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SYSTEM FOR IMPROVED ACOUSTIC PERFORMANCE (SIAP)

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1. BACKGROUND

1.1 The increasing sophistication of domestic hi-fi is making the public more familiar with high quality music recordings with appropriate acoustic environments selected for each recording. As the cost of attending live performances increases relative to the cost of these recordings it becomes even more important to ensure that live performances are acoustically well housed.

1.2 The relative cost of new performance buildings is increasing yet the financial strength and freedom of local authorities in Britain is diminishing and private benefaction of these buildings is rarely available. The capital cost of each building is such that a range of uses is now imperative.

1.3 Revenue account commercial pressures require chamber orchestras to perform in large halls designed for full orchestras; orchestras have to perform in halls designed for speech; orchestras and opera companies perform to huge audiences in arenas, exhibition halls and in outdoor venues. Commercial pressures also require concert halls to serve as conference halls and even purpose built opera houses have to use the same auditorium and the same acoustic for Mozart's *Cosi fan Tutte* as for Wagner's *Ring Cycle.*

1.4 The state of the art (and science) of acoustic adjustment has now reached the point where it is possible to address these problems not by compromise between conflicting demands but by adaptation of the acoustic of each room to meet ideals defined by the acoustician and the client.

1.5 In a purpose built concert hall the specific volume (m^3/person) must be about twice that for a hall meant for speech. If physical adjustment of the acoustic is to be used elaborate installations such as movable ceilings, adjustable reflectors, retractable banner curtains and so forth are necessary to be able to suitably adjust the acoustics to other purposes such as drama and opera. These devices tend to increase the building envelope and place structural loads on the building frame in an uneconomic manner. Tackling the problem in such a way is expensive and places considerable constraints on the architecture. Conversion from one mode to another can be time-consuming and therefore expensive.

1.6 Physical solutions to acoustic problem are not usually practical for the many existing theatres and multipurpose halls. There are also cases of auditoria which have proved to be acoustically disappointing or which now serve a different purpose than for which they were designed. Examples such as the Royal Festival Hall and the Barbican Concert Hall's use for conferences spring to mind.

1.7 As acoustics and theatre consultants we have been confronted again and again during the course of the years with auditoria clearly needing a considerable acoustic improvement or in which variable acoustics were desired and without any possibility of solving the problems by architectural or mechanical means. Some 15 years ago the basic concept arose of an electronic system for variable acoustics, which did not use acoustic feedback for increasing the reverberation time and which achieved the acoustic improvement taking the existing acoustic character of the particular auditorium into account.

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1.8 By 1987/1988 microprocessor technology, especially in the field of digital signal processing, had progressed enough to put the idea into practice. After a first stage of experimenting, the system was tested extensively in a number of theatres in Holland where many purpose built theatres have to serve an increasingly active concert programme.

2. STARTING POINTS FOR THE DEVELOPMENT OF SIAP

2.1 Each auditorium has its own unique acoustic characteristics. These can be expressed by a number of well established parameters like reverberation time (RT), early decay time (EDT), speech intelligibility (STI, RASTI), clarity, lateral efficiency, centre time etc. Modern measurement systems such as TEF (time delay spectrometry) and MLSSA (maximum length sequence system analyzer) are not only capable of measuring these parameters accurately but also provide the facility to analyse the reflection patterns, energy-time-curves etc. in detail.

2.2 From the beginning of the development of SIAP it has been clear that in almost all cases it is not possible to put the complete desired electronically generated acoustics over the existing natural acoustics: the natural early reflections, which play an important role in the acoustic character of each individual auditorium, are too pronounced to make such an approach successful. Furthermore for an average municipal theatre a volume of about 3500 m^3 and an RT of about 1 second are typical, resulting in a sound level in the reverberant field which makes a further significant level increase undesirable because:

- a steady-state-level rise quickly appears unnatural and gives the impression of amplification; the human ear appears to be quite sensitive to this effect.
- the loudness of a symphony orchestra or a brass band would become excessive.

