THE HISTORY OF ACTIVE ACOUSTIC ENHANCEMENT SYSTEMS

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1 INTRODUCTION

Leo Beranek described the 100 best sounding concert halls and opera houses in the world in his book *Concert Halls and Opera Houses*[1]. Other halls, not included in his book, may sound fine as they are but sometimes the acoustics of a hall can be less than optimal to support the musical performances held in it. This can be said to be a "modern," problem because the range of musical styles with differing acoustic requirements has increased substantially since the advent of amplification. Additionally, as concert halls have aged and hence require a degree of renovation, it not uncommon for the visual aesthetic to control a higher proportion of the project budget than for acoustics, resulting in a decrease in the musicality of the room.

A more current limiting factor is the prevalence or trend for the "multi-use," hall or venue where, as well as being presented with multiple types of acoustic and electro-acoustic musical performances, there is an expectation to include provision for meetings, conferences and even surround sound cinema. These limiting factors are commonly found in the business case for a new-build or in a renovated building, which is an acceptable practice from an economics perspective i.e. increasing revenue sources and offering the maximum return on investment within the project. However they present a scenario where either the acoustics of the space are insufficient to provide good quality audio or music reproduction or they have been compromised across the spectrum to offer little or no benefit to any of the users or stakeholders.

In these cases the acoustics need to be altered or improved: internal face materials can be changed to alter the overall absorption coefficient and reflectors or diffusers can be added to further increase or decrease the reverberation field. These are the principal mechanical methods of achieving variable or amended acoustic conditions and their benefits are well known, as are their limitations. However, with the availability of advanced Digital Signal Processing (DSP), power amplification and loudspeaker systems, electro-acoustical tools are often applied to achieve similar results without the physical limitations, or perhaps with a different set of limitations that can be more successfully worked into a design solution.

Mechanical solutions, especially those attempting to make comprehensive acoustic changes, are expensive. They also have ergonomic and logistical limitations i.e. "user-friendliness," issues. In use, a mechanical solution for acoustic variability often requires the assembly and placement of heavy acoustic panels and drapes, with either manual or electrical control systems to provide physical movement. In contrast, an electro-acoustic solution offers a change in room acoustics by recalling a memory pre-set at the touch of a button. Last, but not least, current and future powerful DSP technologies and modern tuning techniques, combined with high quality electro-acoustic systems, allows the acoustic behaviour of a hall to be changed far more extensively and controllably than what is possible with practicable mechanical measures.

Although commercial acoustic enhancement systems have been available since 1959, the market for acoustic enhancement systems is not large: only a few hundred systems have been installed worldwide. Figure 1 lists the commercially installed systems referenced on the Internet from research taken in 2012, including the number of installations found for every system type or product. Only recently, have DSP and electro-acoustic components become available at a high quality against relatively low cost, initiating a faster growth in the number of worldwide system installations.

