A LOUDSPEAKER ORCHESTRA FOR CONCERT HALL STUDIES

J. Pätynen
S. Tervo
T. Lokki

Helsinki University of Technology, Department of Media Technology, P.O.Box 5400, FI-02015 TKK, Finland

1 INTRODUCTION

Concert halls are commonly compared to each other with the help of some acoustical parameters, such as reverberation time or clarity[1-4]. These parameters, however, each provide only a single value computed from an impulse response. In concert halls, the impulse responses are often measured with an omnidirectional sound source and microphone. However, such a single source is far from a typical sound source - an orchestra. Therefore, a wide sound source would intuitively be preferable in studying the concert hall acoustics. This article describes a proposal for a loudspeaker setup that mimics a symphony orchestra. Several loudspeakers are installed on a concert hall stage as a loudspeaker orchestra. Individually recorded anechoic instrument tracks of orchestral works are then played through the loudspeakers as an ensemble in order to produce an impression of a symphony orchestra. The authors are not aware that a loudspeaker orchestra of this scale would have been used in acoustical music reproduction. Instead, large loudspeaker setups for electro-acoustic music performances have been described[5-7]. In this article the loudspeaker setup is demonstrated in a single concert hall, although the system is particularly designed to be repeatable in other halls as well.

This paper is organized as follows. First, the loudspeaker setup as well as the concert hall is described. Then, subjective opinions gathered with in-situ listening of the loudspeaker orchestra are presented. Finally, possible error sources are discussed and future enhancements of the system are proposed.

2 LOUDSPEAKER SETUP

The loudspeaker orchestra was installed in a chamber music hall. The hall has approximately 400 seats and the general shape of the hall is a shoebox[8]. In addition, the audience area rises moderately. The size of the stage is 16.8 x 10.5 m (WxD) while the total length of the hall is 29 m. The total height to the ceiling at the stage is approximately 12.3 m. Acoustically reflective panels above the stage have been suspended at the height of 8.2 m.

The used loudspeaker setup consisted of 24 loudspeakers. The following types of loudspeakers were used. Genelec 1029A loudspeakers were used in 17 positions, Genelec 8030A in five, and Genelec model 1032A in two positions. The plan of the loudspeakers was designed to roughly represent a typical symphony orchestra with the American seating arrangement[9]. The overall positioning is shown in Fig. 1 with the corresponding notation for the loudspeakers. In the layout, loudspeaker nos. 11-13, 14-16, 17-19 and 20-22 stand for the first and second violin players, violas and cellos, correspondingly. In addition, loudspeaker nos. 23 and 24 are positioned to represent the contrabass players. Complete list of loudspeakers in different positions is described in Table 1. It should be noted that loudspeaker no. 9 appears twice in Fig. 1, as it was used for percussion and second timpani tracks as well as for the soprano soloist (see Table 2). The thick bars in Fig. 1 represent one meter each. Thus, the maximum width and depth of the loudspeaker layout was 13 m and 7 m, respectively. Such an arrangement was devised for the repeatability of the experiment in other halls in the future.

