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QUALITATIVE ANALYSIS OF UNDER-BALCONY ACOUSTICS IN CONCERT HALLS WITH MULTIPLE DIRECTIONAL SOURCES

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ABSTRACT
Following the previous work on quantitative analysis of under-balcony acoustics in music performance halls with multiple directional sources (16 directional loudspeakers) [Kwon and Siebein, J. Acoust. Soc. Am. 120, 3263 (A) (2006)], this paper discusses qualitative acoustical assessments of the under-balcony area. Psycho-acoustical listening tests were conducted for the qualitative assessments using the music signals binaurally recorded in a performance hall with the same source array. The room acoustical qualities – such as loudness, reverberance, clarity, warmth, spaciousness, envelopment, etc. – were evaluated in comparison to those perceived in the main orchestra area. The results showed that, at 95% significance level, the room acoustical qualities are perceived with more clarity but less reverberance, spaciousness and envelopment relative to the main orchestra area. The room acoustical qualities were further evaluated in comparison to those perceived from a single omni-directional source.

INTRODUCTION
The use of only one single omni-directional sound source for acoustical measurements or simulations may be unrealistic in investigation of the acoustics of a concert hall because the actual music performances mostly consist of multiple sources. 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 attempted to identify the under-balcony acoustics in concert halls more precisely under a realistic acoustic field condition that is close to an orchestral symphony performance with a number of diverse sound source types and radiation patterns. Following the previous work on quantitative analysis, psycho-acoustical listening tests were conducted to qualitatively assess acoustics of the under-balcony area using the music signals binaurally recorded in the hall with the same source array of multiple directional sources, which was used for the impulse response measurements for quantitative analysis. The room acoustical qualities – such as loudness, reverberance, clarity, warmth, spaciousness, envelopment, etc. – were evaluated in comparison to those perceived in the main orchestra area. The room acoustical qualities were further evaluated in comparison to those perceived from a single omni-directional source.

Measurement venue
The above recordings were taken in the Phillips Center for the Performing Arts (PCPA) in Gainesville, Florida. 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 center 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.

RESEARCH METHOD

A total of sixteen directional sound sources (loudspeakers) 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.

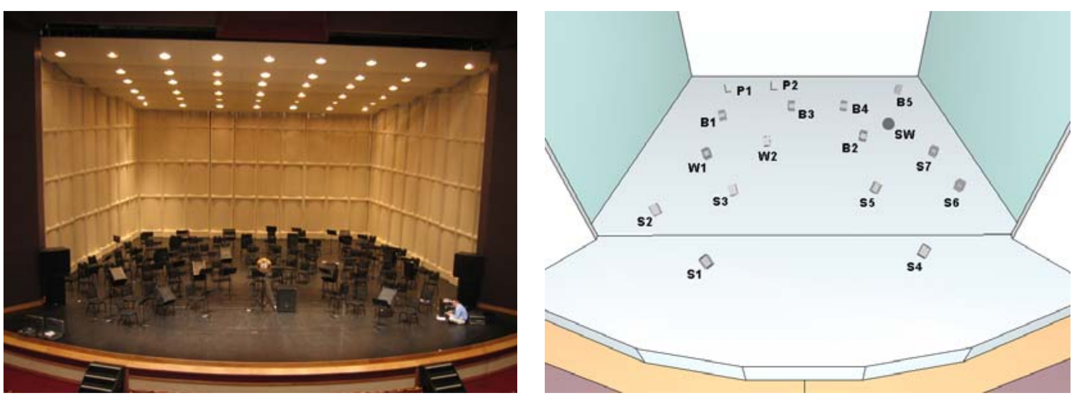
A psycho-acoustic experiment for qualitative assessment of the sounds involved a listening comparison test, which enables one to evaluate room acoustical qualities perceived in the under-balcony area relative to those perceived in the main orchestra seating area. Music playback was binaurally recorded 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.

RECORDING OF MUSIC PLAYBACK

The music signals were binaurally recorded with a single omni-directional sound source (dodecahedron loudspeaker) as well as with an array of multiple directional sound sources in the main orchestra area and the under-balcony area.