2.3 Kleiner et al[1] proved that for masking or dominating the natural acoustic by an artificially generated acoustic, the artificial acoustic needs to be 6 to 10 dB louder than the natural one. This was confirmed in the experimental stage of the SIAP system in theatres. But masking is to neglect the existing natural acoustics of an auditorium. If an artificially generated acoustic, modelled on a large concert hall such as the Amsterdam Concertgebouw or the Vienna Musikverein, is used in a theatre it will result in the problem that the acoustic and visual perceptions are too different, giving the audience and performers the feeling that something is wrong. We call this psycho-acoustic effect, "dissociation".

2.4 The acoustic enhancement system discussed here has been given the name "System for Improved Acoustic Performance", SIAP. As the name indicates the system's purpose is to improve the acoustic **performance** of the auditorium, taking the acoustic character of that auditorium into account. The system is not just a reverberation system, which means that it is not solely intended to increase the reverberation time. It is an electro-acoustic enhancement system capable of influencing the relevant acoustic characteristics of a hall. The total of the direct sound, the energy ratios of early to late and of lateral to total of early reflections, the reverberation time and reverberation level are important factors which together define the acoustics of a room.

2.5 The early reflections are usually only a little weaker than the direct sound and comparatively small in number. With increasing delay time the number of reflections also increases and their individual loudness decreases. The beginning of the reverberation "tail" in auditoria of average size is about 200 to 300 ms after the arrival of the direct sound. The sound quality and naturalness of artificial reverberation are mainly achieved by the reflection density, and the extent to which the reverberant sound reaches the listener's ears from all directions with equal loudness and without noticeable source (loudspeaker) positions. It will be clear that these concepts, now generally accepted in the field of room acoustics, were the starting point in the development of the SIAP system.

3. DESIGN OF THE SIAP SYSTEM

3.1 MICROPHONES

3.1.1 A system that is applicable in theatre practice has in our opinion to meet certain demands:

- Microphones and loudspeakers must have permanent and fixed positions; if they are to be installed before each performance or concert and taken out afterwards, then it has to be expected that the system will not be used as regularly as is acoustically necessary and constant movement also makes breakdowns more likely.
- Microphones are not easily used above a stage for they obstruct the use of stage machinery, lighting and scenery and reproduce stage noises such as the clicks and bangs of heating spotlights, stage machinery, changing of scenery etc.
- In the immediate vicinity of the house curtain, microphones are difficult to use because of noise caused by the runners in the curtain tracks during movement of the curtain as well as noise from the resulting air movement around the microphones and because of shielding of the up-stage playing area by borders and/or a movable lighting bridge to adjust the stage opening height.
- For psychological reasons the microphones have to be positioned in such a way as to be as invisible as possible to the public.

3.1.2 Against this, for the acoustic performance of the electro-acoustic system:

- The whole playing area including the orchestra pit has to be covered very evenly; this is of course of vital importance for the balance of singers and orchestra in a lyric theatre performance
- The microphone-to-source distance must be short enough for the system to be able to reproduce the desired early reflections; however distances of up to 10 m are usually no problem since the distance microphone-loudspeaker plays no role; this presents an advantage over natural acoustics
- The applause of the audience has also to be picked up in order to ensure that this has the same acoustics as the sound coming from the stage. Applause with a 1 second RT after music played in a 2 second RT would sound like a very poor audience response to the performance!

3.1.3 Often in the design of a SIAP system the microphone positions are chosen above the front edge of the forestage or orchestra pit on the long axis of the hall. The microphones are incorporated in a compact cluster consisting of one or two rows of microphones and are located above the "lightlines" from the lighting galleries and the sightlines of the audience. Usually supercardioid microphones are used having a polar pattern which is frequency-independent in the range from 100 - 10,000 Hz; this prevents colouration especially of moving sound sources which is of great importance in the lyric theatre (opera, musical etc.). Not only the direct sound, but also the early reflected sound is picked up as well as some reverberation but, however, no strong late reflections. The advantages of this are that there is less dependence on the directionality and positions of sound sources and a greater reflection density in the reverberation tail, thereby improving the important naturalness of the sound.