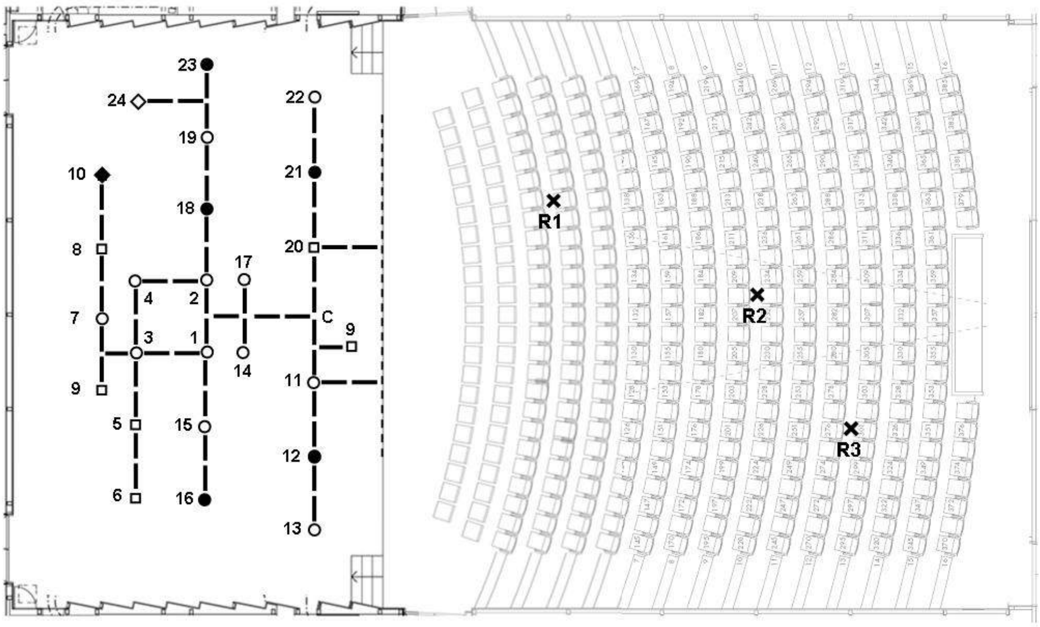

Figure 1 Plan of the loudspeaker arrangement and recording positions R1-R3. The hall is 29 m long and 16.8 m wide. Model 1029A loudspeakers are denoted with circles. Model 8030A are indicated by rectangles and model 1032A with diamonds. A filled symbol indicates a tilted loudspeaker. Conductor's stand, located between loudspeakers 11 and 20, is marked with a letter C.

Figure 2 The stage with loudspeaker orchestra seen from recording position R2.

Position(s)	Model	Orientation	h_{center}
1, 2, 3, 4, 7, 11, 13, 14, 15, 17, 19	1029A	Forward	1.25 m
22	1029A	Forward	0.70 m
12, 16, 18, 21, 23	1029A	Upward, on floor	-
5, 6	8030A	135 deg. clockwise	1.15 m
8, 9	8030A	Forward	1.25 m
20	8030A	Forward	0.70 m
10	1032A	45 deg. upwards, 45 deg. clockwise	0.75 m
24	1032A	45 deg. clockwise	0.70 m

Table 1 Loudspeaker models in different positions. h_{center} indicates the height of the acoustical axis of the loudspeaker from the floor.

LPS	Assigned part(s)	Mozart	Beethoven	Bruckner	Mahler
1	flutes	1	2	3	3
2	oboes	-	2	3	3
3	clarinets	1	2	3	4
4	bassoons	1	2	3	3
5	French horns	I	I	I-IV	I-IV
6	French horns	II	II	V-VIII	V-VII
7	trumpets	-	2	3	4
8	trombones	-	-	3	3
9	soprano / percussions / II timpani	1/-/-	-	-	-/1/1
10	I timpani / tuba	-	1/-	1/1	1/1
11-24	The division of string parts is explained in more detail in Table 4.				

Table 2 Anechoic instrument tracks in the loudspeakers and the number of parts in each recording.

Instruments	Used main direction
flute, percussion, violin, viola	front, slightly above musician head level
soprano	front, at the singer head level
oboe, clarinet, trumpet, trombone	downwards, direction of the bell
bassoon, tuba	high left, direction of the bell
French horn	back right, direction of the bell
timpani	front
cello, contrabass	front, below the floor level

Table 3 Selected signal direction for the recorded instruments. The directions are indicated as seen by the musician.

Loudspeakers were calibrated at their final positions one at a time by using 100-5000 Hz band-limited white noise. The sensitivity of each loudspeaker was adjusted so that the calibration signal produced $L_{p,A}$ = 87±1 dB at one meter distance on the acoustical axis. Loudspeaker nos. 12, 16, 18, 21, and 23 were calibrated in upright position. The reason for their final positioning on the floor was to direct more high frequencies towards the ceiling and to counteract the relatively high directivity of the loudspeakers. This is discussed more thoroughly in the next section.