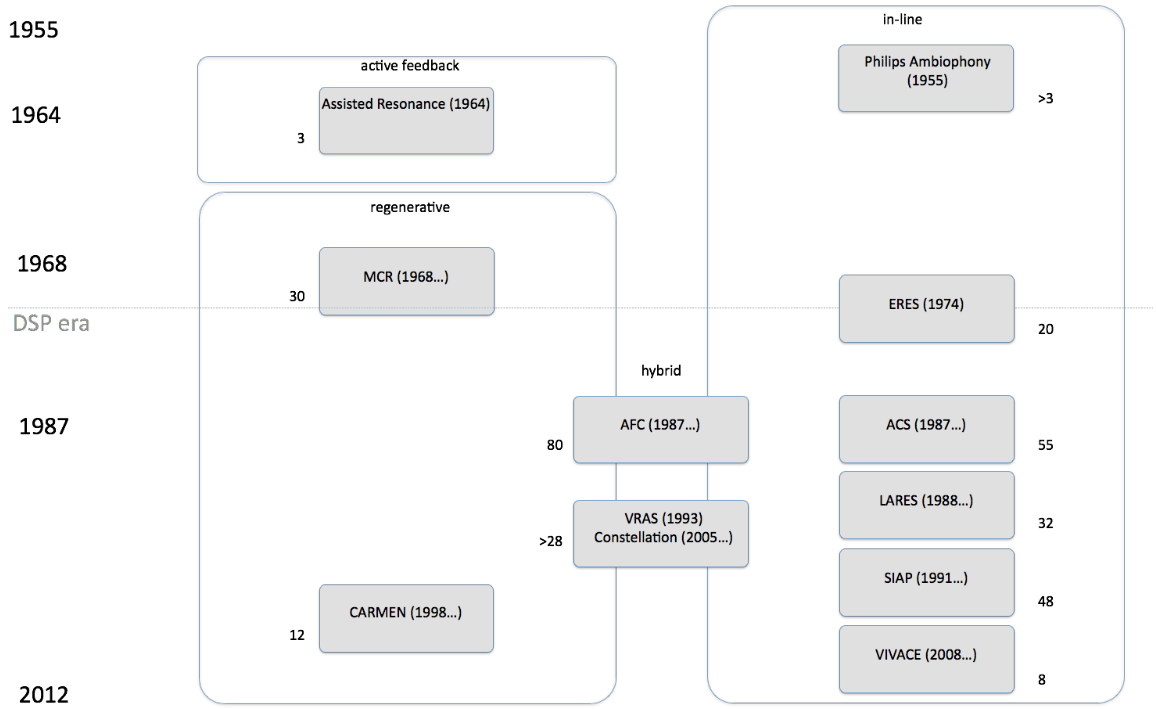


Figure 1: Historic overview of commercially available acoustic enhancement systems

2 SYSTEM CONCEPTS: REGENERATIVE AND IN-LINE

Essentially, the enhancement of the acoustic behaviour of a room can be achieved in two ways: either by synthesizing reflections based on the direct sound, or by adding reflections based on the room's original reflections.

The first method is sometimes referred to as 'Synthesis of Sound Field' S-SF[2], or more commonly as "in-line." These in-line systems work by synthesizing the required reflections in a room based on the direct sound and playing them back to the audience through a speaker system with a relatively low loop gain such that colouration or "ringing," is avoided as much as possible. If the room is highly absorbent, the result can be controlled almost completely by the synthesized reflections. However, if the room already has reflections, then the result is the sum of the original reflections and the synthesized reflections. An in-line system offers a one-way response - generating acoustic energy from the performer area to the listener area. Therefore, if the performer steps out of the performer area e.g. the stage, the system no longer works. Additionally, acoustic energy from the audience response is not included in the system's response, and it is difficult to enhance the performer space acoustics.

