Designing the Concert Hall of the 21st Century: Historic Precedent and Virtual Reality

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INTRODUCTION

There has been a revolution in the design of concert halls in recent years that has had several major components. First has been a rigorous examination of the renowned "shoe box" concert halls of the late nineteenth and early twentieth centuries such as the Grosser Musikvereinsaal in Vienna, the Concertgebouw in Amsterdam and Symphony Hall in Boston (Johnson, 1990).

A more complete understanding of the acoustical qualities of these halls has been undertaken using a variety of techniques developed in allied disciplines. These studies have identified the interactions among the architectural design features and acoustical qualities of the rooms (Siebein, 1994; Chiang, 1994; Beranek, 1996). The techniques used in the studies are listed below.

1. impulse response testing and digital signal processing from electrical engineering
2. laboratory studies of sound quality by human listeners from psychology and neuroscience
3. advanced quantitative tests to determine primary perceptual factors, preference spaces and correlated architectural features of rooms from statistics
4. three dimensional computer and physical modeling of sound propagation in complex spaces from computer science and physics
5. qualitative evaluations of many performances in many rooms by researchers, consultants and musicians
6. deliberate experimentation by consultants and architects to test emerging theories in a series of actual buildings over a thirty year period to evaluate the consequences of this work in holistic architectural settings
7. advancements in virtual acoustics, audio recording, playback and control from digital signal processing and virtual reality.

The combining of these techniques in a hybrid design and research method has resulted in the development of new theories of concert hall design that have been centered on the development of impulse response test techniques.[1]

THE IMPULSE RESPONSE

The impulse response is a physical measurement of the response of a room to a single, impulsive sound. The direct sound and all of the subsequent reflections from the room surfaces are recorded. This is intended to represent the effects of sound reflections from the room on a single musical note or a single syllable of speech. The loudness, frequency content, arrival time and direction of the sound reflections can be identified from an impulse response.[2] Please refer to figure 1. There are three primary components to the impulse response recorded at a seating location in a room.

1. The direct sound is the sound wave that travels directly from the source to the listener without striking any of the surfaces of the room. It is the first sound wave that arrives at a listener's location. It contributes to sensations of loudness, clarity and localization.
2. The early sound reflections are sound waves that strike one of the room surfaces and are reflected to the listener's location. Reflections that arrive within short time intervals after the direct sound (less than 80 milliseconds for music) are usually combined with the direct sound by the ear. These reflections add to the direct sound increasing its apparent loudness. If the reflections arrive within 40 milliseconds or less after the direct sound, they will also contribute to a sense of acoustic intimacy. Early reflections that arrive from the sides of the listener's head also contribute to sensations of envelopment and widening of the acoustic image of the sound source.
3. The reverberant sound field consists of sound waves that have been reflected from multiple surfaces before they arrive at the listener's ears. They travel long distances between reflections and are therefore are progressively reduced in loudness from the direct sound and early reflections. The reverberant sound field may persist for two seconds or longer in concert halls. It contributes to sensations of reverberance. If the reverberant sounds arrive from many directions and are not exactly the same at the two ears of people listening, it will also increase the

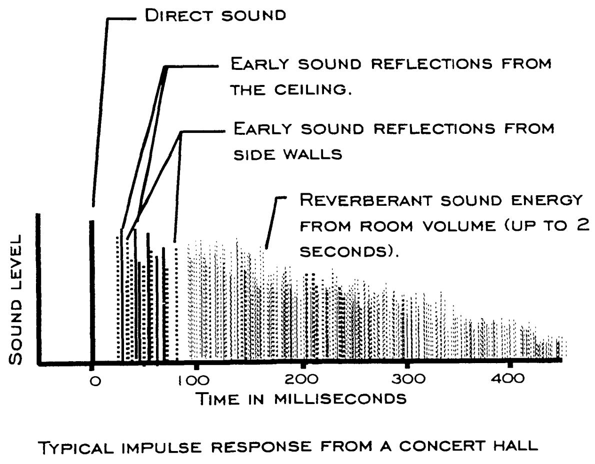


Fig. 1. Diagram of a typical impulse response.

sensation of acoustic spaciousness in the room. If the reverberant sound field has strong low frequency or bass components, it will increase the sense of warmth in the room. If it has strong higher frequency or treble components, it will contribute to the perception of brilliance.