In our recent work we recorded all the instruments of a symphony orchestra in an anechoic chamber[10]. Each instrument part was individually recorded with 20 high-quality condenser microphones positioned evenly around the instrument with an average radius of 2.13 m. Thus, the sound of each instrument was captured simultaneously in multiple directions. The recording programme comprised four excerpts of orchestral works: Mozart's Aria of Donna Elvira from *Don Giovanni*; Beethoven's Symphony no. 7, I movement; Bruckner's Symphony no. 8, II movement and Mahler's Symphony no. 1, IV movement.

In the loudspeaker orchestra, the anechoic recordings were used so that out of the 20 recorded signals only one was selected for each instrument. Therefore, the most representative direction for each instrument has to be chosen, despite the variation in sound radiation characteristics. This was accomplished subjectively by listening to the signals in different directions and comparing the spectrum of the recordings. The “main” directions were ultimately selected by the strongest sound and the highest level at mid and high frequencies, and also by the facing direction of the musician, unless other alternative was clearly feasible. Used recording directions for each instrument are presented in Table 3.

Each instrument part, except for the strings, were recorded once, which corresponds with the correct number of players in an authentic orchestra. Since a symphony orchestra has as many as 16 violinists for first violins alone, a large number of recordings of single parts would be needed for the string instruments. However, only single takes of one of each string instrument were recorded in most cases. Therefore, in loudspeaker orchestra the strings were amplified by stacking the identical tracks in order to gain an acceptable balance between instrument groups. Additionally, the sound levels of the recorded musicians were slightly different. This was compensated by manually calibrating the instrument levels. The final composition and adjustments of the loudspeaker channels is presented in Table 4. Notation 'div I,II' means that at least two parts were recorded. For Bruckner's symphony, multiple takes were combined in string instrument parts. Notation '2x' or '3x' indicates that combined, identical recordings were stacked in one loudspeaker track, thus adding 6 or 10 dB to the channel sound level, respectively. The need of multiplication was estimated subjectively before conducting the experiment. The increase or decrease in sound level indicated in the table refers to the adjustments performed based on the in-situ listening in the hall. Since the first and second flute parts were exactly the same in Bruckner and Mahler, the second flute was substituted by increasing the level of the first flute by 3 dB in order to avoid tuning issues. The same procedure was performed for piccolo part in Mahler's symphony. This is indicated in the first row in Table 4.

Multiplying correlating signals increases the sound level by 6 dB, while fully uncorrelating signals result in a 3 dB level increase. With recorded signals, such as two consecutive takes of the same instrument part, the increase is close to 3 dB. It is noticeable that the stacking performed to the string parts results in a high number of players compared to the typical number in a symphony orchestra. For instance, the multiplication of first violins in Mahlers's symphony equates to 10 mixed uncorrelated signals (representing violinists) for both *divisi* in each loudspeaker channel.

3 IN-SITU LISTENING

A small number of experienced acousticians participated in evaluating the loudspeaker orchestra in-situ in the otherwise empty hall. The loudspeaker orchestra was evaluated by listening to the recorded works in several positions in the audience. The setup was adjusted to the final configuration partially according to the suggestions. The verbal comments and impressions in-situ are described and discussed here.

The first observations on the setup were related to the positioning and orientation of the loudspeakers. Two modifications to the original plan were performed according to the in-situ listening. First, in spite of the multiplication of the string instrument parts discussed earlier, the strings were seen to sound somewhat dull. Originally the strings loudspeakers were rotated to point at the conductor's position. Due to the remark we ended up turning them to point directly to the audience. This procedure was seen to improve the brightness of the strings noticeably. Second, the sound field was characterized to be too horizontal, thus not having sufficiently reflections from the ceiling and the panels above the stage. For this reason one loudspeaker for each strings group (nos. 12, 16, 18, 21, and 23) were laid on the floor facing up, as seen in Fig. 1. As the directivity of the loudspeakers is strong at higher frequencies, this was expected to increase the vertical impression of the hall for the strings. The turned loudspeakers are visible in Fig. 2. To further increase the effect, the output level of the corresponding loudspeakers were increased for Beethoven and Bruckner (see Table 4).

