The Control of Early and Late Energy Using the Variable Room Acoustics System

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ABSTRACT

Electronic enhancement systems are being increasingly used to provide control of the acoustics of multipurpose venues. Since the acoustics of a venue is governed by the power and spatial properties of the early and late sound, enhancement systems must also provide control of these properties. The Variable Room Acoustics System is one product which offers this control. The principles of the VRA system are presented here and its ability to independently control early and late energy is discussed. Two examples of installations are given.

INTRODUCTION

Electronic room enhancement systems can provide flexible control of room acoustics for a variety of performance types. Such systems use multiple microphones and loudspeakers to provide additional energy to the natural energy in the soundfield. Non-regenerative systems use microphones close to the stage and are well-suited to the enhancement of direct and early sound energy, and spatial properties such as apparent source width (Olson 1959, Berkhout et al, 1993). Regenerative systems use microphones in the reverberant field of all sound sources and are well-suited to the enhancement of late energy properties such as reverberation time and envelopment (Franssen, 1968, de Koning 1983/84, Parkin et al 1964).

The Variable Room Acoustics System (Poletti 1994) uses a regenerative system for controlling late energy and a non-regenerative early reflection (ER) system for early energy control. This paper discusses the essential features of the system and presents two examples of recent installations; one which required maintenance of early energy and one which required late energy enhancement.

PERFORMANCE OF VRAS

Regenerative system

The regenerative component of the Variable Room Acoustics system implements an electroacoustic coupled room in which an auditorium is two-way coupled via microphones and loudspeakers to a digital reverberator (Poletti 1998). The regeneration via N electroacoustic channels with loop gains μ produces a steady state power gain (de Koning 1983/84)

$$\Gamma = 1\Big/\left[1-\mu^2 N\right] \qquad 1$$

A coupled room analysis shows that the power decay consists of two components (Poletti 1994)

$$d(t) = A_{s1}e^{-13.8t/T_{s1}} + A_{s2}e^{-13.8t/T_{s2}} \qquad 2$$

When the reverberator RT, T_2, is lower than the room RT, T_1, the decay term with the larger RT (A_{s1}) dominates and the RT gain is T_{s1}/T_1. However, as T_2 increases double sloping begins to occur. The two decay amplitudes are equal for

$$T_2/T_1 = \Gamma/(2-\Gamma) \qquad 3$$

which may be used to specify the maximum value of T_2 for reasonable linearity. At this value the decay is nonlinear over the first 6 dB or so, producing a lower EDT gain compared to the RT gain. For example, for a power gain of 1 dB and T_2/T_1 as in equation 3, the T_{30} gain measured from the theoretical decay is 2.53 and the EDT gain is 1.87 which is 74% of the T_{30} gain. Operating the reverberator with a reverberation time lower than that in equation 3 produces more linear decays. For example table I shows the EDT, T10, T20 and T30 measured from theoretical decays with power gains of 0.25 dB to 1.5 dB for the case $T_2=T_1$. For 0.25 dB the EDT gain is 89% of T_{30} and for 1.5 dB power gain the EDT is 91% of T_{30}. The EDT to T_{30} ratio can be further controlled using the non-regenerative early reflection system, discussed below.

Table 1: Theoretical RT gains for $T_2=T_1$ and power gains Γ from 0.25 to 1.5 dB

Γ	EDT	T_{10}	T_{20}	T_{30}
0.25	1.13	1.20	1.24	1.27
0.5	1.28	1.40	1.45	1.47
0.75	1.44	1.59	1.63	1.65
1.0	1.61	1.78	1.81	1.82
1.25	1.79	1.97	1.99	2.00
1.5	1.98	2.16	2.17	2.18

Thus, the reverberation gain is still significant for values of T_2 less than equation 3. The reverberation gain for the case in equation 3 is

$$T_{s1}/T_1 = \Gamma\Big/\left[1-\sqrt{\Gamma-1}\right] \qquad 4$$

and for $T_2=T_1$ the gain is

$$T_{s1}/T_1 = \Gamma\left[1+\sqrt{1-1/\Gamma}\right] \qquad 5$$

Figure 1 shows these gains as a function of power gain. For $T_2=T_1$ (the matched room case) the RT gain is 2.0 for a power gain of 1.33 which is achievable for larger systems, and the RT can be doubled for a power gain of 1.17 if the reverberator RT is increased to that given by equation 3. While this will produce some curvature of the early part of the decay, the curvature can be reduced by the use of an addition early reflection system as discussed in the next section.