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3.2 LOUDSPEAKERS

3.2.1 Loudspeaker positions are designed such that, in combination with the software programmed in the SIAP processor, the desired parameter values like frontal to lateral and early to late energy ratios are achieved. To make sure that in each position in the audience area as well as on stage the reverberation is heard as coming from all directions with equal loudness, it is necessary that in each position the sound that is heard is coming from all or nearly all of the loudspeakers.

3.2.2 This is achieved by using hemispherically radiating high quality loudspeaker systems which must not have a sound "character" of their own because of the required extreme naturalness of the sound. SIAP has so far obtained the best results with a number of types from the Kef product range (manufactured at Maidstone, England). The hemispherical polar pattern of the speakers which is also quite frequency independent, prevents localization of the individual speakers by the listeners.

3.3. ACOUSTIC FEEDBACK

3.3.1 As is generally known in the field of acoustic enhancement systems, the allowable gain of a single channel microphone-amplifier-loudspeaker configuration is -17 to -20 dB to prevent instability (oscillation or "howl round") and colouration (frequency selective decay or "ringing").[2,3] The consequence is, that with single-channel systems, even if very directional microphones and loudspeakers are used, the sound level of the artificial reverberation has to be set at such a low value that the Early Decay Time, the "running reverberation" which is so important for music, cannot be increased. Only the "terminal reverberation" will then be audible as a low level reverberation tail. In the SIAP system acoustic feedback is reduced by a combination of a number of measures, of which the most important are:

- Microphones with a frequency independent polar pattern, thereby reducing reverberation and late reflections from being picked up
- Equalization of each microphone to loudspeaker transfer function in 1/3 octave bands
- Division of the system in a number of subsystems (channels) each comprising one or more subprocessors
- Elimination of a residue of colouration by means of a modest and sophisticated time-variation of the reflections in the subprocessors if necessary.

3.3.2 The number of subsystems and subprocessors required is calculated during the design process of each individual system. For example, the main auditorium of the Casino Theatre (home of the regional symphony orchestra) at 's-Hertogenbosch, in Holland, comprises 12 subsystems and a total of 46 subprocessors. Each subsystem has 2 microphones which are mounted in a central cluster of 24, suspended from the ceiling at a height of approximately 10 m above the front edge of the forestage/orchestra pit. There are 46 loudspeakers, 10 of which are located in the first lighting bridge and directed to the stage area for foldback.

3.3.3 Without observable colouration a reverberation level of -3 dB at up to 3 seconds RT has been achieved without time variation; a modest time-variation allowed for an extra gain of 3 to 6dB, making possible a steady-state-level rise of 3dB over the natural reverberation level still without the slightest colouration. This appeared to be more than is needed because of the tolerable loudness of a full symphony orchestra. Experiments with system gains up to +5 dB during rehearsals of the regional symphony orchestra, revealed that a higher system gain than +2 dB is not tolerable in this auditorium, which has a volume of 6500 m^3 and a natural RT of 1.2 seconds, the loudness simply becomes excessive. In our experience and confirmed by others, an extensive time-variation can offer an extra system gain of 8 to 10 dB over non time-variant systems.[4] The disadvantage of this technique is however, that it is no longer possible to provide characteristic acoustics as the combined result of the auditorium and the system, since there are no longer typical reflection patterns generated by the processor. The system is then transformed into an ordinary reverberation system instead of being an acoustic enhancement system.

3.4. PROCESSORS

3.4.1 The combination of subprocessors forms the SIAP processor, which is fully digital. These subprocessors have a central operating system and a control panel to switch to the same settings simultaneously. By means of a simple push-button device the operator selects the desired setting for each type of performance. Usually 6 to 9 settings are sufficient to cover the range of desired acoustics for drama to symphonic and choral concerts.