The impulse response is unique to each seating location in a large room because it is derived from the specific paths that the direct sound and all the subsequent sound reflections take as they move from the each source to each receiver. Within large rooms, significant variations in impulse responses have been found. These differences among impulse responses in a room provide physical evidence that helps to explain why certain seats are perceived as being better than others (Beranek, 1996; Kuttruff, 1991; Siebein, 1994).

APPLICATIONS OF THE IMPULSE RESPONSE

Impulse response tests have been the catalyst that has unified the knowledge gained from the disparate fields discussed above into a unified set of design principles that can be analyzed and applied in practice. Impulse responses have been recorded in many concert halls and theaters around the world (Barron, 1993; Beranek, 1996; Carvalho, 1994; Chiang, 1994). This catalog of impulse responses for specific seats in specific halls provides a data base for architects and consultants to use in the design and evaluation of rooms.

There are a number of acoustical measures that can be calculated from the impulse responses. These include reverberation time, early reverberation time, early to late temporal energy ratios such as the clarity index or C80, loudness or strength, lateral fraction, interaural cross correlations and support (Ando, 1985; Barron, 1993; Beranek, 1996; Schroeder, 1965; Siebein, 1994).

LISTENING IN ROOMS

There have been several major studies where questionnaires have been given to people to evaluate the acoustical qualities of rooms during live or recorded performances. The scores for these qualities have been statistically related to the architectural features of the rooms and with acoustical measures (derived from impulse responses) made in the rooms. These studies have identified significant architectural features that contribute to one or more of the acoustical qualities as defined by people listening in the rooms (Barron, 1993; Beranek, 1996; Cremer, 1982; Gade, 1989; Hawkes and Douglas, 1971; Schroeder, et al, 1974).

Many acoustical consultants and researchers spend a lot of time listening in as many different rooms as possible to performances by as many different groups as possible. This allows them to develop a personal, experiential catalog of acoustic impressions and architectural environments that can be related in a cause and effect manner. They will also interview musicians, music directors and critics to gain critical evaluations of many rooms.

Case studies of impulse response measurements made in a number of concert halls have revealed many subtle relations among the architectural features of rooms, the acoustical qualities of the rooms identified by people listening in the rooms and the sound reflections that create these sensations. This has enabled theories that relate the sense of acoustical intimacy for example to the time interval between the direct sound and the first reflection from the room surfaces. In many instances, the impulse response study was conducted after the qualities had been identified by a researcher or consultant through listening in rooms. Table 1 presents a summary of current hypotheses linking acoustical qualities with physical acoustic phenomena, architectural design features of rooms and acoustical measures that have resulted from this research effort (Beranek, 1996; Siebein, 1994).

ACOUSTICAL MODELING

Modeling of sound propagation in computer models of rooms has advanced to the point where the paths of individual sound reflections can be traced through a room to multiple listening locations. The computer models can produce impulse responses from a number of sound sources to locations selected throughout the room in relatively short periods of time. One can chose any of the individual sound reflections in an impulse response and see which architectural surfaces it has struck on its path from the source to the listener. Many of the acoustical measurements derived from impulse responses in actual rooms can also be calculated by the acoustical modeling software packages. Several efficient algorithms have been developed to approximate sound diffusion in recent years increasing the accuracy of the computer models greatly.

Similar analysis can also be undertaken using physical scale models of rooms. Spark impulses or pseudo random noise signals propagated through small loudspeakers are used as source signals and played into scale models of rooms. Impulse responses can be obtained from these sources at a

