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Active Acoustics in Concert Halls – A New Approach

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Active acoustics offers potential benefits in music halls having acoustical shortcomings and is a relatively inexpensive alternative to physical modifications of the enclosures. One critical benefit of active architecture is the controlled variability of acoustics. Although many improvements have been made over the last 60 years in the quality and usability of active acoustics, some problems still persist and the acceptance of this technology is advancing cautiously. McGill's Virtual Acoustic Technology (VAT) offers new solutions in the key areas of performance by focusing on the electroacoustic coupling between the existing room acoustics and the simulation acoustics. All control parameters of the active acoustics are implemented in the Space Builder engine by employing multichannel parallel mixing, routing, and processing. The virtual acoustic response is created using low-latency convolution and a three-way temporal segmentation of the measured impulse responses. This method facilitates a sooner release of the virtual room response and its radiation into the surrounding space. Field tests are currently underway at McGill University involving performing musicians and the audience in order to fully assess and quantify the benefits of this new approach in active acoustics.

Keywords: virtual acoustics, active acoustics, electronic architecture, adjustable acoustics, acoustic support, multichannel convolution.

1. Introduction

The function of acoustic enclosure is to contain the sound produced by musical instruments and voices, and to distribute it adequately to the musicians and the audience. How well this is accomplished depends on the acoustical design of the enclosure taking into account the musical purpose the space is intended for. Different schools of acoustic design employ own tested methods and achieve varied results, especially when multipurpose auditoria are concerned. Modern designs must also consider the listeners' aesthetic bias or preference shaped by experience gained from listening to recorded and reproduced music as well as amplified music. For example, the currently popular 'vineyard terrace' design of concert halls initiated by Lothar Cramer in the Berlin Philharmonie in 1962 is thought to be influenced by the aesthetics of reproduced sound (Gade, 2010). Gade stated this as follows: "Probably influenced by the large consumption of recorded music, clients of today are not just interested in reverberance when listening in the concert hall. They also want a very clear and present sound – like when they listen to recordings through their hi-fi set at home" (Gade, 2008). In this publication Gade compared the values for Reverberation Time and Clarity measured in the occupied seats of the new Aarhus concert hall as well as simultaneously captured through the recording chain of Danish Radio. The values of Clarity and Reverberation were substantially higher in the recording chain than in the audience seats because balance engineers added more than half a second of artificial reverberation to the natural impulse response measured in the hall. They also placed the microphones close to the sound sources on stage, which has generated 4 dB higher clarity than measured in the seats. Interestingly, the values of Early Decay Time measured in the seats and through the recording chain were similar.

One of the methods of achieving simultaneously the presence and the reverberance in a passive acoustic design is to use connected volumes, usually with an adjustable coupling between them. This method typically provides an early presence from one room with an augmented reverberance from the other. A good example of connected spaces is a concert hall where two spaces of 'stage' and 'auditorium' are coupled and feed the acoustic energy into each other. Some concert halls, typically designed by ARTEC Consultants of New York, have the reverberation chambers built near the ceiling that can open or close additional volumes to the main room.

One of the earliest papers advocating the use of variable passive acoustics was published in 1931 by Ernst Petzold (Petzold, 1931) who proposed methods to regulate the acoustics with rotating triangular columns covered alternatively with reflecting, absorbing or resonating acoustic materials. Petzold stated the need for variable acoustics in his introduction as follows: "There is no room for which the lighting and heating cannot be regulated. Why not regulate also the acoustics, all the more, since this is urgent?" A well regarded example of modern facility with variable passive acoustics is IRCAM's ESPRO (Espace de Projection). The variable acoustics hall designed in 1978 by Peutz & Assoc. allows a change of volume from 276 to 3906 cubic meters by rising and lowering the ceiling, and an additional change of reverberation time by automatically rotating wall panels having different acoustic surfaces.