Another note on the strings was that the number of used loudspeakers appeared to be too small, since the strings did not have the authentic feel of blending the sound of multiple players. The strings were also localized too accurately to the loudspeakers. This was apparent especially in front rows of the audience area. In the back of the hall the blending was much better. However, this was seen difficult to characterize explicitly. Besides the relatively small number of loudspeakers, a possible reason could be the limited number of recorded takes for the string parts. Also the small amount of diffusing elements on the stage could be partially the cause, since the only significant objects comprised the stands and the loudspeakers itself. The most likely reason is a combination of these matters.

The overall impression was seen to sound too thin for an authentic orchestra. For this reason, the overall sound level of the instrument tracks was increased. The levels were raised by 3 dB for Mozart's aria and Beethoven's symphony, and by 6 dB for Bruckner's and Mahler's symphonies.

LPS	Assigned part(s)	Mozart	Beethoven	Bruckner	Mahler
1	flutes			I +3dB	I +3dB
2	clarinets	+2dB			
3…8					
9	soprano	+2dB			
10	I timpani / tuba				
11	I violins	2x	div I,II; 2x	div I,II[a]; 3x, +4dB	div I,II; 3x
12	I violins		div I,II; 2x, +2dB	div I,II[a]; 3x, +7dB	div I,II; 3x
13	I violins		div I,II; 2x	div I,II[a]; 2x, +4dB	div I,II; 3x
14	II violins		div I,II; 2x	div I,II[a]; 2x, +4dB	div I,II; 2x
15	II violins		div I,II; 2x	div I,II[a]; 2x, +4dB	div I,II; 2x
16	II violins		div I,II; +2dB	div I,II[a]; 2x, +7dB	div I,II; 3x
17	violas		div I,II; 2x	div I,II[a]; 3x	div I,II; 2x, +3dB
18	violas		div I,II; 2x	div I,II[a]; 3x, +3dB	div I,II; 2x, +3dB
19	violas		div I,II	div I,II[a]; 3x	div I,II; 2x, +3dB
20	cellos	-3dB	+3dB	div I,II; 2x	2x, +3dB
21	cellos		+5dB	div I,II; 2x, +3dB	2x, +3dB
22	cellos	-3dB	+3dB	div I,II; 2x	2x, +3dB
23	contrabasses	-3dB	div I,II; -3dB	div I,II; 2x	2x, +3dB
24	contrabasses	-3dB	div I,II; -3dB	div I,II; 2x	2x, +3dB
[a] Two recordings for each part					

Table 4 Final multiplication and amplification of instrument tracks for the loudspeaker channels. *Div* stands for *divisi*, meaning that an instrument group has more than one part.

According to the linearity assumption in acoustics, the increase of sound level should not have any effect. Still, the impression was improved quite a lot with the sound level increase, which suggests a psychological aspect in in-situ listening. In position R2, the maximum sound pressure level $L_{p,A}$ = 87 dB was measured with Mahler's symphony with the final adjustments.

The wind instruments were considered to be more convincing compared to the strings as the recorded tracks are not multiplied. Also, the number of loudspeakers was slightly closer to the number of musicians in authentic symphony orchestras. Especially in *tutti* passages, the wind instruments did not particularly stand out in an unnatural manner. Also the overall sound in *tutti* was more highly regarded than in more delicate passages.

In the Mozart's aria, some comments stated that the soprano sounded too damped, or, restricted - however, this opinion was not unanimously shared. In the opinion of the authors the soprano was regarded to be convincing and natural.