Acoustic Quality	Architectural Feature	Description of Event	Acoustic Measure
Envelopment & Source Width	Narrow rooms from 70 - 80 feet across Multiple tiers of narrow balconies	Early Sound reflections arriving at the listener from the side (up to 80 ms after the direct sound	Lateral fraction (LF) LF < 0.40
Clarity	Sound reflecting ceiling ceiling canopy parterre walls	Sound reflections that arrive shortly after the direct sound	Clarity Index (C_{80}) Early to Late Energy Ratio
Reverberance	Large room volume, sound reflecting materials, "shoe-box" shape, acoustical banners and reverberation chambers	Prolonging of sound in the room	Reverberation Time (RT) (2.0 sec)
Loudness	Room size (1000 - 2000 seats) proximity to source and sight lnes	Sound reflections from the ceiling and walls shortly after the direct sound	Loudness (G) or Relative Strength (G)
Intimacy	Orchestra in same room volume as audience	Arrival of the first sound reflection from a building surface shortly after the direct sound	Initial Time Delay Gap (ITD) (<20ms)
Warmth	Heavy massive building materials	Persistence of sound at low frequencies or extended low frequency reverberation.	Bass Ratio (> 1.0)
Brilliance	Heavy massive building materials	Persistence of sound at high frequencies or extended high frequency reverberation	Treble Ratio (> 1.0)
Spaciousness	Surface Texture and sound diffusing materials large room volume	Late sound energy arriving from the sides (after 100 ms)	Interaural Cross Correlation IACC (<0.50)
Localization of sound	Clear sight and sound line between listener and source	Strength of direct sound relative to subsequent reflections	Early Loudness Level
Ensemble	Overhead and side wall sound reflecting surfaces at performance area	Sound reflections that allow the musicians across the stage to be heard	Support

Table 1. Summary of current hypotheses linking acoustical qualities with physical acoustic phenomena, architectural design features of rooms and acoustical measures that have resulted from this hybrid research and design effort.

variety of locations in a scale model of a room being designed. Changes can be easily made to the model allowing several alternative design schemes to be explored. An iterative series of impulse responses can be obtained that allows one to understand the acoustic effects of their design decisions while the building is still in the early stages of design.

It is also possible to mix or convolve music or speech recorded in an anechoic environment with impulse responses obtained from scale models or computer models of rooms that are being designed resulting in an aural simulation of the acoustical qualities. One can then listen to the aural simulation of music or speech as it would sound in the room that is being designed. One can compare the aural qualities of scheme 1 with scheme 2. For example, one could compare the aural effects of changing the angle of a ceiling panel or widening the room somewhat (Beranek, 1996; Siebein, 1994).

LABORATORY STUDIES OF SOUND QUALITY

Once one has developed a holistic understanding of the acoustical qualities of rooms derived from listening and measurements in situ, further study can proceed by isolating variables in laboratory tests. Sound reflections from architectural surfaces that contribute to the impulse response can be isolated and studied effectively in physical or computer models of rooms. How individual sound reflections contribute to impressions of acoustical quality can also be studied in laboratory situations.

Recordings of anechoic music that have been mixed or convolved with the impulse response of a specific seat in a hall can be altered and played back to listeners through headphones or loudspeakers in an acoustical listening room so they can qualitatively evaluate the simulated sounds. Similarly, using digital signal processing equipment, rever-