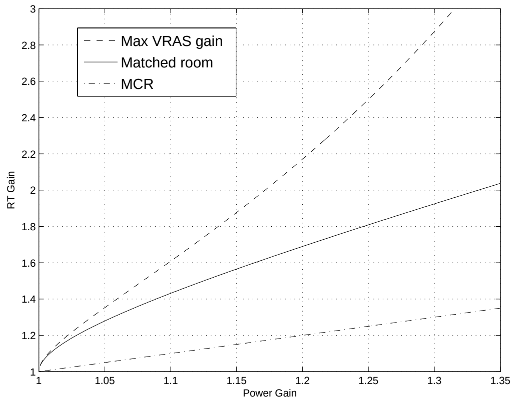

Figure 1: VRAS RT gain from equation 3, for the T_2=T_1 case, and for the T_2=0 case

The VRAS reverberator is a feedback-delay network design which includes a two-stage damping filter which allows control of the reverberation time with frequency. The damping filter may be used to ensure a constant ratio of reverberator RT to room RT with frequency for constant reverberation gain, or may be varied to enhance and alter the RT versus frequency of the room. One stage can be reconfigured as a highpass shelf filter to provide control of low frequency reverberation if required.

Non-regenerative system

The regenerative system is limited in its ability to control early energy from the stage since the microphones must be distributed widely throughout the room. If greater control of early sound energy is required, a non-regenerative early reflection system is available. This uses a number of microphones placed close to the stage, such that the system detects a similar level of total power for all source positions in the area of interest. The microphone signals are processed by an early reflection generator, which does not include reverberation, and are routed to loudspeakers to provide an even distribution of early energy to all seats. The use of lateral loudspeakers allows this energy to contribute to enhanced spatial impression (Barron 1993).

The ER system provides control of early energy parameters such as lateral energy fraction and clarity (Beranek 2004). The performance of the system is dependent on the distances to sources, microphone directivities and the properties of the loudspeakers, and it is therefore less amenable to a general analysis than the regenerative system. However, an analysis of the overall power gain of the combined system gives some insight into how the two systems work together to provide control of early and late energy.

Power analysis of combined regenerative, non-regenerative system

The combined ER and reverberation enhancement system may be represented as shown in figure 2. There are two sets of transducers, with N_E channels for the early reflection system and N_R for the reverberation system. In the simplest implementation, the two systems are electronically independent of each other, but they are cross-coupled through the room. For simplicity of analysis we assume each loudspeaker microphone channel has a mean power gain of one. Each early reflection channel has a loop gain μ_E and each reverberation channel has loop gain μ_R. We represent the source to receiver positions as M source loudspeakers and M receiver microphones, which allows the output power to be determined in terms of squared rms voltages in the same manner as for the electroacoustic system powers.

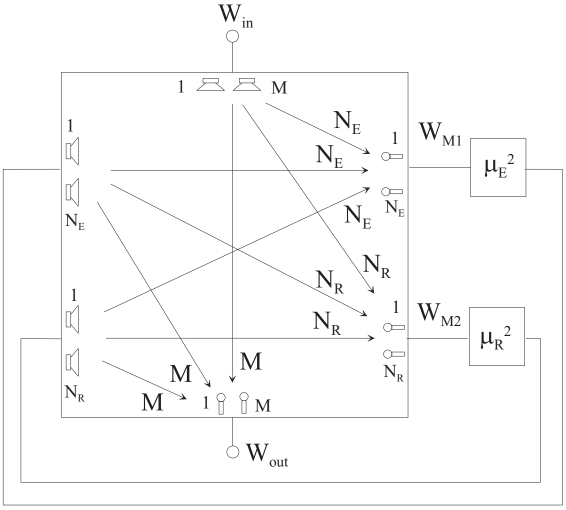

Figure 2: Power analysis of a combined regenerative, non-regenerative system

The power gain of the system is determined by first calculating the powers at the two sets of microphone outputs. W_{M1} is the sum of the squared rms voltages at the N_E early reflection microphone outputs and W_{M2} is the total power at the N_R reverberation microphone outputs. The two powers may be written in vector form as

$$\begin{bmatrix} W_{M1} \\ W_{M2} \end{bmatrix} = \begin{bmatrix} N_E \\ N_R \end{bmatrix} W_{in} + \begin{bmatrix} \mu_E^2 N_E & \mu_R^2 N_E \\ \mu_E^2 N_R & \mu_R^2 N_R \end{bmatrix} \begin{bmatrix} W_{M1} \\ W_{M2} \end{bmatrix} \tag{6}$$

from which

$$\begin{bmatrix} W_{M1} \\ W_{M2} \end{bmatrix} = \frac{1}{1-\mu_E^2 N_E - \mu_R^2 N_R} \begin{bmatrix} 1-\mu_R^2 N_R & \mu_R^2 N_E \\ \mu_E^2 N_R & 1-\mu_E^2 N_E \end{bmatrix} \tag{7}$$