Other discussion in-situ claimed that the loudspeaker orchestra sounded surprisingly good, in particular in the back of the hall and when signals were played quite loud. Naturally, some defects were also noticed, e.g., the system seemed to have slightly a characteristic sound or timbre of the used loudspeakers. In addition, the strings were commented to have a feel of a recording with close microphones. On the other hand, this is partially true. In addition, the amount of low frequencies was seen unnaturally high compared to ordinary concert situation. For decreasing the level of bass frequencies, integrated bass tilt or roll-off adjustment at the loudspeaker control was suggested for flattening the power response, but it was not implemented in this study. All four music passages were also recorded for future use in positions R1-R3 with a Soundfield microphone, an artificial binaural head and a 3D microphone array[11].

4 LOUDSPEAKER POWER RESPONSE MEASUREMENT

One major challenge in implementing the loudspeaker orchestra is related to the differences in the radiation characteristics between loudspeakers and musical instruments. These differences were also seen one of the major error sources between authentic and loudspeaker orchestras. Multiple

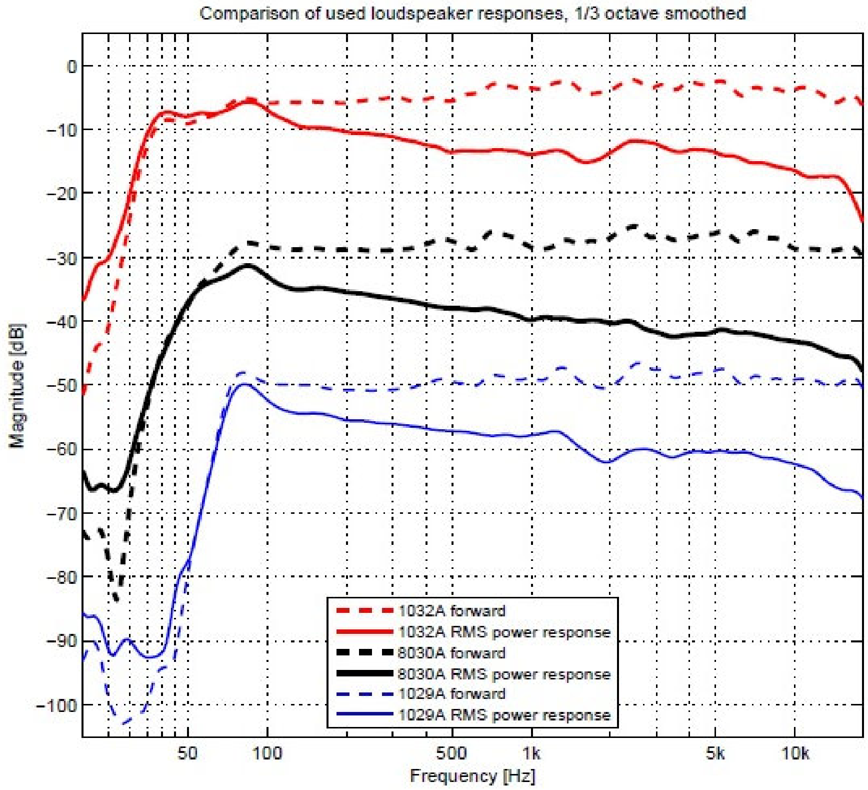

Figure 3 Comparison of loudspeaker magnitude and power responses.

studies have been done with directional loudspeaker with adjustable directivity[12,13]. On the other hand, the use of a loudspeaker as an instrument has been discussed[14,15]. The effect of directivity of a loudspeaker to the subjective impression of sound quality in small spaces has also been studied[16]. However, the perceivable directivity with multiple sources in concert halls is not known to been reported.

While the directivity of a loudspeaker has a considerable function in successfully standing for a musical instrument, actual directivities of the loudspeakers were expected to be different from the real instruments. Therefore, the radiation pattern of the instruments could not be correctly reproduced. For assessing the radiated sound energy from the loudspeakers, the magnitude and power responses were measured from the used loudspeaker models.

Power response measurements were conducted by measuring the magnitude response in an anechoic chamber with 20 microphones evenly spaced around the loudspeaker to approximate a spherical surface. RMS averaged magnitude response from all microphones then provides a relative power response in the frequency domain.

