recording with a single omni-directional source. However, the results of $G_{250}$ indicated an agreement with this qualitative result. The $G_{250}$ values measured with a single omni-directional source was 3 to 4 dB higher than those measured with multiple directional sources.

Table 5-9. Alternative measures of perceived warmth.

<table>
<thead>
<tr>
<th>Location</th>
<th>Category</th>
<th>$G_{\text{low}}$</th>
<th>$G_{250}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main orchestra area</td>
<td>Multiple sources relative to single source</td>
<td>1.2</td>
<td>-3.8</td>
</tr>
<tr>
<td>Under-balcony area</td>
<td>Multiple sources relative to single source</td>
<td>1.1</td>
<td>-3.3</td>
</tr>
</tbody>
</table>

Next, the actual bass sound energy presented in the original anechoic music sample of Handel’s 21 second segment of *Water Music Suite* and its playback recordings in the under-balcony area of the hall was identified. The latter music recordings included the
room frequency responses. First, the bass frequency distributions over time at the octave-band of 63 Hz using a band-pass filter were compared with each other in Figure 5-4. As shown in Figure 5-4 (A), the bass sound energy at the octave-band of 63 Hz presented in the original anechoic music sample is not strong most of the time. As shown in Figure 5-4 (B), however, this bass energy was enhanced in the music signal recorded with a single omni-directional source to some degree possibly by the room. On the contrary, as shown in Figure 5-4 (C), this bass energy rather weakened in the music signal recorded with multiple directional sources. Note that the frequency response of the loudspeakers used for the multiple source tests is actually poor at frequencies below 100 Hz. Also note that the location of the subwoofer for each sound source array might also affect the room responses.

Figure 5-4. Comparison of spectral distributions at the octave-band of 63 Hz of the music signals that were used for the listening tests. A) Original anechoic recording music sample. B) Music signal recorded in the under-balcony area of the hall with a single omni-directional source. C) Music signal recorded in the under-balcony area of the hall with multiple directional sources.
Figure 5-5. Comparison of spectral distributions at the octave-band of 125 Hz of the music signals that were used for the listening tests. A) Music signal recorded in the under-balcony area of the hall with a single omni-directional source. B) Music signal recorded in the under-balcony area of the hall with multiple directional sources.

Figure 5-6. Comparison of spectral distributions at the octave-band of 4k Hz of the music signals that were used for the listening tests. A) Music signal recorded in the under-balcony area of the hall with a single omni-directional source. B) Music signal recorded in the under-balcony area of the hall with multiple directional sources.

The bass frequency distributions at the octave-band of 125 Hz and the treble frequency distributions at the octave-band of 4k Hz presented in the music recordings were compared with each other in Figures 5-5 and 5-6. As shown in Figure 5-5, the music
signal recorded with a single omni-directional source contained more energy over time at the octave-band of 125 Hz relative to the one recorded with multiple directional sources. In addition, in the music signals recorded with a single omni-directional source as shown in Figures 5-5 (A) and 5-6 (A), the 125 Hz octave-band bass energy was stronger than the 4k Hz octave-band treble energy most of the time. On the contrary, as shown in Figure 5-6, the music signal recorded with multiple directional sources contained more energy over time at the high octave-band of 4k Hz relative to the one recorded with a single omni-directional source. In the music signals recorded with multiple directional sources as shown in Figures 5-5 (B) and 5-6 (B), the 4k Hz octave-band treble energy was relatively stronger over time than the 125 Hz octave-band bass energy. The above discussion would be the primary reason explaining why warmth was sensed more from the music signal recorded with a single omni-directional source compared to the one recorded with multiple directional sources.
CHAPTER 6
CONCLUSIONS

