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SYNOPSIS OF REVERBERATION ENHANCEMENT SYSTEMS

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Olivier Warusfel [(1)]; Jens Blauert [(2)]; David Wessel [(3)]
[(1)] Ircam,
1, Pace Stravinsky, 75004 Paris, France.
[(2)] Institute of Communication Acoustics, Ruhr-Universitaet Bochum,
D-44780 Bochum, Germany
[(3)] CNMAT, University of California Berkeley, Berkeley,
California 94720 USA

ABSTRACT

Today there is an emerging tendency – from aesthetical and economical concerns – to create/refurbish venues for a wide variety of performance types, each demanding a specific acoustic. For these multi-purpose halls, electro-acoustic enhancement systems represent the most promising approach, allowing high quality results with the greatest flexibility. This paper reviews the principles of the main categories of reverberation enhancement systems that have been designed and commercialized in recent decades. General and specific constraints of these categories of systems are presented with a set of evaluation criteria and guidelines for selecting a system for use in a given hall and performance context.

1. INTRODUCTION

Electroacoustic enhancement of reverberation has been studied for several decades and different systems are now proposed on the market. The aim of these systems was originally to increase the reverberation time, especially for halls with damped or small volume. Thanks to signal processing improvements, they now represent a flexible and economic approach for adapting venues to a wider range of performances. In the future, new applications may also take advantage of such systems for transmitting performances to a remote audience or gathering different groups into a single assembly, with *tele-presence* technology.

When being consulted for such an installation it is important to know the principles and constraints of proposed reverberation enhancement systems. The aim of this paper is to review the main categories of commercialized systems and to draw some guidelines for selecting them according to the application context.

Two main categories are generally considered with respect to the following choice :

- regenerating sound between arrays of loudspeakers and microphones distributed in the room.
- filtering the sound captured on stage with an external electronic reverberator and broadcast output signals into the audience area.

In the first category, the modification of the reverberation properties of the room relies explicitly on the feedback loop between the loudspeakers and the microphones. These systems are said "regenerative" or "non in-line" since the electroacoustic components are involved in the iterative energy exchanges that drive the reverberation.

In the second category, the reverberation is created by an auxiliary electronic device and is superimposed to the room behavior. Conversely, such systems are said "in-line" or "non-regenerative" since the process from the stage microphones to the rendering loudspeakers does not include a feedback loop or, at least, maintains it as low as possible.

Besides these two leading categories other structures, have been proposed. A hybrid architecture is described in [9] where first reflections are created with an in-line process, while the late reverberation is controlled by an artificial reverberator, inserted in the regenerative process, and acting as a coupled room. In [13], a regenerative system is proposed where a number of electronic cells, distributed in the room, are being composed of a loudspeaker connected to a local microphone. Each cell creates an "active wall" with control of its reflecting properties (frequency response and delay).

2. SYSTEM CATEGORIES AND PRINCIPLES

2.1. Regenerative systems

Assisted reverberation systems using regeneration are based on a multiple feedback channel architecture between microphones and loudspeakers. The well-known Assisted Resonance System, installed in the Festival Hall in London, consisted in a series of independent channels, filtered in narrow band and dedicated each to the enhancement of a single low frequency mode.

Statistical considerations on modal density in room acoustics tends to favor the use of wideband feedback channels aiming at controlling the reverberation time over a large frequency band. A broad overview of the evolution of this category should first mention early work of Franssen using a number of independent feedback channels in order to compensate for the natural damping of the room. First laws could be derived to characterize the gain G on the reverberated energy density, for a given number of channels N :

$G = 1 / (1 - m^2 N)$ where m^2 is the mean power loop gain in individual channels.

This gain automatically defines the reverberation time increase according to Sabine's law. Studying the conditions for stability and acceptable coloration, Fransenn also derived an estimation of the necessary number of channels for obtaining a given gain [6] :

$$G = 1 + N / 50$$

As can be seen, using a reasonable number of loudspeakers (50 < N < 150) does not allow a large variation of the reverberation time. Moreover, such a system is generally wanted for venues with too small volume, thus energy gain is generally not desired nor suited. During the last decade, significant improvements were proposed and developed by M. Poletti with the introduction of a cross coupling matrix and an auxiliary reverberation matrix in the feedback process [8]. This work took also advantage of contemporary work in the field of reverberator design [3]. The main merits of these evolutions are a better control on the frequency statistics of the response and the independent control of the reverberation time and energy.