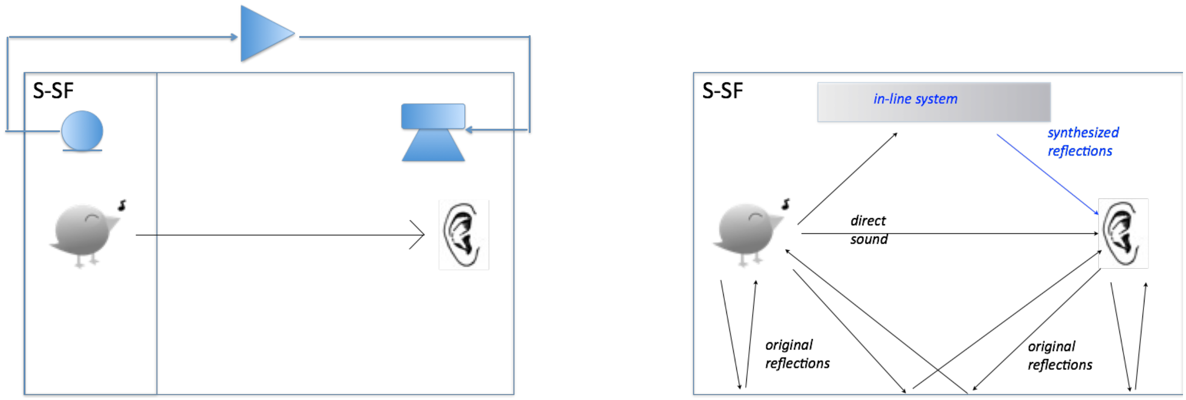


Figure 2: S-SF system concept

The second method is sometimes referred to as 'Assistance of Sound Field' A-SF, or more commonly as “regenerative.” In this design, multiple microphone/amplifier/loudspeaker channels are applied to regenerate reflections in the room, adding acoustic energy with a relatively high loop gain, but requiring additional measures to avoid colouration as a result of feedback. While regenerative systems respond very naturally - including the whole acoustic space in the resulting diffuse reverberation field - they rely, completely, on the nature and timbre of the existing room acoustics, leaving limited freedom to change the character of the enhanced acoustics.

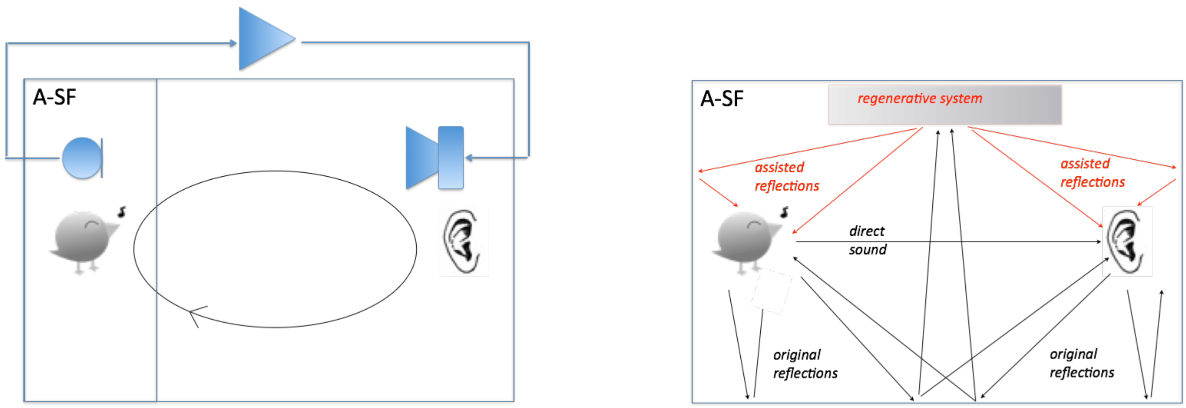


Figure 3: A-SF system concept

3 CHALLENGES

The main challenge for acoustic enhancement system designers is a familiar one in the field of sound reinforcement: if a microphone/amplifier/loudspeaker combination with a high enough gain is placed in a sound field, the sound field will be amplified, but certain frequencies will stand out, or “ring”, thus colouring the sound. If the loop gain is set to an even higher level, the system will start to oscillate at a certain frequency. The reason for this is that the open loop gain G_O of the created loop - including the electro-acoustical transfer function μ (from microphone to amplifier to loudspeaker), and the acoustical transfer function β (from the speaker to the microphone) - becomes close to or greater than 1.

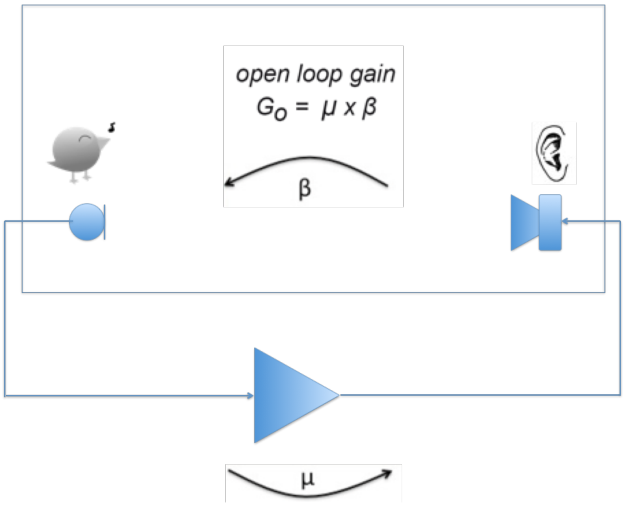


Figure 4: Open loop gain

The acoustical transfer function β consists of the sum of all reflections that occur in the hall between the speaker and the microphone. Depending on the size and shape of the hall and the position of the microphone and speaker, reflections will cancel each other out for some frequencies, and add up for others. The difference between cancellation valleys and addition peaks can be tens of dB.