The study aimed to quantitatively and qualitatively identify the acoustics of under-balcony areas in music performance halls using multiple directional sources (16 directional loudspeakers) that represented the orchestral sound propagation patterns. It is possible to argue that the results from the measurements with these multiple directional sources, in many acoustical analysis respects, disagree with those from the measurements with a single omni-directional source that is used conforming to conventional measurement protocol for room acoustical measurements. Remarkable differences were observed in time-domain impulse responses, frequency content, spectral distribution, directional distribution of the early reflections, sound energy density over time, and in a few room acoustical parameters such as sound strength (G). However, contrary to the differences found in the above observations, many of the quantitative measurements of the room acoustical parameters with multiple directional sources were similar to those measurements with a single omni-directional source. Although some variations were observed across frequencies, the results of the typical room acoustical indicators generally found in literature such as EDT\textsubscript{mid}, RT\textsubscript{mid}, C80\textsubscript{500-2k}, IACC\textsubscript{E3} (or BQI) and IACC\textsubscript{L3} were found to be similar. Results from the qualitative assessments showed that some of the room acoustical qualities of the reproduction of the music signals recorded with multiple directional sources were perceived noticeably different from those recorded with a single omni-directional source. In the under-balcony area at 95% significance level, the music recording with multiple directional sources was perceived more in
loudness, reverberance and intimacy but less in warmth. In the main orchestra area at 95% significance level, the music recording with multiple directional sources was perceived more in reverberance and clarity but less in warmth. Some results from these qualitative assessments were, however, found to contradict their quantitative measures.

The quantitative analysis of the measurements with multiple directional sources compared to those with a single omni-directional source is further summarized as follows where both were measured in the under-balcony area. First, the measured time-domain impulse responses showed many strong early pulses possibly representing the multiple direct sounds and some strong early reflections. The computer simulated impulse responses showed that the direct sounds, which are strong but variable in amplitude, arrived at a listener over an extended time period, for example, a 30 ms time period at 1k Hz. The computer simulations also showed that the reflections arrived one after another without time delays longer than 3 ms, resulting in a dense sound energy distribution over time. Accordingly, a single number of ITDG can not be simply identified from this multiple source impulse response. An alternative way as described in the body text measures the average ITDG of all the time intervals between the direct sounds and their corresponding first arriving reflections. Second, the frequency response showed some variations in amplitude across frequencies but is not clearly differentiated from the one measured with a single omni-directional source. Third, the results from the room acoustical parameters including binaural parameters showed interestingly that variations in only G are of significance across frequencies compared to those measured with a single omni-directional source. Particularly, the $G_{125}$ was approximately 5 dB higher relative to the one measured with a single source. Contrary to expectations, variations in
other room acoustical parameters seem to be less significant. The difference in the EDTs at mid-frequencies was only 0.1 second or so. The RTs varied little within 0.15 seconds across frequencies, indicating those were within 10% margin. The difference in the C80s at 500 through 2k Hz was only 0.3 dB. The $t_s$ varied at low through mid-frequencies but did not significantly vary overall. The coefficients in either IACC_A or IACC_E varied within 0.1 at higher frequencies from 1k Hz but the average coefficients at 500 through 2k Hz were almost same with each other. Fourth, the early sound energy indices of C and D showed to be similar to those measured with a single omni-directional source.

