Proceedings of the Institute of Acoustics

VARIABLE ROOM ACOUSTICS SYSTEM: PHILOSOPHY AND APPLICATION

S. Ellison Level Control Systems, Sierra Madre, CA, USA
M. Poletti Industrial Research Limited, Lower Hutt, New Zealand

1. INTRODUCTION

One of the most important aspects to the enjoyment of any musical performance–live or prerecorded–is the effect that the performance space has on the sounds heard by the audience. The reverberation time of the performance room was first recognized by Sabine as an important parameter affecting sound quality [1]. For example, speech requires short reverberation times to aid clarity, but orchestral music needs relatively long reverberation times to enhance the sense of spaciousness and envelopment. It is increasingly common, however, for a single facility to be shared for music performance, theater, and lectures. To meet this requirement, physical, electronic, and electromechanical systems have been designed to provide variable acoustics.

Since Sabine's early work it has become known that there are aspects of room acoustics other than reverberation time that contribute to the subjective impression of quality. Therefore, other parameters have been sought to distinguish between rooms that have similar reverberation times but which produce different subjective impressions. A number of these parameters have been developed [2, 3]. Some of those that are relevant to this discussion are:

1. Running reverberation: The impression of reverberance during music, quantified by the Early Decay Time (EDT) measured over the first 5 dB of decay
2. Frequency dependence of reverberation time: The variation of reverberation time with frequency. A large RT at bass frequencies compared to mid-range frequencies creates a sensation of "warmth" or "mellowness" [2].
3. Loudness: Related to the sound pressure level produced at the listener, and governed by the source sound power, the distance to the listener and the room absorption [3].
4. Clarity: Related to the relative level of the direct and early reflection sound energy to that of the later reverberance [3].
5. Diffusion: A description of the degree to which reverberant sound arrives from all angles equally [4].
6. Apparent Source Width (ASW): Sound arriving from lateral directions produces an increased in "spatial responsiveness" or "spaciousness" [5]. Early lateral reflections produce a sense of increased source width.
7. Envelopment: Related to the amount of lateral energy arriving in the late part of the impulse response [6].
8. Texture: Describes the fact that the effect of a single reflection after the direct sound can produce a different subjective impression from that produced by a number of smaller reflections [2, 7].

In addition to these, a number of parameters quantify the performers' impressions of sound quality, such as reverberation time, blend, ensemble and attack [2, 8].

2. LOCAL AND GLOBAL ACOUSTIC PROPERTIES

Most of the objective parameters described above may be derived from measurements of room impulse responses using pressure and velocity microphones. A typical room pressure impulse response may be divided into three generic regions, as shown in Figure 1.

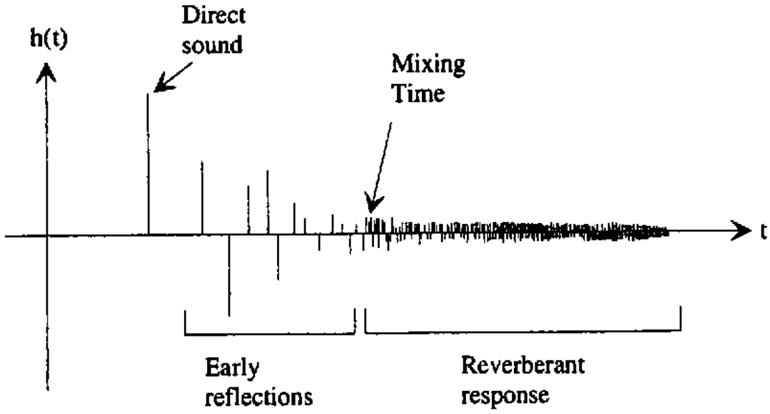

Figure 1: Parts of the impulse response

The first region consists of the direct sound. The second region includes a number of first order early reflections that are produced by surfaces reflecting the direct sound to the listener. The third region is the reverberant part of the response, in which the density of reflections is so high that individual reflections cannot be discerned (excluding undesirable echoes). Reflections occurring later in the impulse response are caused by higher order reflections, and thus the reverberant response tends to be governed by the mean properties of all the room surfaces.