Figure 5 shows an example open loop transfer function. Since β is part of the open loop gain, it becomes obvious that if the electrical gain of the amplifier is increased (increasing μ), the open loop gain first becomes greater than 1 for the frequency with the highest peak - this is the oscillation frequency. For open loop gains slightly lower than 1, the peaks will generate long reverberation times for the frequencies involved, acting as a filter and causing colouration.

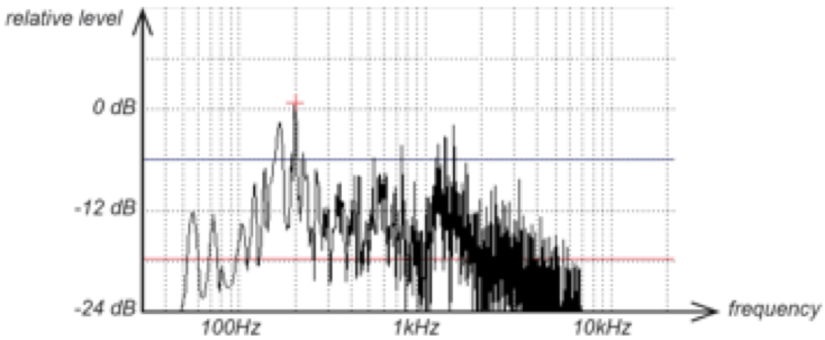


Figure 5: Open loop transfer function

To prevent colouration or oscillation at the peak frequencies, several countermeasures can be taken. Table 1 shows the available options as used by today's commercially available, active acoustic enhancement systems. Countermeasures and system types will be explained in the following chapters.

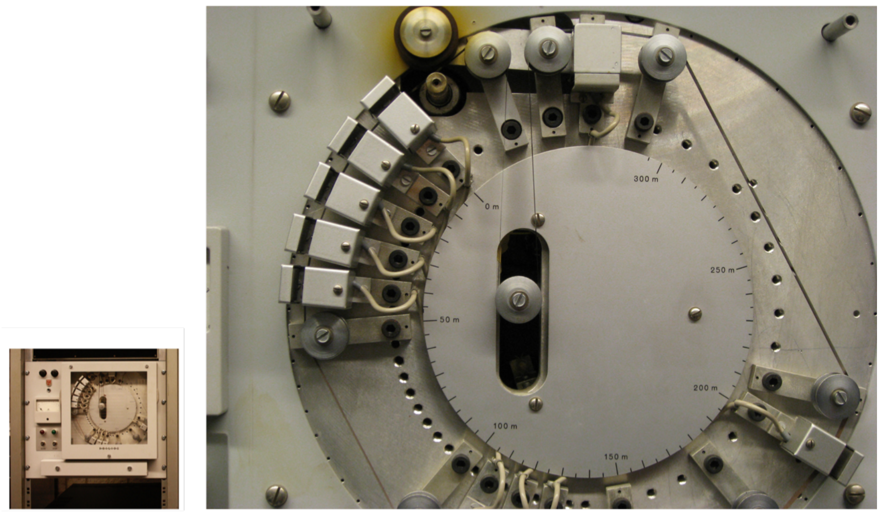
	Regenerative				In-line			
	MCR	Constellation	Carmen	AFC3	ACS	SIAP	LARES	Vivace
Use many independent channels	✓	✓	✓		✓	✓		
Use time variance					✓		✓	✓
Use spatial averaging				✓				
Use DSP/FIR		✓		✓	✓	✓		

Table 1: options to prevent colouration

Note: The above table is generated using information available on manufacturers' websites.