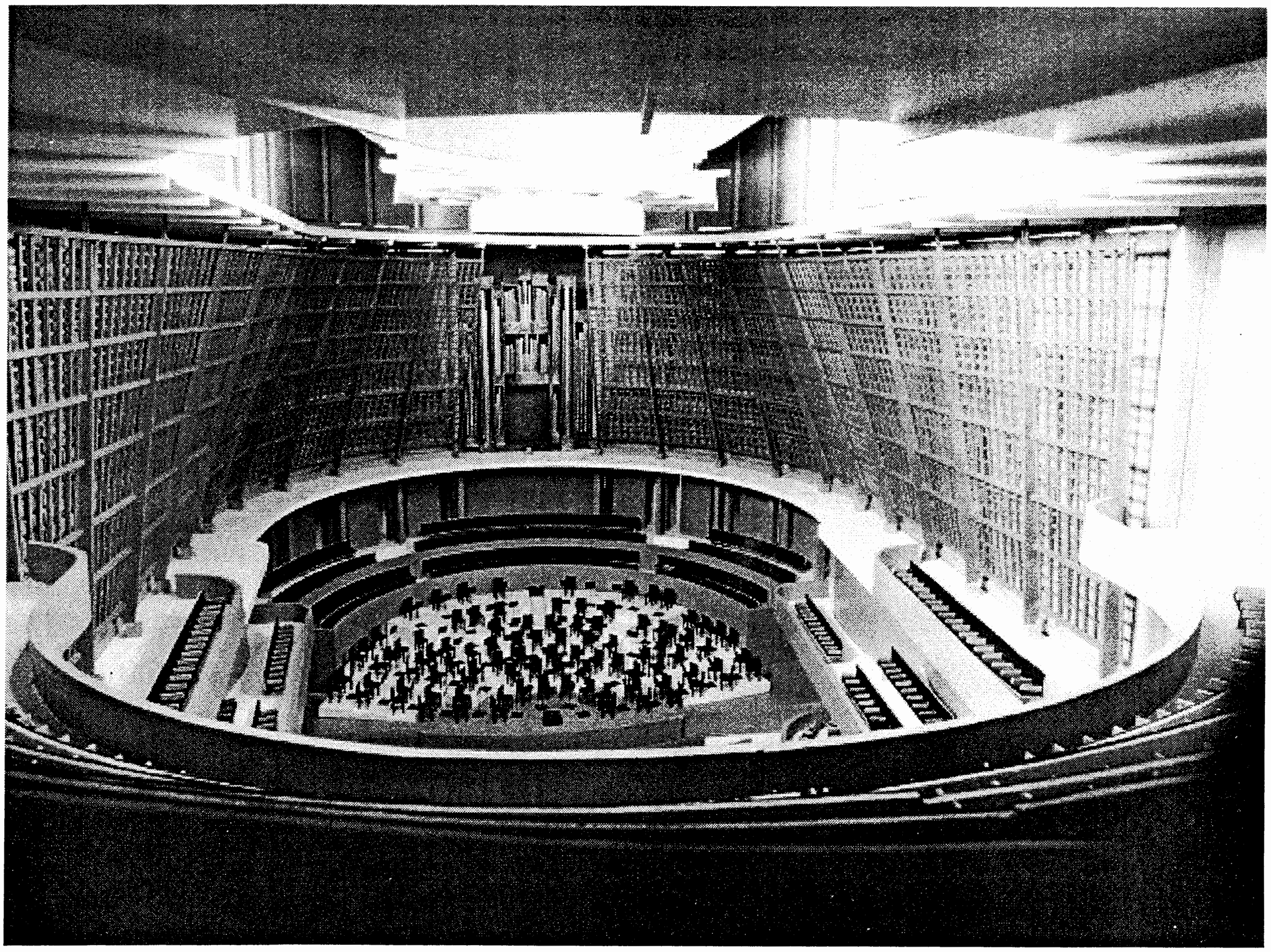


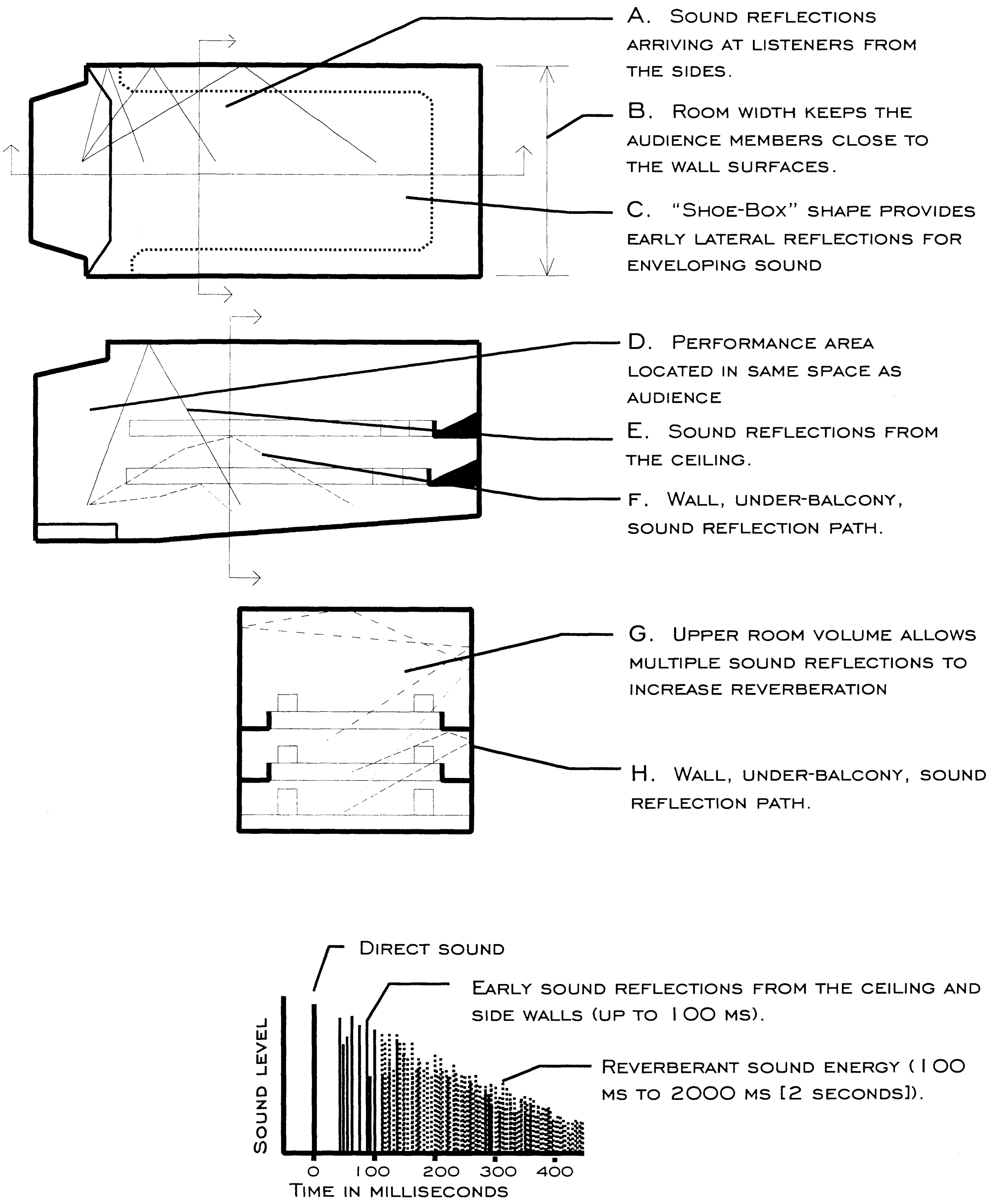
Fig. 2. Acoustical model of a new concert hall in the Singapore Arts Center constructed and tested at the University of Florida with Stirling/ Wolford Architects and Artec Consultants, Inc. This hall is an example of the Concert Hall of the 21st Century described below.