2. Virtual acoustics

Virtual acoustics refers to the process of producing the illusion in a listener of being in a "virtual" acoustic environment that is entirely different from that of the space in which the listener is actually located. Active acoustics indicates the generation of a perceived simulated room response by means of electroacoustics and digital signal processing. The artificial room response may include reflections and reverberation as well as other acoustic features mimicking the actual room. Their presence will cause the listener to have an impression of being immersed in virtual acoustics of another simulated room that coexists with the actual physical room. Depending on the strength of the acoustic response from the actual room, the auditory awareness of the listener may be either dominated by the real or by the simulated environment, or equally by both, although the visual awareness also contributes significantly to the sense of acoustic reality.

Virtual acoustics is also called 'active electronic architecture' as it is produced by 'active acoustics system', in a distinct difference from 'passive architectural acoustics'. An active acoustics system is able to generate active *variable* acoustics, an artificial response that can be adjusted electronically without the need for physical changes required in the case of passive variable acoustics.

2.1. Active systems

While the quality of early active acoustics systems from the 1960's was poor and relying on magnetic tape delays and tube amplifiers, the most modern systems use massive multichannel signal processing devices and powered low-distortion loudspeakers and microphones. The purpose of the early systems was merely to generate assisted resonance or assisted reverberation (Olson, 1959; Parkin, Morgan, 1964).

The technology generating virtual acoustics can be divided into *in-line* and *non-in-line* systems as presented by Svensson and Poletti (Svensson, 1996; Poletti, 2010). The *in-line systems* use a few close microphones to capture the acoustic source, from which they create digitally generated early reflections and reverberation, and radiate the mixture into the room via a large number of loudspeakers. Such systems include LARES (Lexicon Acoustic Reverberation Enhancement System), SIAP (System for Improved Acoustic Performance), and AFC (Active Field Control). For a comprehensive overview of all active systems, the author refers the reader to two publications listed in the references (Prinssen, D'Antonio, 1997; Poletti, 2010).

The *non-in-line systems* capture and regenerate the ambience existing in the room using multiple microphones and loudspeakers distributed around the room. The goal of such systems is to amplify the reverberation using multiple feedback loops between microphone and loudspeaker channels. Such systems include MCR (Multiple Channel Reverberation), MCA (Multiple Channel Ambiophony), ACS (Acoustic Control System), and VRAS (Variable Room Acoustics System). The Meyer Constellation system (Schwenke, Ellison, 2010) and the other systems using this approach increase the reverberation time by reducing the variance in damping of natural modes with the increasing number of channels. The Meyer system includes an early reflection generator and a multichannel reverberator between microphones and loudspeakers (Poletti, 2007; 1999). This approach employs both the regenerated ambiance and the added early reflections and reverberation, and seems to combine the best characteristics of the two system types.

Most recently at IRCAM in Paris, the ESPRO 2.0 (Espace de Projection) has been equipped with digital SPAT (Spatialisateur) driving 2D WFS (Wave Field Synthesis) system containing 280 loudspeakers as well as 60 loudspeaker 3D HOA (Higher Order Ambisonics) system. Details of this implementation are not yet known to the author.

2.2. Applications

Artificial acoustics may be used to augment the existing acoustics or to create new acoustic environments. Active enhancement systems can supply the missing acoustical features and thus expand the usability of the space to support functions now deemed important. This may include extending the reverberation time to accommodate romantic music in an auditorium designed for speech communication, or improving stage acoustics for the ensemble of musicians by allowing them to hear each other and their own sound production more clearly.

Virtual acoustics may also be used in music recording allowing the musicians to control their interactions with a virtual room during the performance. This makes possible a musical interpretation that is adapted to and affected by a specific acoustics, which is not possible to achieve later in the post-production process. Such technique was used to record all keyboard sonatas of Haydn in nine virtual rooms using seven different instruments as originally conceived by the composer (Woszczyk *et al.*, 2009a).

2.3. Advantages

From the initial goal of repairing bad acoustics due to errors in the design and construction of music rooms, there has been a substantial progress in using active acoustics to expand acoustic capabilities of the enclosure. And the improved understanding of the field of electronic architecture allows this technology to be integrated into the design of newly constructed facilities from the early planning stages. This can greatly improve the performance of multi-purpose facilities that have to adapt to a wide range of events from spoken word, to theatrical, to symphonic performances. When a high enough quality level can be achieved, variable electronic architecture may create vastly improved musical experience by immersing the artists and the audience in a range of precisely tuned and orchestrated sonic spaces.