4 THE FIRST ATTEMPTS: AMBIOPHONY & ASSISTED RESONANCE

Around 1959, R. Vermeulen of Philips N.V. patented one of the first active acoustic enhancement systems on the market using a tape wheel or loop with a recording head and multiple playback heads to generate multiple instances of a sound field[3]. In 1975, J.C. Jaffe of Jaffe Acoustics presented a similar system - ERES - based on digital, multi-tap delay lines to generate early reflctions[4]. Both systems picked up the stage sound - including the direct sound and the early reflections on stage - and repeated the reflections in appropriate patterns to construct a realistic reverberation field in the audience part of the hall. The resulting signals are played back by loudspeakers, pointed to the audience and away from the stage microphones, creating enough gain before feedback to provide a stable system. Today, the results would not have satisfied our expectations, but in 1959 the results were perceived as excellent. This is the reason the ambiophony system was built into many halls in Europe, including La Scala in Milan.



Courtesy of Institute of Sonology at the Royal Conservatoire, The Hague, Netherlands

Figure 6: Philips Ambiophony unit

In 1964, P.H. Parkin and K. Morgan of the UK Department of Scientific and Industrial Research presented an experimental 'Assisted Resonance' system installed in the Royal Festival Hall in London[5]. Although the system was never commercially available on the market, the scientific concept is so fundamental to the field of active acoustic enhancement that it is included in most publications on the subject. Parkin and Morgan acknowledged that playing back an amplified signal from a microphone in the same space results in severe colouration, or oscillation with higher amplification. Their solution was to construct multiple microphone/amplifier/speaker loops, each tuned to a very narrow frequency band using microphones placed in tuned Helmholtz resonators, installed at locations where the loop transfer function at that frequency was at its maximum. By adjusting gain and phase for each loop, the energy increase for each individual frequency range could be controlled to achieve a stable, uncoloured result with a higher energy level, as well as a longer reverberation time. It should be noted that this system did not need to avoid feedback at all, simply because it utilised feedback as the basic principle. Although the method was very elegant and straightforward, the minimum frequency range to be controlled was found to be just a few Hertz (Hz), so large amounts of loops were required to cover the target frequency spectrum. In the initial stage of the project, 89 loops were used to cover a frequency range from 70 Hz to 340 Hz. To target a full frequency range up to 8 kHz, more than a thousand loops would be required, which is both physically and financially impractical for most halls. Nevertheless, the acoustic challenge in the Royal Festival Hall was the lack of 'warmth' - or energy in the low frequencies - so the Assisted Resonance system was a perfect solution. The system stayed in service for many years. It was enhanced to include double the amount of speakers to cover up to 700 Hz in a second stage of the experiment.

5 REGENERATIVE SYSTEMS: MCR, CARMEN

In 1969, N.V. Franssen of Philips NV, patented the concept of "Multi Channel Reverberation," or MCR, later developed further by S.H. de Koning[6]. The scientific concept of MCR is as fundamental and elegant as the Assisted Resonance concept, presenting a different approach to the same, basic challenge: how to prevent colouration and oscillation when fitting a room with microphone/amplifier/speaker loops.

Where the Assisted Resonance method uses channels with a narrow bandwidth and high gain, the MCR concept shows that full bandwidth channels can be used, as long as the loop gain per channel stays below -21dB. Channels can be added without the risk of colouration and oscillation provided the channels are not correlated i.e. they have independent open loop transfer functions. This can be achieved by carefully distributing the microphone/speaker loops across the hall. This means that to double the acoustic energy in a room (and also increasing the reverberation time), about 100 channels are required. This is a significant number, but still well below the amount of channels that Parkin needed for a full range solution. In modern systems, powerful parametric equalisers and delays can be applied to reduce the colouration, allowing 50 channels or fewer, to be used in a medium size hall.