beration and individual reflections can be added to music or speech. The reflections can be programmed to come from specific directions, at specific loudness levels and at particular time intervals after the direct sound to simulate the effects of reflections from a ceiling or wall in a room. The arrival time, frequency content, loudness and direction of the reflections can be changed to simulate a second location for a wall or an alternative material selection. The second sound can be played to listeners so they can give an appraisal of the relative qualities of each condition (Ando, 1985; Beranek, 1996; Blauert and Lindeman, 1986; Cremer, 1982; Gold, 1994; Haas, 1972; Soulodre and Bradley, 1994).

This ability to isolate specific sound reflections in a complex impulse response has been a major contribution to the understanding of room acoustics. One can identify which reflections are responsible for specific sound qualities. One can also identify which architectural features of the room have produced the reflections. This allows one to design the aural environment of rooms and evaluate the aural consequences of the design before the room is built in a manner that is similar to the way in which architects have traditionally designed the visual environment of rooms.

NEW METHODS FOR ACOUSTICAL ANALYSIS AND DESIGN

The concert hall of the 21st century has evolved as an interesting hybrid that assimilates principles of shape, proportion, material, configuration and program from the historic precedents of the late nineteenth century. The acoustical and architectural qualities of the halls of the future have been extended beyond those of the precedent halls through an extensive research effort that has been integrated and explored in practice in an exemplary manner. The remarkable acoustical qualities of these halls have been obtained in a rich and varied contemporary architectural vocabulary. The acoustical attributes of the precedent halls have been identified through impulse response tests conducted in the rooms. Aural simulations have been used in laboratory studies to evaluate the subtle qualities of sounds heard in the precedent rooms. These techniques allow specific acoustic or architectural variables to be isolated and examined in detail. This hybrid method that combines architectural analysis of historic halls, qualitative evaluation performances in existing rooms and simulated sound fields in the



IMPULSE RESPONSE FROM PRECEDENT CONDERT HALL

Fig. 3. Summary of the architectural features of precedent halls.

laboratory, impulse response measurements in buildings and models and a series of actual buildings constructed over a thirty year period has produced the first series of successful halls since the end of the last century (Johnson, 1990; Siebein, 1994).