2.4. Restraints

As of today, virtual acoustics systems still face challenges in delivering superior acoustic performance and meeting the expectations of the users including performers, critics, and members of the audience. Some users expect changes of acoustics to be dramatic, easily tunable, and simple to implement. However, as in physical acoustics, sonic environments must remain stable, dependable and constant rather than surprisingly different each time a performer returns to give a concert. Electronic enhancement of natural acoustics cannot be perceived as just an effect but rather it must render a true representation of the best natural acoustics if it seeks to receive a wider acceptance.

There is also a stigma attached to the belief that any enhancement is fundamentally unnatural and should not be trusted and accepted (Poletti, 2010). A belief persists that any amplification or electronic enhancement of the natural sound is bound to change the acoustic personality of an instrument or voice, and by doing so take away from their naturalness and musicality. Thus, if employed, electronic enhancement is often hidden and not obviously acknowledged. Nevertheless, modern systems can now offer improvements that go far beyond fixing bad or insufficient acoustics. They can provide affordable acoustics of equal or superior value to the passive designs found in variable architecture, although they can easily add but not subtract the acoustic energy.

A robust protection is needed from acoustic feedback in all active systems that capture, amplify and radiate sound back into the capture zone. Using high feedback loop gains may result in instability, sound coloration and howling that are highly undesirable distractions in music. Time variance, mostly done with frequency shifting, is used in some systems (e.g. AFC and LARES) to reduce the risk of instability (Kawakami, Shimizu, 1990; Griesinger, 1991). Simulated early reflections are typically time-invariant because any pitch shifting due to variance processing tends to interfere with tuning and intonation in music even if it may seem acceptable in speech.

Poletti (Poletti, 2010) compared the stability of time-varying and time-invariant systems and concluded that the improvement in stability produced by time-variance is marginal when larger numbers of microphone-to-loudspeaker channels are used. For 16 and more channels the useable loop gain is the same and no benefit in stability may be attributed to time-variance. Therefore, in-line systems using a small number of microphones tend to use time-variance to increase feedback margin whereas non-inline regenerative systems that use larger numbers of channels are time-invariant. Large systems with multiple channels offer excellent stability and regenerative systems that use additional synthetic in-line reverberation can produce substantial extension of the reverberation time without dependency on excessive loop gains.

3. A new approach to active acoustics at McGill University

The audibility of simulated acoustics is achieved by means of loudspeakers therefore both the type and the location of the loudspeakers play a critical role in the intended outcome. A typical solution practiced by the industry is to employ monopole radiation type loudspeakers flush-mounted into the walls and the ceiling of the enclosure. This method is expedient because it allows the active enhancement system to be hidden in the room boundaries, where the speakers, the wiring and the mounting hardware find structural support. However, there are some negative consequences of this solution, which need to be addressed.

First, the loudspeakers located at room boundaries are far away from most of the audience members and from the musicians, causing the sensations produced by the enhancement system to be reduced. In the middle of the audience area, the audible presence of the virtual enclosure becomes minimized due to a considerable distance from all loudspeakers. For audience members near the walls, virtual acoustics is usually too strong in amplitude and may be localized in the direction of the nearest wall. This creates a contradiction because the room and its ambience are continuing beyond the wall, which is obviously not the case visually. The aural contribution of the ceiling loudspeakers down at the plane of the audience is likewise limited in amplitude due to a substantial distance. Distance also results in late arrival of the critical components of the simulations.

Secondly, the power response of a flush-mounted monopole loudspeaker is not flat requiring a compensating equalization that makes the diffuse field generated by such loudspeakers evenly balanced across the radiated power spectrum. However, the compensating electronic equalization makes worse the on-axis free-field response of the loudspeaker, so now creating the flat diffuse field response produces a penalty that restricts the placement of the loudspeakers to within largeer distances from the musicians and the audience.