The quantitative analysis of the measurements in the under-balcony area is compared to the main orchestra area. Both locations were measured with multiple sources. First, the time-domain impulse responses showed that relatively larger early pulses were observed in the under-balcony area over the first 100 ms. On the other hand, the early reflections arrive in the main orchestra area through variable directions in the vertical and horizontal dimensions. According to sound roses and hedgehogs as well as arriving direction of the early reflections identified from the early impulse responses that were simulated with a single source, a number of strong early reflections were seen in the under-balcony area. These reflections came through a narrow incidence angle (a maximum incidence angle of 33 degrees at position C in the under-balcony area) limited by the balcony overhang and few early reflections were identified to come from the main ceiling or under-balcony ceiling within 100ms. These early arriving strong lateral reflections contribute to enhancing the early energy in the under-balcony area, resulting in a shorter EDT, a higher C80, a shorter $t_s$, a higher LF and a lower IACC_E. Second, the frequency responses showed that sound energy clearly decreases in the under-balcony
area across frequencies, significantly at low and high frequencies: 3 to 10 dB lower at low frequencies and 5 to 20 dB lower at high frequencies than the main orchestra area. The reduction tendency in sound energy in the under-balcony area is supported by the result from the room acoustical parameter of G. The G values decreased by approximately 4 dB on average across octave-band center frequencies relative to the main orchestra area. Third, the results from the room acoustical parameters in the under-balcony area showed shorter EDTs, higher C80s, shorter $t_s'$, lower G values, higher LFs and lower IACC$_E$ or higher BQI coefficients across octave-band center frequencies relative to the main orchestra area. The under-balcony area was measured with approximately 0.35 sec shorter in EDT$_{mid}$, 3 dB higher in C80 at 500 through 2k Hz, 30 ms shorter on average in $t_s$ across octave-band center frequencies, 4 dB lower in G$_{mid}$, 4 dB lower in G$_{125}$, and 0.2 lower in IACC$_{E3}$. A similar overall tendency was also observed in the single omni-directional source measurements when compared between two areas. Fourth, the early sound energy indices of C and D increased in the under-balcony area.

The qualitative analysis of perception of the music signals recorded with multiple directional sources is compared to perception of those recorded with a single omni-directional source where the signals were recorded in the under-balcony area. Some qualitative assessments resulted from the listening tests agreed to the quantitative measurements of the corresponding room acoustical parameters but some assessments did not agree. Among those room acoustical qualities, the perceptions in loudness, clarity and warmth of sounds were found to contradict the quantitative measurements in the corresponding parameters of G, C80 and G$_{125}$, respectively. The sound from multiple directional sources was perceived more in loudness and clarity and perceived less in
warmth than the sound from a single omni-directional source. However, the average G at mid-frequencies is actually about 3 dB lower and the $G_{125}$ is much higher by 5 dB than those measured with a single omni-directional source. In this case, the perceived loudness contours approximated from the impulse responses following Zwicker and Fastl’s ideas may be helpful for identification of acoustical quality. A number of strong early sounds and dense sound energy distribution produced by multiple sources may affect perceived loudness in this regard. The average C80 at 500 through 2k Hz was actually similar to the one measured with a single omni-directional source. A number of strong successive direct and reflected sounds densely spaced with each other that were found in the early impulse response measured with multiple sources may affect perceived clarity. From the listening tests, it was found that the sound from multiple sources was perceived more intimately than the sound from a single source. The average ITDG measured from each of the multiple directional sources was approximately 9 ms shorter than the ITDG measured from the single omni-directional source, although the interpretation of the alternative way to measure the ITDG from the multiple source tests leaves uncertain in this study. Some strong early local reflections coming from the nearby surfaces and densely distributed early sound energy including multiple direct sounds may also contribute toward building up perceived intimacy.

The qualitative analysis of perception of the music signals obtained in the under-balcony area is summarized below compared to perception of those obtained in the main orchestra area where the signals were recorded with multiple sources. Among room acoustical qualities, the perceptions in reverberance, spaciousness (apparent source width) and envelopment of the sounds were found to contradict the quantitative
measurements in the corresponding parameters of RT, IACC\textsubscript{E3} and IACC\textsubscript{L3}, respectively. The sound in the under-balcony area was perceived less in reverberance, spaciousness and envelopment relative to the sound in the main orchestra area at 95% significance level. However, the actual values of RT\textsubscript{mid} and IACC\textsubscript{L3}, quantitative measures of reverberance and envelopment, respectively, varied little within 5% margin regardless of the measurement positions. The IACC\textsubscript{E3} lower by 0.2 relative to the main orchestra area should yield more perceived spaciousness from the sound in the under-balcony area but it did not. The reverberant energy that is relatively lower in the under-balcony area affects envelopment to be perceived less compared to the main orchestra area.