THE ARCHITECTURAL AND ACOUSTICAL QUALITIES OF THE PRECEDENT HALLS

The concert halls of the late nineteenth century were relatively narrow rooms with a high ceiling and parallel walls. There were several narrow balconies wrapped around the sides and rear of the rooms. The walls and ceilings of the rooms were built of heavy, massive materials, yet they were covered with ornate, diffusing surface textures. The halls provide a rich blend of articulate, clear sound that is simultaneously enveloping and richly reverberant. A summary of the architectural features of the rooms and the corresponding acoustical qualities is presented below.

1. Narrow room width. The rooms were typically 70-80 ft wide. This narrow width allows sound reflections from the side walls to arrive at the listeners' ears shortly after the direct sound. These early lateral reflections contribute to a sense of acoustic envelopment and a broadening of the apparent size of the acoustic source (Barron, 1993).[3]
2. Shoebox shape. The long, parallel side walls that resulted from the shoebox shape helped to increase the sense of reverberance in the rooms. Multiple sound reflections would move between the parallel surfaces from the front of the room to the rear. This would create a longer reverberation time than would otherwise occur for a room of a given volume and absorption (Johnson, 1990).[4]
3. Multiple tiers of narrow balconies. The rooms were wrapped with two or three tiers of narrow balconies. These balconies extended along most of the length of the side walls and along the rear wall. In some halls these balconies even wrapped around the front wall of the room behind the orchestra. There are several interesting acoustic effects that are attributed to these tiers of narrow balconies (Johnson, 1990).

   Sound from the orchestra could be reflected from the bottom of the balcony to the side wall of the room and back to the center of the main floor. This "cue ball" reflection contributed to the sense of acoustic envelopment in the rooms and also made the acoustic image of the sound source appear wider than it actually was (Barron, 1993; Cremer, 1982).

   The faces of the balcony rails were usually curved or ornately detailed so they would diffuse sound into the room. This surface would help create the differences in the sounds that arrive at the left and right ears of the listeners increasing their preference for the sound field (Gold, 1994).
4. Room size. The rooms were relatively small by today's standards. There were usually between 1,000 and 2,000 seats in the rooms. The room surfaces are located in close proximity to listeners in rooms of this size so sound reflections can arrive at their ears shortly after the arrival of the direct sound. These early sound reflections will heighten sensations of clarity and intimacy. The sound will also be louder in a smaller room. Adequate loudness is an important factor that contributes to the dynamics of music.[5] It is also important in providing the balance between loud crescendos and very quiet, subtle moments when only a single string or flute may play (Beranek, 1996; Johnson, 1990).
5. Ceiling height and reverberation. The precedent concert halls typically had high ceilings and a relatively large room volume that contributed to the rich, full, reverberant sound for which they are known (Beranek, 1996; Johnson, 1990).
6. Ceiling height and early sound reflections. The high ceiling height, however, did not provide an overhead surface close to the main floor seating from which early sound reflections could arrive at listeners ears. The early sound reflections from overhead have been shown to increase the sensations of loudness and clarity if the reflections arrive within 80 milliseconds after the direct sound (Haas, 1972).

   Many musicians have trouble hearing each other or maintaining a sense of ensemble in rooms where the ceiling is too high. Musicians rely on sound reflections from the stage enclosure to keep time with each other and to maintain a sense of ensemble (Beranek, 1996; Gade, 1989; Siebein, 1994).[6]
7. The location of the orchestra. The orchestral platform was located within the main volume of the room. Many halls even had some seating behind the orchestra. This resulted in an enhanced sense of acoustic intimacy in the rooms.[7] It established a direct connection between the music played by the performers and the audience that far exceeds that which is achieved when an orchestra plays within the confines of a proscenium stage (Johnson, 1990).
8. Floor slope and seating. The low floor slopes and unupholstered seats in many of the precedent halls contributed to relatively high loudness levels. As the floor slope increases, more of the direct sound strikes the absorbent surface of the audience and is attenuated. This absorption is increased when heavily upholstered seats are used (Johnson, 1990).