Thirdly, the in-wall loudspeaker location is not ideal for dispersing the contributions of active acoustics into the existing acoustic enclosure. This may limit the coupling between the virtual and actual rooms, and their acoustic presence may become perceptually separated and independent, and therefore less natural sounding.

The new method of active acoustics originated at McGill University (McGill VAT – Virtual Acoustics Technology) employs omnidirectional loudspeakers to supply the simulated early reflections and reverberation into the room. The dodecahedrons are suspended freely in the airspace above, have flat power and flat free-field pressure response and do not color the diffuse sound field in the room, therefore the compensating equalization is not needed.

3.1. Loudspeakers

The omnidirectional loudspeakers are suspended in an open space above the stage and the audience. The dodecahedron type radiators are positioned relatively close to the performers and the audience members allowing them to hear the benefit of active acoustics directly and via the diffuse field of the room. Each of the loudspeakers radiates a mix of early, mid, and late portions of the impulse response representing the simulated room. The goal is to radiate these parts adequately into the existing room so that they may become sufficiently diffused within the enclosure. This is where the loudspeakers' omnidirectional radiation pattern reveals strong advantage. Both the room and the listeners benefit equally from all loudspeakers unrestricted by their directivity. Omnidirectionality produces rich and dense sonic presence of the virtual room within the existing room. Loudspeakers' contribution to the room sound is flat and no equalization of the speaker signals is required to achieve a flat diffuse field response and a natural sounding reverberation.

The omnidirectional loudspeakers employed in the McGill VAT system are distributed in the room in three dimensions, in width, depth, and height. This has proven to render a deeper natural sounding auditory presence of the virtual room and a more effective coupling between the virtual and actual room. Rather than on the room boundaries, the loudspeakers are now distributed in the central open space of the room near the people. Figure 1 illustrates how the loudspeakers are distributed in the McGill VAT system.

Fig. 1. McGill Virtual Acoustics Technology applying horizontal and overhead radiation of early, mid, and late components of measured spaces to support live music performance in existing natural acoustics.

The McGill VAT system uses multiple microphone-to-loudspeaker channels and employs an in-line synthesis of a complete room. The 16 dodecahedron loudspeakers contain 192 individual radiators that create multiple channel loops with eight microphones. Each of the loudspeakers radiates a different balance of early, mid, and late components of the simulated room therefore multiple loops are created for each time segment of the synthetic room. The McGill VAT system uses as little regenerative ambiance as possible and instead renders a strong measured virtual enclosure within the existing room.

3.2. Electroacoustically coupled spaces

Coupling a virtual room electroacoustically onto a physical room may create a total combined response that is similar to the response of passively coupled rooms. What is different when applying active acoustics is that virtual room can be adjusted to be just as prominent as the actual room, or even more aurally present than the physical room. Consequently, the rendering quality of virtual rooms must be superior to the quality of an average sounding physical space. This is why the measured multichannel impulse responses used for the convolution originate from the very best acoustical enclosures.

The electronic architecture allows much more flexibility in coupling an active enclosure to the physical architecture than it is possible with two physical spaces joined together. Virtual room may be adjusted to dominate the perception of auditory space or to merely augment some aspects of it. The measure of successful outcome is the perception of unity, of well matched integration of the physical and electroacoustic architectures into a single plausible and fully functional auditory space. The electroacoustic coupling may offer benefits but it may also lead to some detrimental outcomes for musical performance. Virtual room's energy onset and dissipation occur via the physical room and must be carried out with a broad linear spectrum, good tonal balance, and accurate dynamics. If the coupled room responds late to the musical signals, its energy loads the tail end of the combined response of the enclosures, which pulls back in time its interactive acoustic support of the musical performance. This perceived 'dragging' of the room makes musical performance difficult. The McGill's VAT system is able to release the early, mid, and late response components of the virtual enclosure with adjustable amplitudes and time delays, so that even the late segment may be introduced early into the existing enclosure. The early release of the synthetic response may enrich the room acoustics without pulling the energy too far behind the pulse of the music. This is one of the benefits of the segmentation and of multiple low-latency convolution processing featured in the McGill system.