3.4.2 The dynamic range of the SIAP processor is better than 95dB, i.e. greater than the dynamic range of a 120 piece symphony orchestra. Starting from a tolerable electronically generated background noise level by the system of 20 to 25 dBA in the auditorium (NR 15 to 20), the system can produce sound levels of 115 to 120 dBA in the reverberant field without distortion since plenty of amplifier power is available in each system. Limiters, compressors etc. are therefore superfluous and must be avoided since they affect the natural dynamics in music and thereby degrade the system.

3.4.3 The acoustic parameters programmed into the processor for each individual loudspeaker are amongst others:

- Reverberation times over the full frequency range
- Reverberation level
- Time delay, level and frequency response of the (early) reflections; this way a "sustain" or "plateau" of early reflections in the first 200 to 300 ms can be generated followed by the reverberation tail; this is considered by some acousticians as being a typical characteristic of a shoebox shaped concert hall
- Reflection density in the reverberation tail
- Time-variation if relevant.

3.5. SIAP PROGRAMMING

3.5.1 The system is unique in that the approach is to modify the natural acoustics by providing the missing reflections from each surface (or lack of surface) in the auditorium in question.

3.5.2 The existing acoustics are carefully analyzed for this process by means of MLSSA measurement system which provides pulse responses, energy-time-curves etc. Measurements may be made with directional microphones to obtain "geographically specific" information. For auditoria not yet built computer simulation using ray-tracing techniques and so forth are used. The system adds sound energy in the appropriate geographical position to adjust early reflected energy as well as reverberation that would be expected were the natural acoustics to be good for the purpose selected.

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3.5.3 Thus SIAP models the actual auditorium and corrects its deficiencies, accurately taking into account the important relation between the visual and acoustic perceptions. As mentioned before, too great a difference will cause the listener to develop a feeling of "dissociation". An auditorium sounding considerably wider or higher than it appears to be visually, should be avoided.

3.5.4 Acoustic shortcomings like echos, flutter-echos or excessive reverberation can of course not be eliminated by SIAP. However they can be made less disturbing: if not easily removed by absorption or diffusion, an echo can be "surrounded" with adjacent reflections making it less discretely audible. "Filling in" of reflections in the gaps of a flutter-echo appears to work in practice.

3.5.5 Adding early reflections allows us to make a reverberation tail sound less reverberant by improving the early to late energy ratio (Clarity). It is also possible to greatly reduce clarity without the need of a long reverberation time. Experiments at the Casino Theatre show:

System off: C_{80} = +6.9 dB, RT = 1.2 secs, EDT = 0.7 secs
System on: C_{80} = - 1.4 dB, RT = 1.8 secs, EDT = 2.1 secs

4. COMPARISON WITH OTHER SYSTEMS

4.1 The principle of SIAP contrasts with other systems which over the years have used different approaches. Assisted Resonance (AIRO) and Multiple Channel Reverberation, the MCR system (Philips), generate reverberation by means of acoustic feedback (recirculation of the input sound reproduced by the loudspeakers back to the microphones) and therefore have to operate close to oscillation ("howl-round"). They are therefore prone to colouration caused by frequency-selective decay and comb-filter effects. Such systems do not generate early reflections and are not (yet) capable of influencing a number of important acoustic parameters independently.

4.2 Systems have been tried to create an "acoustic holograph" analogue to visual holography by reconstructing wave fronts (as in ACS and other systems) by means of loudspeaker arrays.[5] These can only work satisfactorily in a dry natural acoustic because the synthetic acoustics need to be dominant, that is 6 to 10 dB louder than the natural one. For example, in such a system a shoebox type concert hall is electronically modelled around a fan shaped theatre with very dry natural acoustics. According to oral reports, existing systems applying acoustic holography (as is to be expected with loudspeaker arrays) show that the interference between the individual loudspeakers limits the range of a more or less successful wave-front-reconstruction to about a one or two octave bandwidth.

4.3 Since SIAP provides the reflections missing in the natural acoustics of the particular auditorium, the total result is naturally sounding acoustics without making it noticeable that an electro-acoustic enhancement system is doing a (major) part of the job. This is very different from a simple collection of digital delays and reverberation units for it contains geographically specific source information and output responses. Each processor performs the function which could otherwise be attempted only by enormous numbers of delay and reverberation units, even if suitably adjustment from programmed settings could be arranged for the multitude of items required.