The output power is the sum of the unassisted output power MW_{in} and the power supplied by the system

$$W_{out} = MW_{in} + \begin{bmatrix} \mu_E^2 & \mu_R^2 \end{bmatrix} \begin{bmatrix} W_{M1} \\ W_{M2} \end{bmatrix} \tag{8}$$

Substituting from equation 7 yields

$$W_{out} = \frac{M}{1-\mu_E^2 N_E - \mu_R^2 N_R} W_{in} \tag{9}$$

This shows that the combined power gain of the system is governed by the loop power gain $\gamma = \mu_E^2 N_E + \mu_R^2 N_R$.

The stability of the system is governed by the combined feedback between all loudspeakers and microphones. If $\mu_E = \mu_R$ then the stability limit is that for a system with N_E+N_R channels (Poletti 2000). This provides a greater power gain than that of either system alone. If μ_E or μ_R is zero, the system stability reduces to that of an N_R or N_E channel system, respectively. The early reflection and reverberation loop gains can thus be traded off against each other to control the ratio of the early decay time gain to late RT gain.

Unitary processing

A limitation of all room enhancement systems is the risk of colouration artefacts due to feedback from loudspeakers to microphones. This occurs for both regenerative and non-regenerative systems as demonstrated by equation 9. (The term non-regenerative must therefore be viewed as an idealisation of actual performance.)

Both regenerative and non-regenerative processors in VRAS have a unitary property, which minimises the risk of colouration and instability.

A single channel processor is said to have an all pass property if the magnitude of its frequency response is constant with frequency. An all pass processor therefore has a constant power gain with frequency. A multichannel processor can also have a constant power gain with frequency if the sum of the output powers is constant for a constant input power. The system is then said to have a unitary property because the transfer function matrix of such a system, $X(f)$, is unitary at each frequency. This property ensures that the inclusion of the processor in a sound system does not increase the risk of instability over an equivalent system without the processor (Poletti 2000).

Hardware and software

VRAS is run on one or more digital audio "Matrix^3" mainframe processors (Matrix^3 brochure). Each processor frame has three audio expansion slots which may contain 8-channel audio input or output modules, plus further slots which contain the system DSP board, VRA processor, plus modules such as CobraNet^{TM} and inter-frame link modules. Up to 32 frames can be linked in a fault-tolerant network with up to 32 km network size, allowing up to 400 audio inputs and 512 audio outputs. This allows very large VRA systems to be built using multiple frames (and this limit has been approached with some VRAS installations).

The frames and VRAS processors are controlled with the Level Control Systems CueStation software, which provides a virtual mixer interface for metering and level control, plus a number of other windows for system configuration, automation, equalisation, and VRAS-specific control. The software runs as a client/server architecture, that enables multiple users to access the system simultaneously.

EXAMPLES

As examples, we consider a VRAS installation for which the design requirements included enhancement of early energy, and one for which the late energy was of most interest.

Prague Congress Centre

A VRA system was installed in the Congress Hall, Prague Congress Centre, in 2000. This hall has a volume of 41,000 m^3 and seats 2,766. The unassisted RT$_{mid}$ was 1.74 seconds, with a bass ratio of 0.95. The acoustic consultants made passive acoustical changes to reduce absorption and designed a new demountable orchestral shell for the stage area. VRAS was then employed to add additional reverberation enhancement whilst maintaining reasonable early energy levels.

Twenty four microphones were used, with eight hyper cardioids mounted above the stage for early reflection enhancement and 16 reverberation microphones mounted in the ceiling. A total of 64 loudspeakers was used, with 21 in the ceiling, 35 around the walls and 8 under the balcony. One Matrix^3 frame was used as an ER processor and two were used for reverberation processing. A fourth was added for routing purposes. The system was time-aligned to ensure that the direct sound reached all seats before any electroacoustic signals.

Figure 3 shows the EDT in the Hall with VRAS off and for the Chamber and Symphony settings. The EDT at mid frequencies is increased from 1.48 to 1.73 and 1.89 respectively, producing EDT gains of 1.17 and 1.28.