Loudspeaker setup

The layout of a dodecahedron omni-directional loudspeaker with a subwoofer next to it for the single source music recording is shown in Figure 1 (A). As shown in Figure 1 (B), on the other hand, 16 directional loudspeakers also with a subwoofer for the multiple source music recording were placed according to the positions of each musical instrument group: 7 speakers for the string group; 2 speakers for the woodwind group; 5 speakers for the brass group; 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.



(A) (B)

Figure 1. 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.

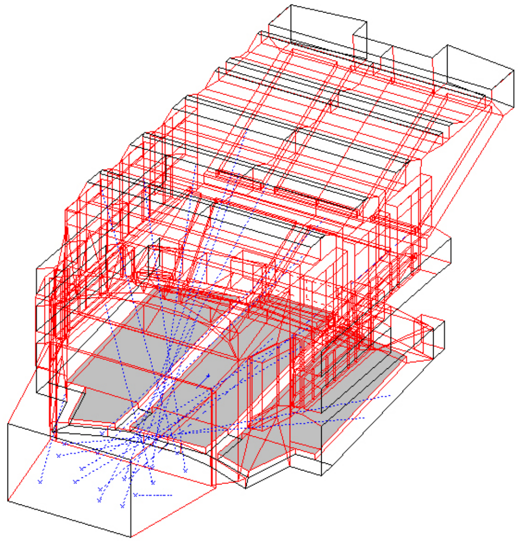


Figure 2. Loudspeaker source directions in the *CATT-Acoustic* 3D model

Loudspeaker source directions

As shown in Figure 2, 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.

Music signal and recording locations

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. Recording of this music piece was taken at two locations: one location in the main central orchestra seating area and one location in the deep under-balcony area.

PSYCHO-ACOUSTIC LISTENING TEST

The music signals recorded in the performance hall were reproduced through stereo headphones 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.

Design of listening test

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 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*. A total of thirteen subjects with normal hearing sensitivity participated in the tests.

RESULTS AND DISCUSSIONS

Under-balcony area versus main orchestra area

This section discusses the results obtained from the listening tests comparing the music signal recorded in the under-balcony area with the one recorded in the main orchestra area where both signals were recorded with multiple directional sources. The results are summarized in Table 1.

Table 1. Results: under-balcony area versus main orchestra area

Room acoustical qualities	Responses, %		
	Main orchestra area	Under-balcony area	No perceived difference
Loudness	53.8 (7)	23.1 (3)	23.1 (3)
Reverberance	100.0 (13)	0.0 (0)	0.0 (0)
Clarity	23.1 (3)	69.2 (9)	7.7 (1)
Warmth	61.5 (8)	23.1 (3)	15.4 (2)
Intimacy	46.2 (6)	46.2 (6)	7.7 (1)
Spaciousness	84.6 (11)	15.4 (2)	0.0 (0)
Envelopment	84.6 (11)	15.4 (2)	0.0 (0)
Overall impression	61.5 (8)	38.5 (5)	0.0 (0)

* 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.

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 1, 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.

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 approximately 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.

Second, the coefficient of IACC early ($IACC_{E3}$) in the under-balcony area was measured about 0.2 lower than the one in the main orchestra area regardless of the sound source array. As known, as the coefficient of $IACC_{E3}$ decreases or as the value of Binaural Quality Index (BQI or $1\text{-}IACC_{E3}$) increases, sounds are perceived as more spacious (Berenek, 2004). In addition, the values of lateral energy fraction (LF) from the *CATT-Acoustic* simulations are 6 to 12% higher across octave-band center frequencies in the under-balcony area than the main orchestra area. The LF_{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. 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.

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 $IACC_{L3}$ were measured almost consistently regardless of sound source array and measurement locations. Among the factors affecting perceived envelopment, reverberant energy that is relatively lower in the under-balcony area may explain more or less 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 should be discussed further.