4.4 As far as we know SIAP is the only system which feeds early reflections as well as reverberation and other specific information to each individual loudspeaker. Contrary to other systems (ERES + RODS, or ACS) there are no separate "early reflection speakers" and "reverberation" speakers. Furthermore for this purpose SIAP processing uses 100% digital processors (contrary to some other systems; ACS for instance uses analogue delays of the so called bucket-brigade type). Apart from the very powerful character of the processor, digital processing has important advantages:

- Full audio bandwidth 20 - 20,000 Hz
- Dynamic range better than 95 dB (not attainable with analogue delays); this makes limiters, compressors etc. superfluous since this exceeds the dynamic range of symphonic music, brass bands etc.
- Minimal distortion.

5. SIAP IN PRACTICE

5.1 Practical experience of SIAP applications have now been gained in eight auditoria. It is clear that SIAP has much to offer in the following areas:

- Variable acoustics to make an auditorium suitable for a wide range of performance use.
- Speech reinforcement (public address), particularly where there are difficult existing conditions.
- Constructing the acoustics for large scale opera productions in sports halls, arenas , and outdoors.

5.2 VARIABLE ACOUSTICS AND THE IMPROVEMENT OF ACOUSTICS

5.2.1 Since the introduction in 1989 SIAP systems have been installed in a number of existing theatres and in a new theatre where it could be incorporated in the architectural design. A number of systems are ordered for auditoria in various countries including the Cliff's Pavillion, Southend-on-Sea, here in England, re-opening in 1993 with some 1600 seats.

5.2.2 All these systems have at least 6 preprogrammed settings like the Casino Theatre main auditorium system. The following settings proved to be preferred after a number of rehearsals and concerts.

Setting	Purpose	Reverberation Time (seconds)	Early Decay Time (seconds)
0 (off)	Film, popconcert	1.2	0.7
1	Speech, drama	1.2	1.1
2	Chamber music, musical, operetta	1.3	1.2
3	Opera, ballet	1.6	1.4
4	Average symphonic music	1.9	1.8
5	Late romantic symphonic music	2.2	2.0
6	Choir, without orchestra	4.6	3.2

5.2.3 Setting 1 does not increase RT, it only adds early reflections for better speech intelligibility in the audience area and for improved foldback for the actors on stage. Setting 4 is the most popular setting for symphonic concerts. The home orchestra as well as guest orchestras like the Royal Concertgebouw Orchestra in total give about 40 concerts in this theatre each season. Musicians, soloists (including Jose Carreras), conductors as well as radio and recording engineers without exception are very enthusiastic about the achievements of the SIAP system and especially note the considerable effect it has whilst maintaining a completely natural sound.

5.2.4 In our experience a reflecting stage environment, for example a full size orchestra shell, is not needed with the SIAP system. However reflecting surfaces like a stage rear wall or a simple (incomplete) orchestra shell are recommended. The Casino Theatre already had a manageable

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orchestra shell which is still in use and works very well in combination with the foldback loudspeakers in the auditorium lighting bridge. Therefore a full SIAP stage system is not required here.

5.3 PUBLIC ADDRESS

5.3.1 When using SIAP as a public address system for speech reinforcement through close-miking, the system offers a particular advantage for "difficult" spaces. The powerful SIAP processor makes it possible to provide each individual loudspeaker system with its own appropriately delayed signal. Furthermore the achievable system gain is considerably higher than with conventional PA systems. In the central hall of the Auditorium of Eindhoven University for Technology, these characteristics of the system were necessary to design a successful PA system to replace the old unsatisfactory system.