Since the physical room is the acoustical processor of the loudspeaker generated synthetic room, its response follows in time the electroacoustic rendering of virtual acoustics. Both the amplitude and latency of the simulated room segments, and the distribution of the dodecahedron loudspeakers in the room must be carefully planned, implemented and tested using different program material. The Space Builder engine stores the presets of the balances of loudspeaker and microphone signals together with the selected measured room impulse response data for subsequent recall.

3.3. Microphones

The microphones capture direct and reflected sound of the source, the ambient sound of the stage and the auditorium, and the virtual acoustics response of the enhancement system radiated by the loudspeakers. All these sound contributions should be captured without tonal colorations as they arrive at the microphones from multiplicity of directions.

Active acoustics employs multiple microphones placed in the room to collect the sound with which to feed the enhancement system. Depending on the distances of the microphones to the sources of sound on stage, the enhancement system will use either more of the direct or the ambient sound. Regenerative systems employ room microphones whereas in-line systems use stage microphones. Because of the substantial latency and insufficient level of source sound in the room microphones, regenerative systems are not capable of creating a complete simulated response of a virtual room. Their purpose is mainly to increase the gain of the reverberant energy and thus the reverberation time of the existing room. Microphones located near the stage can be used to create a completely new virtual room with strong early reflections and reverberation to complement the existing room in all aspects of the room response.

3.4. Preferred microphone type and placement

The majority of active acoustic systems use unidirectional microphones to capture the sound from which the electroacoustic response of virtual room is derived. However, the polar pattern of a unidirectional microphone is not independent enough of frequency and direction for use in the ambient sound field of the room. The benefit of directional attenuation at a specific angle of incidence does not offer any useful advantage in such field because there are too many angles of sound approaching the microphone. Directional alignment of the axis of maximum attenuation (180° for a cardioid microphone) with the direction of undesired source of sound (such as a loudspeaker) might be a difficult task to carry out. Moreover, directional microphones of pressure-gradient type have insufficient low-frequency response for sources that are more than 1 meter away, and for plane waves in general. Such attenuation of low-frequency response applied to both the direct and ambient sounds results in a reduced fullness of the virtual room that limits the contribution of the enhancement system to the overall sound.

Because of these factors, the McGill VAT system uses microphones with 'wide-cardioid' characteristics showing a mild directivity that is sufficiently broad and useful in balancing the sound contributions from the stage and the auditorium. The microphone combines the characteristics of the omni and of the cardioid, however its directivity does not increase with the rising frequency similar to the omni. Its smooth on and off axis response extends to the lowest frequencies and this maintains the fullness of the captured sound used for the convolution. A wide-cardioid directivity pattern with a consistent directionality throughout its frequency range is especially recommended when the microphone exhibits a slight boost in high-frequency response (in order of +4 dB at 7 kHz) giving it a flat diffuse field response and a desirable brilliance of direct sound for sources at larger distances from the microphones. The off-axis attenuation is 4 dB at 90° increasing gradually to 11 dB at 180°, which is sufficient to control the balance between the sounds of the stage and the auditorium.

The McGill VAT system incorporates both 'stage' and 'off-stage' microphones all located relatively close to the sources of sound assuring low latency of virtual acoustics. The off-stage microphones allow the system to process any audible audience reactions and this improves the sense of realism within the synthetic space. The microphones are distributed from the left to the right side of the stage and their signals feed the corresponding loudspeaker areas also distributed from the left to the right. This supports the directional distribution of the stage sound within the rendered virtual acoustics. Each loudspeaker generates all three components of virtual room: the early, mid, and late reflections and reverberation, all in the proportions determined by the distance of the loudspeakers to the stage. For example, the loudspeaker in the rear of the auditorium far from the stage radiates predominantly the late and mid response of the virtual room, while the loudspeaker close to the stage generates a strong early response. Spatial distribution and orientation of sound sources on stage is therefore reflected in the directionality of the response from the virtual room towards the stage and the audience. Because of this, singers and players on the stage hear the returning synthetic room response as they would in the real hall. The electroacoustically coupled room in the McGill VAT system does not merely produce an equivalent of a back-door reverberation chamber, but rather a fully functional complete room superimposed on the physical room, yet with highly selectable and adjustable response.