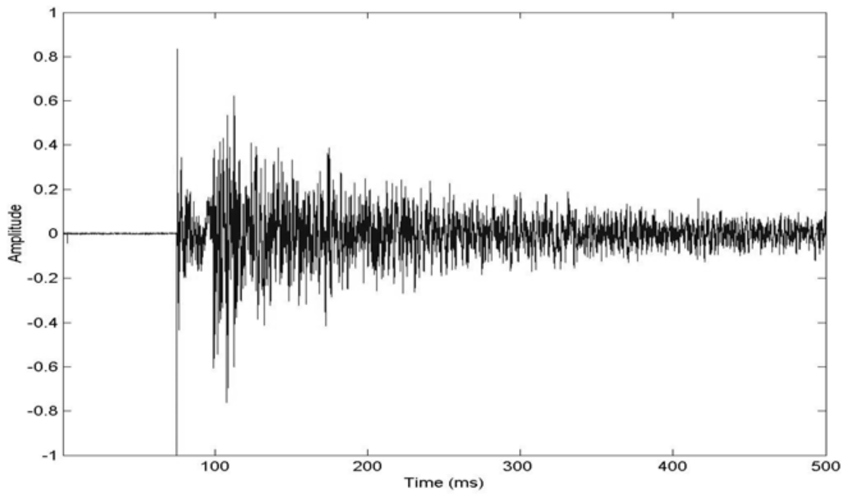
Multiple directional sources versus single omni-directional source

This section discusses the results obtained from the listening tests comparing 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 2.

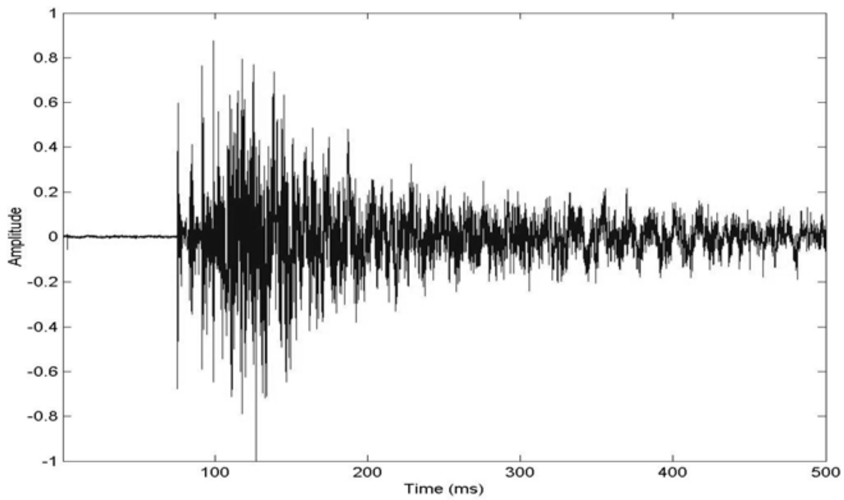
Table 2. Results: multiple directional sources versus single omni-directional source

Room acoustical qualities	Responses, %		
	Single	Multiple	No perceived difference
Loudness	15.4 (2)	69.2 (9)	15.4 (2)
Reverberance	46.2 (6)	38.5 (5)	15.4 (2)
Clarity	0.0 (0)	100.0 (13)	0.0 (0)
Warmth	100.0 (13)	0.0 (0)	0.0 (0)
Intimacy	23.1 (3)	76.9 (10)	0.0 (0)
Spaciousness	38.5 (5)	46.2 (6)	15.4 (2)
Envelopment	38.5 (5)	53.8 (7)	7.7 (1)
Overall impression	38.5 (5)	61.5 (8)	0.0 (0)

[*] 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.



(A)



(B)

Figure 3. Broad-band impulse responses measured within 500 ms. A) Measured with a single omni-directional source. B) Measured with multiple directional sources.

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, the signal recorded with a single source was perceived as warmer than the one recorded with multiple sources. As shown in Table 2, 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.

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. Some possibilities that explain the contradiction in perceived loudness or clarity may be found from the measured impulse responses. Figure 3 compares the impulse response measured with multiple directional sources with the one measured with a single omni-directional source. As shown in Figure 3, a number of successive strong early sounds and dense sound energy distribution that are found in the impulse response measured with multiple sources may contribute to perceived loudness and clarity.

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