5.3.2 The hall is of square shape (40 x 40 x 9 m^3), and accommodates an audience of over 2000 on the flat main floor and in a gallery. The SIAP system installed in 1991 comprises a central cluster of high quality column loudspeakers above the end stage, a supporting cluster in the centre of the hall and 28 speakers built into the ceiling and the gallery overhangs for even coverage of the audience and for reproduction of background music. In the unoccupied hall (RT = 2.0 s) RASTI measurements by the client exceed 0.65 in almost all seating positions and are better than 0.60 everywhere in the hall. Without the system the values are between 0.30 and 0.50. The system gain in the speech frequency range was measured to be between 30 and 32 dB resulting in a still excellent speech intelligibility with capacity audience of over 2000 noisy students.

5.4 TEMPORARY INSTALLATIONS FOR LARGE SCALE OPERA PRODUCTIONS

5.4.1 In August 1990 Sportshaal De Maaspoort at 's-Hertogenbosch was temporarily converted into a venue for an ambitious opera production of Verdi's *Aida*. The hall seated an audience of 2800 surrounding a sand covered playing area measuring 30 x 18 m^2. The orchestra platform was in a corner of the hall. Measurements during the planning of the production showed that with audience the reverberation time would drop below 1 second and that there would be a serious lack of early and especially lateral reflections. Furthermore the directionality of the human voice would cause various problems with this audience and stage lay-out. In the SIAP system design the hall was divided into a number of sections each having their own loudspeakers for frontal, lateral and overhead reverberant sound. The microphones were concentrated in 3 clusters about 8 m high above the playing area and the orchestra, of course out of the lightbeams of the spots.

5.4.2 Application of an acoustic enhancement system for such a production is a rather different approach from the PA systems which are commonly used. These normally work with great numbers of radio microphones and an elaborate mixing console with an operator, and they provide only amplification often with some reverberation effect but no real acoustic enhancement.

5.4.3 Because of the acoustic success of this *Aida* the SIAP-system was also selected for a production at the Sportshaal South in Amsterdam in August/September 1991. Although it was a repeat of the successful 's-Hertogenbosch production, the scale was somewhat larger:

-cubic volume: 40,000 m^3 (hall measures 75 x 55 m^2)
-playing area (central stage): 40 x 20 m^2 (sand covered)
-seating capacity: 4000.

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5.4.4 According to measurements the natural acoustics for opera appeared to be even worse than at the Maaspoort Hall, especially because of the complete absence of surfaces that could provide early reflections and the curved roof causing focussing effects. This was a particular disadvantage, since the seating area surrounding the stage means that a singer continuously has his back to about 75% of the audience. Here also an extensive SIAP system was installed comprising 60 microphones divided over 5 clusters 8.5 m above the stage and orchestra and 128 loudspeakers flown from the rigging divided over a number of sections as described before. Apart from the desired RT, reflection patterns etc., the system also featured correct localization of the sound sources (singers, choir, orchestra, brass group) and compensation for the directionality of the singers' voices in a natural way. The latter means that:

- Singers are heard well, no matter in which position they are projecting their voices
- The sound level and spectrum of a singer changes when he or she is turning away, but not as much as in natural acoustics.

5.4.5 Because of the large volume of the hall, a certain amplification was considered desirable. The system gain, reflections as well as reverberation, was set at 5 dB above the natural reverberation level of the hall. RT was set at 1.8 s as a result of experiments during rehearsals established in collaboration with conductor, singers and stage manager. Even the very loud fireworks at the end of Act II (the Triumphal March; approx. 106 dB(A) on the system microphones) did not overload the system and still showed a safety margin of about 10 dB. So, if enough power is available in the amplifiers, in this case a little over 12 kiloWatts peak power, limiters are indeed superfluous.

6. CONCLUSION

6.1 From the experiences gained up to now with the SIAP systems we conclude that:

- The system offers variable acoustics that are applicable in practice
- The sound quality is very natural, which together with the way the processor is programmed, makes it difficult to notice that a system is doing the job
- Large systems are applicable in practice for large scale opera and musical producions etc. as an alternative for or in combination with PA systems.
- A SIAP system can offer individually or combined in one installation both acoustic enhancement and speech reinforcement and can also provide at small extra cost the reproduction of effects such as Dolby film sound.

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SIAP is patented in the USA (1992) and patents are pending in a number of other countries.