The boundary between the early reflection and reverberant regions of the impulse response is usually taken as about 80 milliseconds in typical concert halls. More generally, the mixing time describes the boundary between the early reflections due to individual surfaces and reverberation, and is given by the square root of the room volume in milliseconds [9]. For example, a large concert hall of volume 15,000 m^3 has a mixing time of 122 milliseconds and a smaller opera hall of volume 10,000 m^3 has a mixing time of 100 ms.

Acoustical parameters may be termed "local" or "global" according to whether they depend on the properties of the impulse response before or after the mixing time. Local parameters are dominated by the individual reflections that occur before the mixing time, and include clarity, apparent source width, and early decay time. They are most often of interest for sources in the stage area, and many concert hall designs include reflectors and diffusers positioned to direct the stage sound usefully onto the audience.

Global parameters are dominated by the impulse response after the mixing time, and are governed by the *mean* properties of the room. Examples are the reverberation time, the loudness (for distances greater than the reverberation radius) and the envelopment. These parameters do not vary appreciably with source or receiver position (ignoring source and receiver effects near room boundaries and under-balcony effects). They are typically controlled in the design of concert halls by specifying the orientation and absorption coefficients of wall surfaces, and by the positions and number of diffusing surfaces.

3. GENERAL MODEL OF CONCERT HALL ACOUSTICS

A general model of concert hall acoustics may be proposed that includes the communication from the audience to the performers, and the feedback from the audience to themselves. The former could be termed "audience response" and the latter "ambience". The four communication processes are depicted in Figure 2.

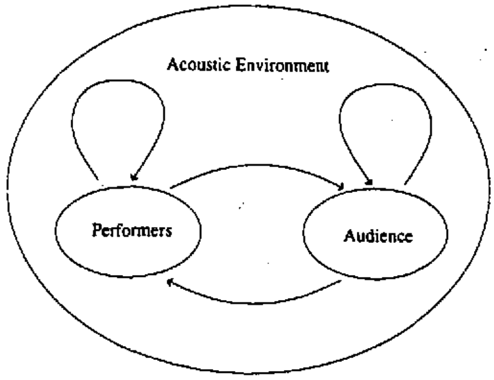

Figure 2: The four communication processes that occur in live performance

This clearly shows that in a live performance there is a two-way communication between the performers and the audience, and "feedback" from the room to both performers and audience. All of these parameters are important to the live experience, and are governed by both the local and the global properties of the room.

4. PASSIVE CONTROL OF LOCAL AND GLOBAL ROOM PROPERTIES

A number of techniques have been used to provide passive variation of room acoustics [3]. Reverberation time is often varied by altering the amount of absorption in the room. The disadvantages of variable absorption are that it also creates variable sound level, and that too much absorption may reduce loudness seriously and reduce lateral reflections and diffuseness.

A second means of controlling room acoustics is the adjustment of room volume. However, this technique is not practical in typical auditoria. A more common technique is to couple extra acoustic spaces to the main auditorium [10]. If the absorption in the coupled space is low, a useful increase in room reverberation is achieved.

5. ELECTRONIC CONTROL OF AUDITORIUM ACOUSTICS

Electronic systems are being increasingly applied to the enhancement of room acoustics in multipurpose venues, despite the resistance often encountered to their use, particularly in prestigious and long-standing venues. This resistance may sometimes be for purist or ideological reasons, but in practice electronic enhancement systems can produce artefacts that do not occur in passive rooms, and so some judicious caution is warranted. Nevertheless, high quality systems are increasingly available which do not produce these artefacts, and which both compensate for deficiencies in existing room acoustics and provide variable acoustics that could not be achieved by any passive means.

A number of electronic systems have been developed over the last 40 years [11-22]. These systems may be broadly classified into two groups. In the first group are those systems that use microphones close to the stage in order to detect predominantly the direct sound (plus some early stage reflections) produced by the performers. The second group uses microphones placed away from the stage to detect predominantly the reverberant field produced by any source in the room.