The comparison of the loudspeaker power responses is presented in Fig. 3. Each line pair shows the difference between the overall sound radiation and the forward direction for each used loudspeaker model, Genelec 1032A, 8030A, and 1029A. Typical behavior of declining power response is visible in all curves[15]. At the same time, the response at forward direction is relatively flat. With 1029A and 1032A slight fluctuation near the crossover frequencies were measured. However, manufacturer's measurement shows fluctuations of the same kind[17]. Relative power responses are well comparable to the reported values in the specifications. Note that the overall level of the curves has been adjusted for a clearer illustration.

It is plausible to assume that the declining power response of the loudspeakers is a prominent reason for the comments received during in-situ listening on the dull-sounding strings. Originally the corresponding loudspeakers were pointing to the conductor's position, which resulted in lack of certain brightness in the timbre. According to Meyer, the violin sound is radiated to a half-space pattern at highest frequencies[9]. As the loudspeaker power responses are considerably lower above 1 kHz, suggesting a narrowing directivity, turning the loudspeakers to the audience did improve the situation. A problem with the reflected sound remains with loudspeakers featuring ordinary directivity characteristics. As the strings are assumed to be more omnidirectional than the other instruments, the loudspeakers cannot provide sufficiently sound energy to arbitrary directions, which results in lower excitation in the acoustics than with authentic instruments. This aspect could be improved by turning more loudspeakers with string instrument tracks to point to various directions or to apply more omnidirectional loudspeakers.

As the wind instruments were seen to sound more like their authentic counterparts, it is feasible that the directivity of the loudspeaker is closer to the radiation pattern of these instruments. The flute, however, has differing radiation pattern as the instrument has several radiation sources. While the other woodwind instruments have been reported to present an alternating directivity, the radiation is more concentrated to the forward directions[9]. According to Meyer, the brass instrument directivities have a narrowing radiation pattern which resembles the directivity of the loudspeaker, thus, a declining power response. Maybe due to this reason, the brass instruments were not noticed to have notable deficiencies compared to the string instruments.

5 FUTURE WORK

The experiment on the loudspeaker orchestra resulted in a number of future research options. To obtain more comprehensive evaluation on the sound quality of the loudspeaker orchestra, a listening test is planned to be organized. The music passages recorded with the loudspeakers should be assessed against an authentic symphony orchestra recording. In addition, the power responses of the instrument recordings provide more information on the differences between the authentic instruments and the loudspeakers.

Referring to the research on the required number of recorded instruments in auralization[18], the impression of an authentic string sections can be enhanced by modulating the recorded signals and altering the instrument channels in the loudspeaker setup. In addition, the directivity of the used loudspeakers could be physically modified in order to break up the high directivity at high frequencies.

With the current design of the loudspeaker orchestra it is possible to perform the same measurements in multiple halls. The recordings from various halls provide material for comparison between performance spaces while the excitation signal remains exactly the same in all halls. Besides real halls, the acoustics can be compared between an existing space and a virtual model of the space. As a side product of the loudspeaker orchestra, measurement of impulse responses from each loudspeaker channel is easily conducted with the setup.

6 CONCLUSIONS

The use of anechoic instrument recordings with a loudspeaker orchestra has been investigated for future use in concert hall acoustics comparisons. For this purpose an orchestra consisting of twenty four active loudspeakers was installed on the stage of a small concert hall to conform to the seating layout of a symphony orchestra. Four music excerpts from orchestral works were played through the loudspeakers. The used instrument tracks were recorded individually in an anechoic chamber. Music passages reproduced with the loudspeaker orchestra were recorded with several microphone techniques, which can be used later in listening tests against an authentic symphony orchestra. The measurements of the loudspeaker power responses are analyzed and discussion from the in-situ listening are presented. While the experience from the project is encouraging, the received comments in-situ suggests that the loudspeaker orchestra leaves possibilities for further improvements. Thus, this experiment opens room for future work and development.

7 ACKNOWLEDGMENTS

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