2.2. In line systems

The "in-line" category resorts to the synthesis of a room effect by an auxiliary device, the output signals of which are broadcast into the audience. Although any system necessarily increases the total energy in the room, this category easily allows the creation of not physically possible situations like freezing sounds in infinite reverberation. The design of such assisted reverberation process will generally address simultaneously the synthesis and distribution of early reflections and of the late reverberation.

In order to offer the largest possible variability, input signals must be as dry as possible, using close microphone settings or super-directive recording techniques like microphone arrays. Arrays may also be applied for a Wave field Synthesis approach as in [12] for the recording and rendering of the wave fronts produced by the instruments on stage. In practice, according to spatial aliasing considerations, an accurate sampling and reproduction of the wave fronts can only be achieved at low frequencies.

Although feedback is not considered part of the system, live conditions imply installation precautions and/or signal processing techniques for maintaining the feedback as low as possible. The problem is generally solved by specializing the different volumes of the room (recording on stage and rendering in the audience), or by using directive transducers and, finally, by introducing time variation of the parameters of the reverberators [2].

2.3. Active wall

The last studied case consists in installing a number of cells acting as artificial reflectors with controllable reflecting coefficient (possibly > 1.)[13]. Each cell is made of a microphone which signal is amplified, filtered and locally delivered to its associated loudspeaker. The behavior of the system may be interpreted as enhancing and delaying locally the reverberated field or, as well, as compensating for the energy loss on the room boundaries. Controlling the filter characteristics of the cells (delay and frequency dependent gain) allows adjusting independently the reverberation time and the apparent volume of the room. The directivity of the transducers together with echo cancellation algorithms are required for minimizing the internal feedback of the cell. The behavior of the system, considering the late reverberation, is similar to regenerative category where the feedback matrix is diagonal. Although the general architecture is designed for controlling the late reverberation of the room, the spatial distribution and the adjustment of the cells allow controlling the first reflections on stage or in the room. However, this requires acoustic consulting expertise, whereas previous system categories, especially when relying on in-line systems, belong more to the sound mastering skill.

3. GENERAL ASSESSMENT CRITERIA

3.1. Coloration / Stability

One of the main issues of reverberation enhancement systems has been, for a long time, the conditions for a stable and coloration free behavior, the term coloration here being focused on the ringing artifacts linked to the electroacoustic feedback. In [7] an objective measure is proposed to characterize the sound coloration of the reverberation tail. It is based on the analysis of the frequency magnitude distribution of the late reverberation. A few indices are proposed to characterize the deviation from a Rayleigh distribution corresponding to an ideal diffuse field. Among relevant values are the standard deviation of the distribution and the quadratic error between the integrated histograms of the measured and ideal distributions. The standard deviation shows interesting properties like a monotonic evolution with the gain before instability and its correlation with perceptual coloration detection seems reliable and selective.

During the last decade, theoretical studies have been dedicated to the statistics of multichannel feedback systems in order to improve the reverberator technology [4] as well as regenerative reverberation enhancement systems. As a starting point, considering the series connection of n transfer functions which frequency magnitudes are Rayleigh distributed, the product transfer function is known to diverge progressively from Rayleigh properties and to present increasing variance as n is incremented. It explains why a single feedback channel with a microphone set in the reverberation field of a loudspeaker will present worse stability properties than in free field. This observation, together with the perceptual selectivity mentioned above, also highlight the fact that even with non-regenerative systems, audible coloration artifacts can occur. Actually, if the sound recording on stage does not present a high direct to reverberant ratio, its convolution with a reverberator will diverge from ideal distribution properties. This justifies the use of time variant algorithms for reducing these risks.

The use of a cross-coupling feedback matrix with unitary properties [3] allows maintaining the frequency magnitude distribution closer to Rayleigh. As proposed in [8], the insertion of a unitary reverberator also allows an independent control on the reverberation duration and level.