**Overall Summary and Applications**

The above findings can argue that the use of a single omni-directional source seems to remain effective in acoustical measurements but only in measurements of the typical room acoustical parameters as mentioned above. However, the room acoustical parameters alone should not be the acoustical representative characterizing a performance hall or a specific area such as the under-balcony area. The primary reason is that the quantitative measures of the room acoustical parameters did not always support the results of the qualitative assessments. Therefore, for accurate acoustical assessments, the multiple directional sources can be used as measurement sound sources and attention should be carefully paid to other acoustical analysis respects such as analyses on structures of time-domain impulse responses, frequency-domain responses and spectral distributions, sound energy distributions and density over time, directional distributions of early reflections, and the like. In this case, types, frequency responses, and directionalities of the sound sources (loudspeakers) need to be specified or standardized.
To summarize the under-balcony acoustics measured with multiple directional sources, first, reduction in sound energy occurs across frequencies from low through high frequencies. Second, there are a number of strong early reflections mostly coming laterally and few reflections coming from upside. The overhang limits distribution of sounds. Third, this second result contributes to shorter early decay times (EDT), shorter center times ($t_c$), higher early-to-late sound energy index (C80), higher lateral energy fraction (LF) and lower early interaural cross-correlation ($\text{IACC}_E$) compared to the main orchestra area. Fourth, the sound qualities are perceived with more clarity but less reverberance, spaciousness (source width) and envelopment relative to the main orchestra area at 95% significance level. At 90% significance level, warmth is perceived less in the under-balcony area.

To increase reverberation and low frequency energy in the under-balcony area for better perception of reverberance, warmth, spaciousness and envelopment, the area should not be restricted by the overhang barrier. Several ways to increase the acoustical qualities include 1) increase of the opening height (H) of the balcony overhang in consideration of cut-off frequency limited by the vertical dimension, 2) decrease of the depth (D) and maintaining a lower D/H ratio, and 3) some absorption or diffusion treatment on the rear side walls and under-balcony ceiling as well as on the rear wall to reduce too strong early sounds relative to the late sounds. Items (1) and (2) allow more reverberation from the main volume including some reflections in the vertical dimension, providing better distribution of sounds in directions.