3.5. The Space Builder engine and the control interface

The generator of the virtual rooms in the McGill VAT system is a low-latency multichannel convolution engine processing three-dimensional multichannel impulse responses of the measured rooms. Twenty-four impulse responses are measured in each room location in width, depth, and height directions. Because impulse responses are segmented into early, mid, and late portions on the time axis, the convolution is done separately for each of these segments and each loudspeaker radiates an appropriately adjusted balance of the three parts. This permits the use of a higher magnitude level of early reflections in some loudspeakers and a stronger reverberation level of the late part of the simulated response in the other speakers. We can also combine the impulse response segments from different measured rooms into one hybrid room response by choosing the most desirable features from each individual room. Such composite room does not exist in nature but it may be created virtually in an acoustic space. For example, a high density of the 'early' reflections from a smaller room may be combined with a 'mid' response from a medium size church, and the 'late' response from a large cathedral or a concert hall, which would normally lack strong early reflections. The details of room impulse response segmentation can be found in the related publication (Woszczyk *et al.*, 2009b). Twenty-four channels of hardware convolution produce only 10 milliseconds of system latency (Anderegg *et al.*, 2004). System controller, signal routing, mixing and distribution, plus equalization and convolution processing are all integrated in the Space Builder rack (Woszczyk *et al.*, 2010a). Figure 2 shows the block diagram of the Space Builder. The added feature of time delay adjustments in the Space Builder allows the mid and late segments to be advanced it time relative to the early segment because separate convolutions of all segments may be initiated at the same instance of time. This feature allows for the late parts of the response to appear closer to the early reflections. The Space Builder rack plus the microphones and loudspeakers with their respective wiring and interfaces constitute the complete McGill VAT system.

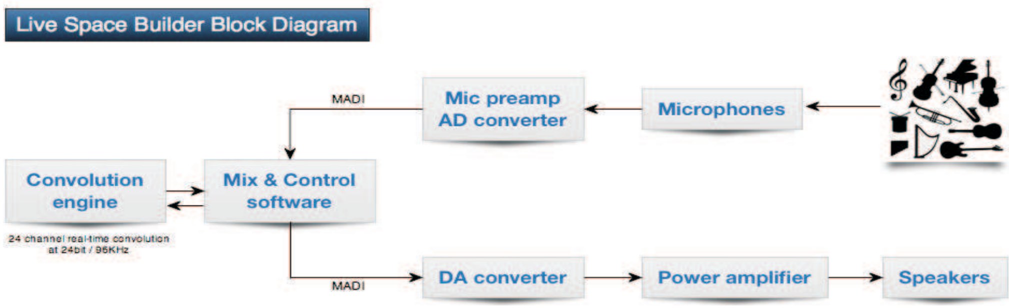

Fig. 2. Block diagram of the Space Builder.

4. System performance verification

Some verification is desirable of the contributing quality of active acoustics to the overall acoustical performance of the enclosure. Both the physical measures and subjective assessment ought to be carried out, although typically in the industry only questionnaires are used to poll the opinions of audience members and musicians. Sometimes, opinions of expert acousticians are solicited based on their experience and analytical listening skills. The McGill VAT system has been tested with respect to its ability to provide useful acoustic stage support for musicians. Although only horizontal linear-array type loudspeakers were used for these tests to generate virtual acoustics, the methodology described in the related publication may serve as a useful model for future tests (Woszczyk *et al.*, 2010b).

Two violinists were performing duets while sitting at three distances from each other (1 m, 7 m, 13 m) in a large rectangular room. The musicians were receiving virtual acoustic support in the horizontal plane from an active system radiating early, mid, and late components of another measured space. The performances were evaluated blindly by fellow violinists judging perceived "musicality" and "ensemble". In addition, tempo, synchronicity, and sound pressure level were measured using the analysis of recorded close microphone signals. With musicians seated 1m and 7m apart, and the virtual acoustic support system on, the musicians achieved better performance than with the system off. The improvements in sound field conditions were also verified objectively by measuring the support quantities ST1 and ST2 indicating the degree to which the room supports musicians by supplying acoustical reflections.