3.2. Sound recording

One of the main discrimination between the system categories concerns the constraints on the microphone positioning. In-line systems require a high direct to reverberant sound energy ratio, which implies the use of directional and/or close microphones. An obvious reason is that dry recording allows a larger range of variation for the synthesized room effect. A second reason, reminded in the previous paragraph, is that coloration considerations call for feeding the reverberator with signals presenting high direct to reverberant ratio. Finally, close pick-up maintains the acoustic feedback as low as possible. As stated in [11] the distance of the microphone to the source on stage should not exceed the reverberation distance, which can be typically 5m. Using time variant reverberator parameters allows increasing this distance.

A trade-off must also be found between this requirement and the necessary homogeneity of stage covering regarding the position and orientation of the instruments. Moreover, in order to emulate diffuse field conditions, each instrument should be recorded with respect to its power spectrum, i.e. to the spatial integration of the sound radiated in every direction. These conditions are automatically fulfilled by regenerative systems (including active wall approach) provided that the room shows good diffusion properties, which makes them particularly indicated in venues where flexible stage is desired. The counterpart is that the system is only able to act on the late contribution of the room effect and does not allow fine tuning of first reflections. This justifies the development of hybrid systems where part of the microphone are set on stage and are dedicated to the synthesis of first reflections by an in-line sub-process.

Another important aspect for coloration and stability constraints is that the microphones should be separated enough in order to be uncorrelated before feeding a multichannel reverberator or the regenerative process. According to the spatial properties of cross-correlation in diffuse field, this minimal distance varies with the frequency and is about 1.7m for a lower frequency limit of 100Hz. In practice, a simple rule is to use the reverberation distance as a minimum.

3.3. Loudspeaker positioning

Among practical issues when designing a reverberation enhancement system is the determination of the number and spatial distribution of the loudspeakers. Main criteria are a homogeneous coverage of the audience, an average spacing between the cells that respect the cross-correlation properties and a distance from the audience that avoids their auditive detection. The evaluation and relative importance of those criteria follow different rules according to the system category.

Considering in-line systems, the spatial density of the loudspeakers can be conducted as for conventional enhancement systems. The even coverage of the audience demands a sufficient overlapping of the directivity lobe of the loudspeakers. Another important requirement is to avoid auditive artifacts like the localization of the loudspeakers. In order to feel subjectively in diffused conditions, each listener should be surrounded by several uncorrelated reverberation signals.

The loudspeakers dedicated to the reverberation follow different rules, especially in regenerative systems. If the room has good diffusion properties, each cell contributes equally and moderately to the energy density gain. Moreover, as designed for controlling the global absorption of the room, these cells will be preferably not directly addressed to the audience. The following lines draw a rough estimation of the number of cells needed for avoiding the detection of the loudspeakers dedicated to the reverberation enhancement. Although not being restrictive enough for a "detection criteria", the study of the reverberation distance in an ideal diffuse field is a convenient indicator. The reverberation distance R_{ON} associated to the perception of a loudspeaker depends on the number of channels N, the directivity coefficient of the loudspeakers *D*, and the natural properties of the room. For in-line systems the relation is:

$$R_{ON} = R_{OFF} (D / N)^{1/2}$$ where R_{OFF} is the reverberation distance in natural conditions.

As can be seen, this relation does not depend on the synthesized reverberation time but only on the natural conditions. This can be very constraining if the room is damped, especially at high frequency where the RT is lower and the directivity factor of transducers is high. For regenerative systems the relation takes into account the gain of the reverberation energy G [8]. If the gain is maintained moderate, the conditions are more favorable than for in-line systems.

$$R_{ON} = R_{OFF} (1 - 1/G)^{1/2} \quad (D / N)^{1/2}$$

This simple relation must however be refined if the room does not fulfill Sabine's hypothesis. For example, under-balcony areas often show a strong attenuation of the reverberation energy density. Hence, the detection conditions are less favorable. Moreover, these seats will precisely need a higher room effect enhancement to compensate for the heterogeneity of the sound field. These conditions call for an increase of the spatial density of cells.