**Future Studies**

First, some other issues such as listening test method and sound energy density
over time should be further taken into account to identify the qualitative assessments. Listening through headphones can produce a sound image localized in the middle of a listener’s head, affecting judgment on perceived sound qualities. Second, the method of recording the music signals with multiple sources also needs to be refined. The use of multi-track music sample and adjustment of output levels according to the musical instrument groups are to be included in the future studies. Third, listening tests in the actual hall comparing sounds from the multiple directional sources with those from the single omni-directional source can be within the future studies. Fourth, for determining accuracy of multiple source measurements, acoustical measurements of an actual orchestra performance can be conducted and compared with acoustical measurements using equipment for multiple source acoustical analysis.
Figure A-1. EDTs in the PCPA as the position moves back toward the under-balcony area.
Figure A-2. C80s in the PCPA as the position moves back toward the under-balcony area.
Figure A-3. *CATT-Acoustic* simulated LFCs in the PCPA as the position moves back toward the under-balcony area.
Figure B-1. Broad-band impulse responses within 3 s at position A. A) Measured with a single omni-directional source. B) Measured with multiple directional sources.
Figure B-2. Broad-band impulse responses within 500 ms at position A. A) Measured with a single omni-directional source. B) Measured with multiple directional sources.
Figure B-3. Early impulse response at 1k Hz within 100 ms at position A simulated with multiple directional sources. 1<sup>st</sup> order reflections: sounds that reflect off one surface before arriving at the receiver position, 2<sup>nd</sup> and 3<sup>rd</sup> order reflections: sounds that reflect off two or three surfaces before arriving at the receiver position. Direct sounds in order from the earliest: S4, S1, S5, S2, S3, S6, S7, W1, W2, B2, B1, B4, B3, B5, P2, and P1 (these tag numbers are defined in Figure 4-3).
Figure B-4. Examples of the early reflection paths to position A from the main ceiling or ceiling reflector or from the ceiling above the stage in longitudinal section views (not to scale).
Figure B-5. Frequency responses at positions A and C measured with a single omni-directional source.
Figure B-6. Early decay times (EDT) measured at position A.
Figure B-7. Early decay times (EDT) at positions A and C measured with a single omni-directional source.
Figure B-8. Reverberation times (RT) measured at position A.
Figure B-9. Reverberation times (RT) at positions A and C measured with a single omni-directional source.
Figure B-10. Early-to-late sound energy index (C80) measured at position A.
Figure B-11. Early-to-late sound energy index (C80) at positions A and C measured with a single omni-directional source.
Figure B-12. Center times ($t_c$) measured at position A.
Figure B-13. Center times ($t_c$) at positions A and C measured with a single omni-directional source.
Figure B-14. Relative sound strength (G) at position A measured with multiple directional sources to a single omni-directional source.
Figure B-15. Relative sound strength (G) at position C measured with a single omni-directional source to position A measured with the same source.
Figure B-16. Early-to-late sound energy over 500 through 2k Hz at position A.
Figure B-17. Early-to-late sound energy over 500 through 2k Hz at positions A and C measured with a single omni-directional source.
Figure B-18. Early-to-total sound energy over 500 through 2k Hz at position A.
Figure B-19. Early-to-total sound energy over 500 through 2k Hz at positions A and C measured with a single omni-directional source.
Figure B-20. Comparison of broad-band binaural impulse responses within 1000 ms measured at position A. A) Left channel impulse response measured with a single omni-directional source. B) Right channel impulse response measured with a single omni-directional source. C) Left channel impulse response measured with multiple directional sources. D) Right channel impulse response measured with multiple directional sources.
Figure B-21. IACC total (IACCₐ) at position A.
Figure B-22. IACC total (IACC_A) at positions A and C measured with a single omni-directional source.
Figure B-23. Comparison of broad-band binaural impulse responses within 100 ms measured at position A. A) Left channel impulse response measured with a single omni-directional source. B) Right channel impulse response measured with a single omni-directional source. C) Left channel impulse response measured with multiple directional sources. D) Right channel impulse response measured with multiple directional sources.
Figure B-24. IACC early (IACC$_{E}$) at position A.
Figure B-25. IACC early (IACC$_E$) at positions A and C measured with a single omnidirectional source.
### APPENDIX C
SUPPLEMENTARY TABLES TO ROOM ACOUSTICAL MEASUREMENTS

#### Table C-1. Early decay times at positions A and C (in second).

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
<th>At mid (500-1k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Single</td>
<td>63 1.35 1.81 2.02 2.48 2.16 1.71 1.38 0.80</td>
<td>2.32</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>1.18 1.82 2.28 2.38 2.07 1.78 1.44 0.90</td>
<td>2.23</td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>1.59 1.96 1.86 2.21 1.81 1.77 1.36 0.80</td>
<td>2.01</td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>2.24 2.30 1.57 1.92 1.83 1.70 1.16 0.68</td>
<td>1.88</td>
</tr>
</tbody>
</table>

#### Table C-2. Reverberation times at positions A and C (in second).

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
<th>At mid (500-1k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Single</td>
<td>63 1.82 1.85 2.30 2.24 2.02 1.87 1.71 1.19</td>
<td>2.13</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>2.05 2.22 2.24 2.32 2.11 2.01 1.60 1.17 2.22</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>1.98 2.05 2.21 2.21 2.04 2.13 1.80 1.31 2.13</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>2.07 1.96 2.06 2.24 2.04 2.01 1.63 1.19 2.14</td>
<td></td>
</tr>
</tbody>
</table>