Those systems with directional microphones close to the stage can detect high levels of sound from the stage area with minimal time delay. They are thus able to alter the local properties of the room acoustics for sources on the stage, these properties including clarity, apparent source width, and early decay time. These systems may be termed in-line systems, since their primary goal is to affect the communication process between the performers and the audience, and to minimize any feedback from the loudspeakers to microphones [11-18]. As a result, such systems do not affect the reverse communication process from audience to performers (unless audience microphones are included), or the performer and audience feedback processes. However, some commercial systems can provide foldback for the performers by including a special subsystem for the stage area.

In-line systems are not well-suited to altering the global acoustic properties of a room. For example, including a reverberator in an in-line system means that the reverberation time and loudness of the room are enhanced only for sources in the stage area. For sources at other positions in the room, the reverberator will not produce the same enhancement. This means that the sense of ambience the audience hears in the room is largely unaltered and the sound of applause is not enhanced. Furthermore, in venues where the performers wish to leave the stage as part of the performance, the acoustics of the performance will suddenly change.

Systems in which the microphones are placed throughout the room to detect the reverberant sound are able to alter such global properties of the room acoustics as loudness, reverberation time, and envelopment. These are termed non-in-line systems because they use the regeneration that occurs between the loudspeakers and microphones in a controlled manner [19-21]. The microphones in a non-in-line system are not placed to detect high levels of direct sound. By remaining in the reverberant field, they respond approximately equally for all sound sources: in effect, these systems use the reverberant properties of the room to distribute the sound to all microphones, avoiding coverage issues.

Non-in-line systems are not well-suited to controlling the local properties of the room since the microphones do not detect large levels of early, direct sound. The system microphones are however typically placed so that the system produces its initial reflections before the mixing time. Thus the system can contribute to the fine structure of the early response, improving texture. In smaller rooms, non-in-line systems are able to control the early reflection-related parameters, but they do not offer the direct-sound amplitude pickup available from close, directional microphones.

6. THE VARIABLE ROOM ACOUSTICS SYSTEM

The above discussion suggests that in-line and non-in-line systems (local and global control systems) have complementary roles in room acoustics. For natural control of room acoustics any electroacoustic system should therefore offer both in-line and non-in-line capability. The in-line system is suited to control of the local room properties such as apparent source width, while the non-in-line system is suited to controlling the global room properties such as reverberation time and envelopment.

The Variable Room Acoustics System (VRAS) is a system that provides a non-inline reverberation enhancement component that overcomes many of the problems associated with previous systems of this type [22-26]. VRAS uses a number of independent wideband microphone/loudspeaker channels, as in the MCR system (Figure 3) [20]. The microphone signals are fed into a multichannel reverberation matrix, which both cross-couples and reverberates the signals before sending them to the loudspeakers for transmission back into the room.

The system allows the reverberation time in the room to be increased by increasing the reverberator's reverberation time (RT) without increasing the loop gain, so that high reverberation gains can be achieved at low loop gains. The reverberator is a unitary design that provides a flat power gain with frequency [23], and thus eliminates the increased risk of coloration and instability that can occur when using standard reverberators in sound systems [24]. The reverberator includes damping filters that allow the frequency dependence of the reverberation time to be controlled, and further digital filters are provided for equalization of the system. The enhancement of reverberation also produces greater envelopment and diffusion in the room and an enhanced acoustic experience.