4. GUIDELINES FOR SELECTION

4.1. Initial context

The analysis of the initial architectural and acoustic properties of the room is obviously decisive when selecting the system. According to the volume characteristics and targeted gain of the reverberation time, it may be mandatory to use a system offering strong decoupling between the energy density and time duration gain. Other important features concern the constraints on the spatial distribution of transducers. Highly flexible stage setup demand a careful study of the microphone positioning for in-line systems. On the contrary, regenerative systems offer, a quasi-optimal sound recording if no variability or correction is needed for the early room contribution.

A common situation concerns venues with deep under-balcony areas or strongly decoupled volumes. The constraints on loudspeaker positioning may become severe. On the one hand, the reverberation level is generally poor in these areas. Hence, it calls for a trade-off between raising the level and the risk of sound localization of the loudspeakers and leads to an increase of the number of loudspeakers. In the case of regenerative systems, this number is however constrained by the minimal spacing between adjacent cells (cf. § 3.3).

Another issue, when adjusting a regenerative system in those conditions, is the influence of the heterogeneous couplings on the overall sound quality. The use of cross coupling matrix in the electronic feedback was shown efficient for limiting the coloration risks, an interesting property being the even distribution of coupling coefficients. The same argument applies to the natural room itself: in case of strongly decoupled volumes, the odd distribution of inter-cell coupling may alter the coloration of the reverberation. It may also result in enhancing only the local reverberation of each sub-volume – subsequently boosting the audience noise - while the original aim was to create a single large volume.

4.2. Variability

Even when the system is designed mainly for increasing the reverberance sensation, it is worth considering the multidimensional properties of room perception. While *late reverberance* is noticed on stop chords or sharp transients, the *running reverberance* corresponds to the sensation of a *background reverberant stream* that perception can segregate from direct sound events even in the course of a musical phrase. As stated in [1] and [5], this segregation ability, musically appreciable, will be driven negatively by the amount of first reflections between 50ms and 150ms: a high energy level in that time section reduces the transparency between the source events and the room contribution. Small rooms often present too much energy in this time section and call for systems that can reshape the early to late room effect transition.

In-line systems generally offer high flexibility and their control parameters may be easily connected to perceptual attributes, as their interaction with the natural room is simpler to model. When the room is not dry, a method proposed in [4] and based on echogram convolution, predicts the effective room response according to the reverberator setup and compensates for the response of the room. For regenerative systems, the correspondence between the control parameters of the feedback process (loop gains and filters, delays or auxiliary reverberator) and the global response of the room is less obvious. However, applying coupled rooms theory allows predicting the conditions for double slope decays [10]. It is believed that future generations of room simulation software should integrate a complete model of electroacoustic components for conducting the installation and setup optimization of the system.

4.3. Possible artifacts and practical aspects

- *Coherence between sound perceived on stage and in the room*: the feedback sensation of musicians should make them feel in the same room as the audience. In case the coupling between stage and room is poor, it requires extending the cell distribution of a regenerative systems into the stage or providing a specific in-line sub-system for the stage.
- *Time alignment between early and late reverberation contributions*: some in-line systems specialize parts of the loudspeakers to the first reflections or to the reverberation. This needs a careful study of time alignments of signals (avoid gaps and time inversion) for every seat.
- "*Propagation shortcuts*": when using regenerative systems, the sound recorded on stage or in the audience area might be addressed electronically sooner than the direct sound, which will cause localization artifacts. This problem is avoided by the active wall design.
- *Background noise enhancement*: regenerative systems are very sensitive to the enhancement of the natural background noise of the room (ventilation opening, audience noise).
- *Occupied or empty conditions*: as for natural acoustics, the behavior of the room may change drastically according to the presence of the audience. Different settings like "rehearsal", "recording session", etc… should be proposed.

5. CONCLUSION

The general principles of the main categories of reverberation enhancement systems, namely "regenerative" and "in-line" structures, have been reviewed. This paper was based on different studies that have been dedicated, in the last decade, to the assessment and improvement of these systems, notably in terms of coloration, stability, and constraints on sound recording and loudspeaker positioning. These criteria constitute a basic guideline for selecting a reverberation system in venues with a multi-purpose ambition.

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