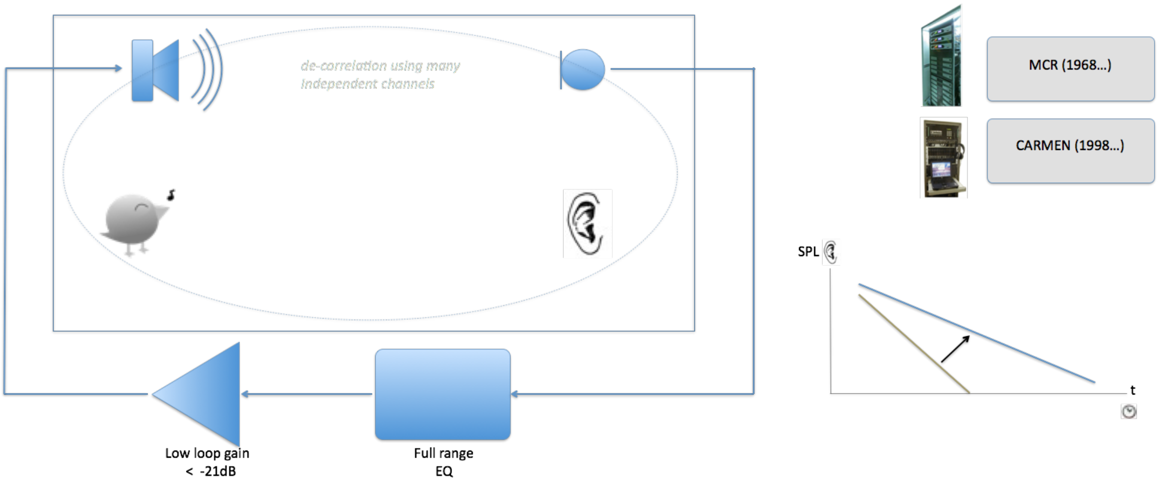


Figure 7: A-SF (regenerative) system concept

The MCR system has been built into many concert halls in Europe, and is now still offered by the Dutch company Event Acoustics as XLNT-MCR. The French public research organisation "Centre Scientifique et Technique du Bâtiment (CSTB)" developed the Carmen system - an alternative way of using the MCR concept by offering integrated microphone/speaker modules to form a "virtual wall[7]."

The advantage of regenerative systems is that they re-use (re-generate) the existing acoustic response of the hall, thus sounding very natural because the system does not add artificial content to the enhanced response. The inherent disadvantage of this design is that the enhancement of the response is limited to amplifying what is already there. In addition, making the reverberation time longer always means that the amount of acoustic energy has to be amplified: longer means louder and louder means longer. This constraint corresponds, in figure 7, with the slope of the reverberation tail changing with increasing loop gain.

6 IN-LINE SYSTEMS: ACS, SIAP, VIVACE

From 1987 to 1991, three systems were brought to the market taking a completely different approach that would break away from the regenerative "longer is louder." constraint: ACS (1987, ACS bv, van Berkhout)[8], LARES (1988, Lexicon, D. Griesinger)[9] and SIAP (1991, SIAP bv, van Munster & Prinssen)[10]. In 2008, Stagetec brought the Vivace system to the market (Stagetec, Muller-BBM)[11]. Each system uses specially developed reverberation algorithms running on DSP hardware that became available at that time, minimising acoustic feedback by placing directional (cardioid, supercardioid) microphones as close as possible to the stage so the loop gain can be maintained as low as possible. Additionally in LARES, ACS and Vivace, time variance is sometimes applied to modulate the reverberation algorithm delay times by a small amount. Although it is reported to be slightly audible in some circumstances, it suppresses feedback, avoiding colouration and instability for systems using a limited amount of independent channels. If an in-line system is installed with many independent channels, de-correlation occurs automatically, and time variance is no longer required (ACS, SIAP).