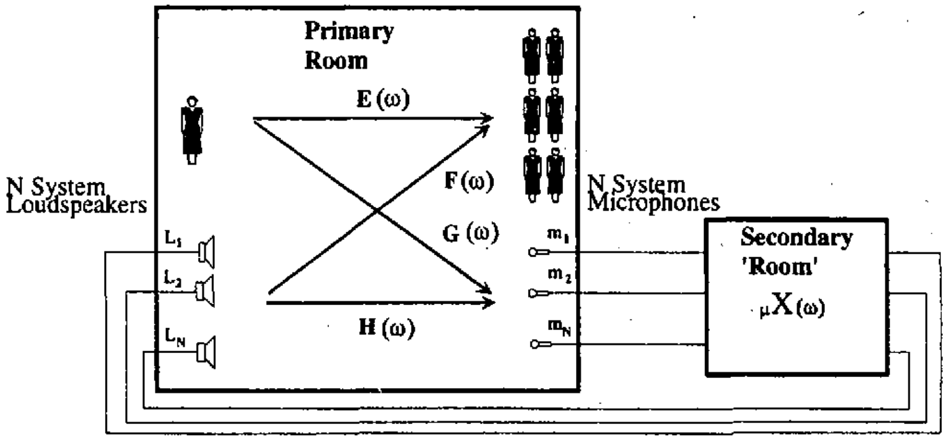

Figure 3: Variable Room Acoustics System (VRAS)

VRAS is the electroacoustic equivalent of a passively coupled room, since it couples the auditorium electroacoustically to a second, digitally implemented, "room" [25]. The performance of the system depends on the two reverberation times and an electroacoustical coupling coefficient that is analogous to the passive coupling coefficient. This electroacoustic coupling coefficient is equal to the mean power loop gain of the system. As in passive coupled rooms, double-sloped decays can occur if the coupling coefficient (loop gain) is too low. Configurations that produce double-sloping can be utilized to provide higher clarity while still producing long decays.

The microphones in the VRAS reverberation system are typically placed at distances from all source positions (including the stage) greater than the reverberation radius and where the reverberant level exceeds the direct sound level. This means that the system does not detect large levels of direct sound from the stage. However, every channel of the reverberation system produces a configurable direct component at its output so that the reverberator may be operated with a wide range of direct to reverberant levels and delays. Large direct levels through the reverberator produce a non-reverberant but live room, with maximum enhancement of early decay time, ASW and texture, whereas low direct levels produce a highly reverberant room with maximum enhancement of envelopment.

In cases where the stage sound needs greater direct reverberation enhancement, some microphones may be positioned close to the stage. The input cross-coupling matrix in the reverberation system allows these direct signals to be fed to subsets of the system loudspeakers while the reverberator still feeds the reverberated signals to all loudspeakers. This provides signals to the system at earlier times, which provides a larger power gain for sources on stage and an increase in early reflection and reverberation gain for these positions [26].

A separate VRAS subsystem may be used to provide early reflections by operating only as a delay matrix that produces no reverberation. Such a system uses a small number of directional microphones positioned so that they evenly cover the stage area. These microphone signals are fed into a cross-coupled delay matrix which has a unitary property—so that stability is maximized without requiring time variation—and which provides a large number of reflections, resulting in enhancement of texture, early decay time and apparent source width. Input and output delay lines can be provided for user-specific requirements and matrix crosspoint delays can be utilized to create strong first reflections of desired amplitudes and delays. The outputs from these available subsystems may be matrixed to the total set of loudspeakers utilized in the room. This matrixing, along with transducer equalization, delay settings, and VRAS settings are stored as system presets.

7. VRAS INSTALLATION: CHURCH OF THE LIVING WORD

A 16-channel VRAS system was installed at the Church of the Living Word, North Hills, California. Although the acoustics of the untreated church are felt to be acceptable for speech, the overall consensus of listeners is that the room is overly non-reverberant–that is, "dry". The mid-band reverberation time ("RT-mid"–the average of 500 and 1 kHz octave bands) of the untreated room is 0.9 seconds, which is non-optimal both for spoken word in a church and for music. Overly dry speech will cause a speaker to feel that he or she must exert more effort, due to a lack of vocal support from reverberation. Musical ensembles, including piano, organ, and choir, have greater difficulty performing with this low a reverberation time, and the enjoyment of the music by the congregation is diminished.