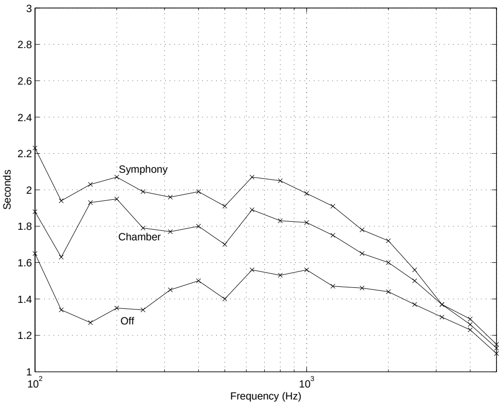

Figure 3: Prague Congress Hall EDT

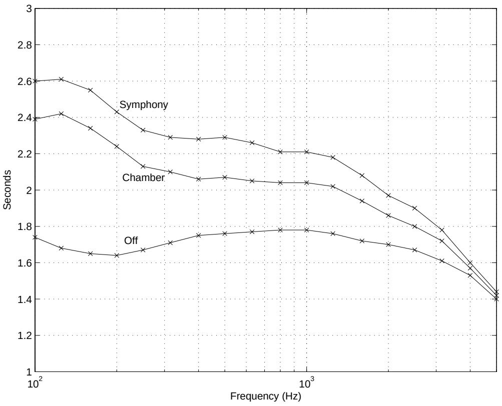

Figure 4: Prague Congress Hall RT

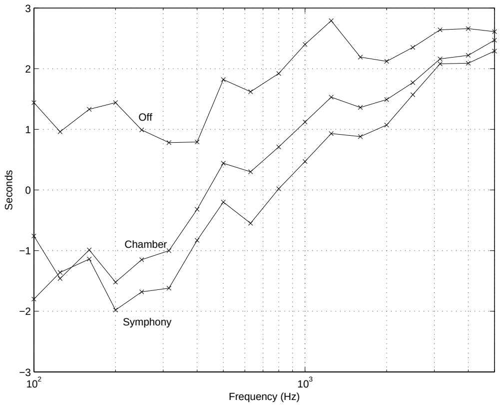

Figure 5: Prague Congress Hall Clarity

The reverberation times in figure 4 show a mid RT of 1.74, rising to 1.99 and 2.15, gains of 1.14 and 1.24 respectively. The EDT gains are thus slightly larger than the RT gains, showing the effectiveness of the early reflection system in maintaining enhancement of the early energy.

Figure 5 shows the clarity. C80$_{mid}$ reduces from 2 dB to 0.9 dB for the chamber setting and 0.4 dB for the symphony setting. The clarity reduction is moderate given the reverberation enhancement and remains within an acceptable range (Barron 1993).

Christ United Methodist Church

A VRA system was installed in the Christ United Methodist Church in Sugar Land, Texas in 2003 (Application Note for Houses of Worship). The primary requirement was to increase the reverberation from the naturally occurring 1.6 seconds (mid-frequency, unoccupied) for choral singing, to provide support for a newly installed pipe organ, and to increase warmth. Two Matrix3 frames were used, with 16 microphones and 44 VRAS loudspeakers, with some energy fed to the House sound system. The loudspeakers were installed in the ceiling, along the walls, and behind columns (to minimise direct radiation of reverberation onto the congregation).

Table II: Midband Reverberation Times in CUMC

Setting	T_{30} Midband	Bass Ratio
Off	1.60	1.02
Short	1.97	1.11
Short+	2.15	1.12
Medium	2.63	1.19
Medium+	3.15	1.14
Long	3.79	1.11
Long+	4.37	1.21
Demo	4.82	1.15

Table II shows the mid-band RT and Bass Ratio obtained with the system off and for seven settings. The RT was increased to a maximum of 4.37 seconds for normal use, with a longer setting to demonstrate a maximum RT gain of 3.0. The Bass ratio has been increased by between 10% and 20% across the settings. The enhancement sounded subjectively natural for all settings. For example, according to Mr, Ken List, the Schantz Organ Voicer:

> VRAS is the most natural, absolutely convincing enhancement I've ever heard. The effect is tangible, enveloping and incredibly realistic. VRAS was able to bring the organ's sound effectively into areas where, without VRAS, the building would not have permitted.

CONCLUSIONS

This paper has discussed the electroacoustic enhancement of early and late energy in rooms using the VRA system. This system has a regenerative component for enhancement of late energy and a non-regenerative component for early energy enhancement. The two component systems are coupled via the room, and the overall power gain of the combined system is limited by the multichannel stability limit for the sum of channels. This allows the loop gains in each subsystem to be altered relative to each other to alter the relative enhancement of early and late energy. While the stability limit of a multichannel system with two sets of distinct loop gains is more complicated than the equal loop gain case considered in (Poletti 2000), it is clear that the total power gain increases with additional channels, allowing the use of an additional early reflection system for control of early energy. Experience with recent installations containing both components has further confirmed that the early and late energy enhancement can be traded off in the manner discussed above. In one case the EDT to RT ratio could be varied from below 1 (regenerative system only), to 1.25. The two examples discussed have also shown that early and late energy can be enhanced to provide acoustic conditions appropriate to the venue.

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