#### Table C-3. Early-to-late sound energy index (C80) at positions A and C (in dB).

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
<th>At 500-2k</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Single</td>
<td>63 0.6 0.4 -5.2 -1.5 0.6 0.4 1.3 5.4</td>
<td>-0.2</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>-2.1 -3.6 -5.5 -3.2 -1.6 -1.0 -0.1 2.0</td>
<td>-1.9</td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>3.4 -0.9 -1.7 -1.6 2.1 1.8 2.1 4.9</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>-2.0 -2.7 -1.0 0.2 0.7 2.3 3.5 5.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

#### Table C-4. Center times ($t_s$) at positions A and C (in millisecond).

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Single</td>
<td>109 126 171 168 119 110 94 53</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>137 165 189 174 146 132 115 85</td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>113 155 153 155 108 108 99 64</td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>181 173 132 140 122 108 92 68</td>
</tr>
</tbody>
</table>
Table C-5. IACC total (IACC_A) at positions A and C.

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
<th>At 500-2k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>63</td>
<td>125</td>
</tr>
<tr>
<td>A</td>
<td>Single</td>
<td>0.97</td>
<td>0.93</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>0.96</td>
<td>0.91</td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>0.98</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table C-6. IACC early (IACC_E) at positions A and C.

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
<th>At 500-2k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>63</td>
<td>125</td>
</tr>
<tr>
<td>A</td>
<td>Single</td>
<td>0.97</td>
<td>0.94</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>0.96</td>
<td>0.92</td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>0.99</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Table C-7. IACC late (IACC_L) at positions A and C.

<table>
<thead>
<tr>
<th>Position</th>
<th>Source array</th>
<th>Octave-band center frequency (Hz)</th>
<th>At 500-2k</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>63</td>
<td>125</td>
</tr>
<tr>
<td>A</td>
<td>Single</td>
<td>0.97</td>
<td>0.92</td>
</tr>
<tr>
<td>A</td>
<td>Multiple</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>C</td>
<td>Single</td>
<td>0.97</td>
<td>0.89</td>
</tr>
<tr>
<td>C</td>
<td>Multiple</td>
<td>0.98</td>
<td>0.95</td>
</tr>
</tbody>
</table>
APPENDIX D
QUESTIONNAIRE USED FOR LISTENING TESTS

Listen to the paired music recordings and evaluate which one is preferably perceived in terms of each of the room acoustical criteria. In other words, select which one is louder; which one is more reverberant; which one is more intimate; and so on. You can listen as many times as you wish. There are 4 test sets of paired music recordings.

Please check or circle one of three choices given for each of the room acoustic quality criteria.

Test Set X

<table>
<thead>
<tr>
<th>LOUDNESS</th>
<th>A</th>
<th>B</th>
<th>No perceived difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>REVERBERANCE (LIVENESS)</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>CLARITY</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>WARMTH</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>INTIMACY</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>SOURCE WIDTH</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>ENVELOPMENT</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
<tr>
<td>OVERALL IMPRESSION</td>
<td>A</td>
<td>B</td>
<td>No perceived difference</td>
</tr>
</tbody>
</table>

COMMENTS:
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Youngmin Kwon’s educational background stands out with a BS in architectural engineering at Hanyang University in Seoul, S. Korea and an MS in building sciences with an emphasis in architectural acoustics at Rensselaer Polytechnic Institute, Troy, New York. With his master’s thesis, he was awarded the Robert B. Newman Medal from the Acoustical Society of America (ASA). In addition, he received a certificate in the Graduate Summer Program in Acoustics at Pennsylvania State University, State College, Pennsylvania.

His primary focus lies in architectural as well as acoustical analysis and design of performance spaces such as concert halls, auditoria, opera houses, theaters, recital halls, music studios, and the like. Building noise control and environmental acoustics are also within his interests.