Reverberation time was measured for several settings of the VRA system, as well as with the system off, according to procedures outlined in international standard ISO 3382. Figure 4 shows RT-mid without VRAS and with VRAS at various reverberation time settings. The resulting measurements of RT-mid correspond well with desirable reverberation times. Speech can be usefully enhanced in the 1.2-1.4 second range without significant loss of intelligibility. Smaller musical ensembles or soloists will benefit from the 1.4-1.6 second range, while larger ensembles or certain soloists might prefer longer reverberation times from 1.8-2.6 second. A choir, instrumentalist, or organist who wants to convey the sensation of being in a large cathedral can utilize reverberation times from 2.6-4.0 seconds.

VRAS Setting	Measured mid-band RT	Application
(off)	0.93	System off (speech)
0.5	1.1	Speech support
1.0	1.4	Speech/Small Ensemble
1.5	1.7	Small Ensemble
2.0	2.3	Large Ensemble
2.5	2.7	Choir
3.0	2.9	Congregational Singing
3.5	3.3	Pipe Organ

Figure 4: Reverberation times (measured RT-mid versus VRAS settings).

8. INSTALLATION SURVEY

Permanent and temporary VRAS systems have been installed in over 20 facilities to date. The motivation for installing these systems, and considerations in integrating with other A/V systems, are described.

Bellagio Theater, Las Vegas – The permanent home of Cirque du Soleil's "O" is an 1800 seat "cavernous" theater that is served by a sound system with 80 discrete and fully automated amplification channels. The acoustics were designed to be dry, allowing clarity in amplified performance. However this hinders the audience's response, both to performers and to each other. VRAS will be installed both to assist in audience-performer interaction and to provide a more reverberant acoustic for the less amplified sections of the performance.

Hayden Planetarium, New York City – The new Rose Center for Earth and Space utilizes VRAS to create a more natural acoustic ambience between shows and for corporate events. During the pre-programmed show, VRAS is turned on and off for dramatic effect. The LCS matrix mixer is also used for multichannel audio playback, panning, and matrix mixing.

P&O Cruises' "Aurora" cruise ship – VRAS is integrated into the multichannel sound system of the ship's multi-purpose theater, so that the system may be used both for electroacoustic enhancement during classical music recitals, and matrix mixing and system tuning when presenting current release films in 5.1 playback format.

Blinn College, Texas – VRAS is installed in a 3 cubic meter practice room, designed to accommodate up to 4 musicians. A range of reverberation times is provided, to assist the musicians in preparing for performance in different spaces.

"The Music Man," Neil Simon Theatre, New York City – This Broadway production utilizes VRAS throughout the show. Acoustic modulation is used for theatrical emphasis.

9. CONCLUSION

It has been shown that the acoustics of a concert hall are governed by a number of parameters that quantify the sound quality perceived by the audience and the performers. These parameters include the effects of the transmission of sound from performers to audience and vice versa, the "feedback" of sound from the performers to themselves, and from the audience to themselves. Each of these four processes contains both local sound properties that are source-position dependent (such as clarity and apparent source width), and global properties that tend to be the same for all source positions (such as reverberation time and envelopment). Electronic room enhancement systems must therefore provide the ability to alter both local and global properties in order to provide natural enhancement. In-line systems are suited to local property enhancement and non-in-line systems to global properties, and so elements of both are applicable in a general electronic system for enhancing room acoustics.

Variable Room Acoustics System (VRAS) offers global reverberation enhancement with low coloration. VRAS may also be utilized to provide an in-line early reflection system for local reflection enhancement. System presets may be recalled from external control systems, allowing the room acoustics to be altered dynamically. This provides the basis for the comprehensive electronic control of room acoustics.

10. REFERENCES

1) R. B. Lindsay, *Acoustics: Historical and Philosophical Development*, Dowden, Hutchinson and Ross, Inc. 1973.

2) L. Beranek, *Concert and Opera Hall, How They Sound*, Published for the Acoustical Society of America by the American Institute of Physics, 1996.

3) M. Barron, *Auditorium Acoustics and Architectural Design*, E. and F. N. Spon, London 1993.

4) C. Haan and F. R. Fricke, "An evaluation of the importance of surface diffusivity in concert halls, *Applied Acoustics*, vol. 51, no. 1, pp 53-69, 1997.