The authors suggest that not only questionnaires and physical sound field measures such as Support ST1 and ST2 should be used, but also tests should be carried out showing the actual improvements in the musical performance with the enhancement system on and off. Such tests evaluate the improvements in the ensemble quality, synchronicity of players, errors in articulation and intonation. The tests are based on the analysis of the recordings made with unidirectional microphones placed close to the musicians who are immersed in different acoustical conditions provided by the virtual acoustics system. The recordings only reveal the direct musical performance and not the acoustical conditions surrounding the musicians.

5. Essential remarks

Most of the active acoustics systems merely boost the energy of reverberation tail and do not deal sufficiently well with the early reflections. The segmentation of the impulse responses introduced by Woszczyk (Woszczyk *et al.*, 2009b) allows the McGill VAT system to run several simultaneous convolutions of the time segments in parallel and to adjust the relative time of arrival and the output level of each convolution according to the acoustical requirements of the room and the music. It is generally best to release all time segments of the room response at the same time, as early as possible, in order not to retard the room response away from the music. The unavoidable latency in electronic architecture is due to the delays in acoustic propagation from the sound source to the microphones, and from the loudspeakers to the audience and to the room boundaries. The accumulated delay might be substantial and consist of, for example, 20 ms from source to microphone, 30 ms from loudspeaker to listeners, 30 ms from loudspeaker to room boundaries, and 50 ms of latency in signal processing (e.g. convolution). Such summed delay would put the onset of the virtual room response some 130 ms behind the direct sound, which would inhibit musical communication in the concert hall and weigh heavily on the timely responsiveness of the acoustics to the music. By using parallel segmented convolutions and smaller distances to loudspeakers and microphones McGill VAT system is able to advance in time the delivery of electronic architecture compared to other systems.

6. Conclusions

The new approach in active acoustics offered by the McGill Virtual Acoustics Technology (VAT) contains a number of departures from the solutions practiced currently by the industry. These departures include the use of low-latency multichannel convolution, the measurement and temporal segmentation of the measured impulse responses, the use of omnidirectional loudspeakers arrayed in three dimensions close to the stage and the audience, and the use of quasi-directional microphones with smooth off and on axis response. All of these changes amount to a substantial cumulative improvement in the quality of active acoustics, and to its greater adjustability and usability in music related applications.

Research has shown (Gade, 1989; Dammerud, Barron, 2008) that the most useful portion of room response for a performing musician is the early part, which improves the audibility of musicians' own sound and that of the fellow players in the ensemble. The late response becomes audible either as 'stop reverberation' during breaks in the music or within the early decay time as 'running reverberation'. Timely delivery of the early specular and diffuse reflections to the musicians and the audience are therefore a critical requirement of virtual acoustics, and a considerable challenge. The core principles of McGill VAT are ultra low latency from convolution (10 ms maximum), shorter distances from sources to microphones and from loudspeakers to listeners, and zero additional delays in delivering the time segments of simulated acoustics. This means that only the early portion (the first 80 ms) of the simulated room response is delayed, whereas the mid and the late responses are not delayed and may actually arrive slightly early, mixing appropriately with the time response of the physical room.

What remains, therefore, is the challenge of delivering the early sound (the initial 80 ms) with as little latency as possible. To solve this, the McGill VAT system generates the early sound out of the direct sound captured by microphones, reproduced immediately through the loudspeakers without electronic processing. The direct sound is redistributed to the omnidirectional loudspeakers, which then radiate the direct sound energy as specular and diffuse reflections, together with the products of the convolutions. This is where the omnidirectional radiation pattern of the loudspeakers gives the most desirable benefit of approximating the directivity of diffuse and specular reflections for the aural appreciation of all listeners. Continued work is conducted on further improving the McGill VAT system with the intent of delivering the ultimately flexible and powerful tool offering active architecture for musical applications.

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