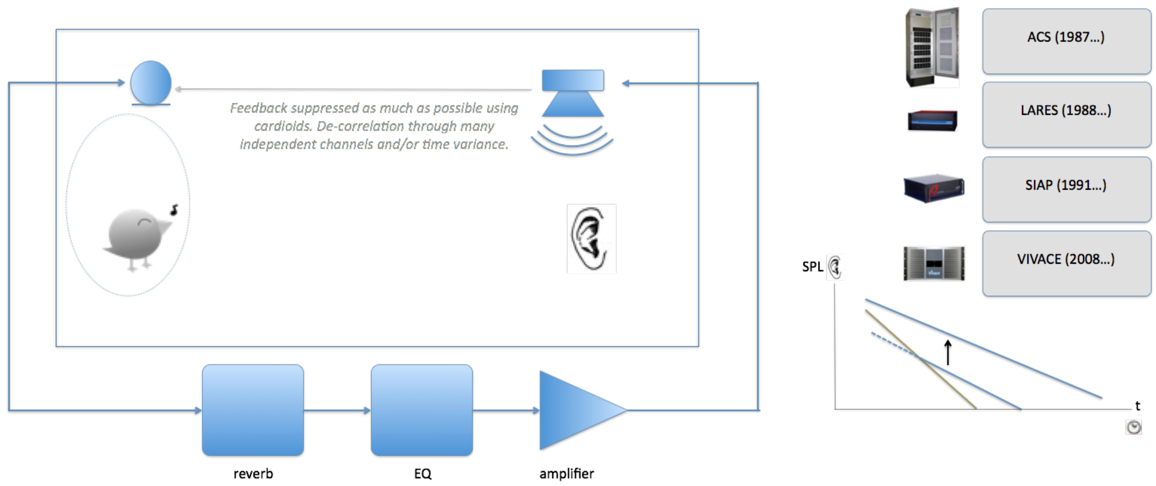


Figure 8: S-SF (In-Line) system concept

Assuming that in-line systems are feedback-free, any reverberation pattern can be added to the existing acoustics. If the existing acoustics are “dry,” (low energy/low reverberation time), the result is almost fully dependent on the active system, which is ideal to achieve multi-purpose usage of venues. Also, because the reverberation and early reflection patterns can be designed in detail, and directional microphones are used, powerful Early Reflections and localization features can be supported.

A disadvantage of in-line systems is that only the area covered by the directional microphones – e.g. the stage - is enhanced. Sound coming from other areas e.g. from the audience - are not included unless they are equipped with their own system. It is very difficult for in-line systems to support a natural acoustic behavior covering a complete hall.

7 HYBRID REGENERATIVE SYSTEMS: AFC, VRAS

Applying a combination of in-line and regenerative system concepts, a “hybrid regenerative.” system can be constructed with fewer channels compared to pure regenerative systems, e.g. with 16 microphones and 16 loudspeakers, constituting 16 independent channels. In medium sized and large halls, this is probably insufficient to increase the acoustic energy required to significantly enhance the reverberation time using only regenerative techniques. By applying a digital reverberator per channel, the reverberation time can be increased without adding energy, while the number of 16 independent channels is just sufficient to increase the acoustic energy to an appropriate level. This way, the system allows for more freedom in changing the acoustic response compared to purely using many independent channels. This approach also escapes the “longer is louder,” constraint of pure regenerative systems. An example of a hybrid regenerative system using digital reverberators within its channels is the LCS VRAS system, renamed in 2005 to Constellation by Meyer Sound[12].

VRAS still uses the method of multiple independent channels in a system to achieve a colouration free sound field, but far fewer channels than found in pure regenerative systems. To achieve consistent sound pressure level (SPL or L_P) coverage over the hall and to avoid localization of speakers, multiple speakers can be connected to each channel. It is important to note that more speakers does not constitute more independent channels - the number of independent channels is equal to the number of independent microphones.

By using a loop-flattening algorithm, the open loop gain of a system's channels can be flattened to allow for higher loop gains. This way, fewer independent physical channels have to be used to add the same amount of acoustic energy to the room. An example of this approach is the Yamaha AFC system.[13] This design uses a spatial averaging flattening algorithm that cross fades only 4 system busses through 4 microphones, preventing feedback energy from accumulating at peak frequencies[14]. Additionally, Finite Impulse Response (FIR) filters are used, to add early reflection patterns to the reverberation channels without causing colouration. Compared with the VRAS system, AFC uses fewer physical channels and fewer reverberation modules but achieves a similar result.