5) M. Barron and A. H. Marshall, "Spatial impression due to early lateral reflections in concert halls: the derivation of a physical measure," *J. Sound Vib.*, vol. 77, no. 2, pp 211-232, 1981.

6) J. S. Bradley and G. A. Soulodre, "Objective measures of listener envelopment," *J. Acoust. Soc. Am.*, vol. 98, no. 5, pp 2590-2597, 1995.

7) T. Okano, L. L. Beranek and T. Hidaka, "Relations among interaural cross-correlation coefficient ($IACC_E$), lateral fraction (LF_E), and apparent source width (ASW) in concert halls," *J. Acoust. Soc. Am.*, vol. 104, no. 1, pp 255-265, 1998.

8) A. H. Marshall, D. Gottlob and H. Alrutz, "Acoustical conditions preferred for ensemble," *J. Acoust. Soc. Am.*, vol. 64, no. 5, pp 1437-1442, 1978.

9) J. Jot, L. Cerveau and O. Warusfel, "Analysis and synthesis of room reverberation based on a statistical time-frequency model," *103rd AES convention*, preprint 4629 (H-4).

10) J. Ouelette, "Science and art converge in concert hall acoustics," *The Industrial Physicist*, pp 20-23, September 1997.

11) R. Vermeulen, "Stereo-Reverberation", *J. Audio Eng. Soc.*, Vol. 6, No.. 2, pp 124-130, April 1958.

12) H. F. Olson, "Acoustoelectronic auditorium," *J. Acoust. Soc. Am.*, vol. 31, no. 7, pp 872-879, 1959.

13) P. S. Veneklasen, "Method for synthesising auditorium sound," *US patent 3,535,453*, 1970.

14) J. C. Jaffe and P. H. Scarborough, "Electronic architecture: towards a better understanding of theory and application," *Audio Eng. Soc. 93rd Convention, Preprint 3382*, 1992.

15) W. Ahnert, "Complex simulation of acoustic wave fields by the delta stereophony system (DSS)," *J. Audio Eng. Soc.*, vol. 35, no. 9, pp 643-652, 1987.

16) W. C. J. M. Prinssen and M. Holden, "System for improved acoustic performance," *Proc. I.O.A.* pp 93-101, 1992.

17) A. J. Berkhout, D. D. Vries and P. Vogel, "Acoustic control by wave field synthesis," *J. Acoust. Soc. Am.*, vol. 93, no. 5, pp 2764-2778.

18) D. Griesinger, "Improving room acoustics through time-variant synthetic reverberation," *Audio Eng. Soc. 90th Convention*, Preprint 3014, 1991.

19) P. H. Parkin and K. Morgan, "A special report on the experimental 'Assisted Resonance' system in the Royal Festival Hall," *J. Sound and Vibration*, vol. 1, no. 3, pp 335-342, 1964.

20) S. H. de Koning, "The MCR system – multiple-channel amplification of reverberation," *Philips Tech. Review*, vol. 41, no. 1, pp 12-23, 1983/84.

21) J. P. Vian and X. Meynial, "Virtual reflecting walls for improving the acoustics of defective halls," *J. Acoust. Soc. Am.*, vol. 103, no. 5, part 2, p 2862, 1998.

22) M. A. Poletti, "The performance of a new assisted reverberation system," *Acta Acustica*, vol. 2, pp 511-524, 1994.

23) M. A. Poletti, "A unitary reverberator for reduced colouration in assisted reverberation systems," *International Symposium on Active Control of Sound and Vibration (ACTIVE95)*, pp 1223-1232, 1995.

24) M. A. Poletti, "The stability of single and multichannel sound systems," *Acta Acustica*, vol. 86, pp 123-178, 2000

25) M. A. Poletti, "A comparison of passive and active coupled rooms for acoustic control" *Internoise 98*, Christchurch 16-18 November.

26) M. A. Poletti, "The analysis of a general assisted reverberation system," *Acta Acustica* Vol. 84, pp 766-775, July/August 1998.