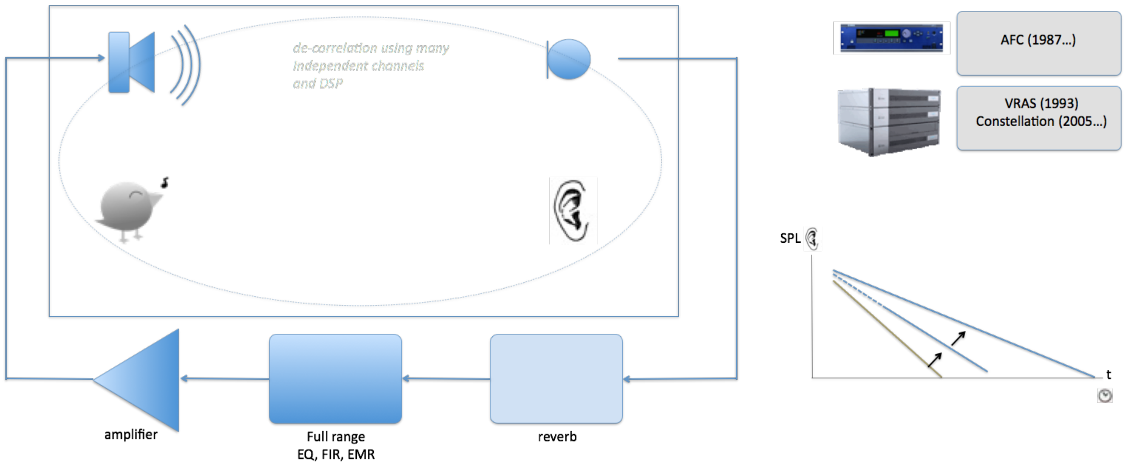


Figure 9: Hybrid regenerative system concept

8 SYSTEM APPLICATIONS

With the improved performance and affordability of DSP and electro-acoustic equipment, and the possibility of applying hybrid-regenerative systems, the acceptance of acoustic enhancement systems has increased significantly in the past decade - and continues to increase.

Although some scepticism still exists - especially in the acoustic arts such as opera and symphony orchestras, experiencing the exceptionally high quality of recently installed systems has convinced many Musical Directors, architects, consultants, musicians and investors to consider an acoustic enhancement system as a viable, cost-effective and most importantly - excellent sounding option. Some potential users may still prefer to apply a pure regenerative concept to avoid using any digital signal processing, while accepting it's constraints into the equation, while others might prefer to apply the in-line concept as an effect in a theatrical environment.

The general adoption or acceptance trend, tends towards the application of hybrid regenerative concepts. In theory these systems are able to provide both regenerative and in-line modes of operation, but the best sounding systems utilise the hybrid concept, achieving natural and powerful variable acoustics without the constraints of the single mode systems. The most obvious benefit is the improved listening experience of the audience, but perhaps more importantly, a hybrid regenerative system also improves the listening experience for the artists on stage. By regarding the artists or contributors as the primary users, the system adds positive acoustics to the sounds the artist or speechmaker creates. If the improved acoustics benefits the performance, the listening experience of the audience is even greater.

9 CONCLUSION

Being in existence for more than half a century, acoustic enhancement systems slowly but surely have become a viable option in architectural acoustics, offering excellent sounding results and providing effortless variability to support efficient venue economics. With recent improvements in digital signal processing, power amplifiers and transducers, as well as the development of enhanced hybrid regenerative modes of processing, the quality of systems has increased to an impressive level. At the same time, the cost of system components has decreased to a level where applying a system also becomes a viable option for small venues. Three types of enhancement systems are commercially available from multiple manufacturers, offering a good set of systems to choose from for individual applications. To assess if a system is suitable for a certain hall or room is easy: just purchase a ticket for an event in a similar venue, opera hall, concert hall, theatre, multi-purpose hall or auditorium, etc - that had a system installed recently. Our strong recommendation is to go on stage during or after the performance to also experience the on-stage enhancement - after all it's the performing artists who have the greatest influence on the listening experience of the audience.

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