   Strong direct sound waves and early reflections also allow one to localize or pinpoint the position of the sound sources on stage. This is an interesting acoustical quality because one notices that composers deliberately move the source of sound through the orchestra at various moments in a musical piece (Siebein, 1994).
9. Materials. The materials in the rooms were generally heavy and massive. Thick plaster that was richly detailed, masonry walls and other heavy construction materials were typically used. These materials are sound

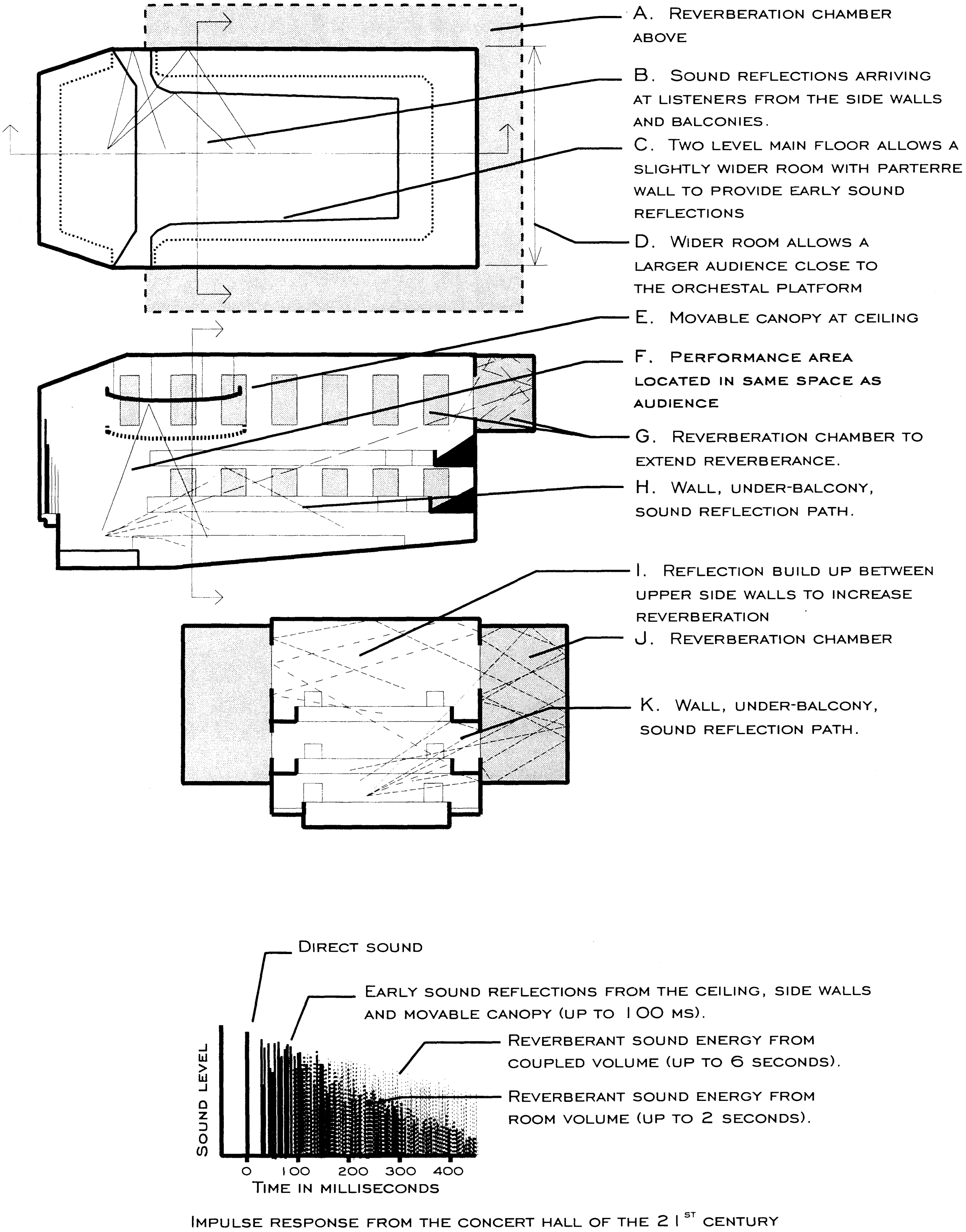


Fig. 4. Summary of the architectural design features of the Concert Hall of the 21st Century.

reflective in all frequencies.[8] The relatively large surface areas insured that even low frequency sounds with long wavelengths would be reflected in the room. There were few if any sound absorbent surfaces used in the rooms with the exception of the audience and seats. This resulted in maximizing the reverberation time and loudness in the room for a given size and shape (Beranek, 1996, Johnson, 1990).

10. Textured walls and ceilings for sound diffusion. The walls and ceilings were usually covered with surfaces that would diffuse the sound. Sound diffusing surfaces included the faces of several narrow balconies that lined the walls; the recesses and protrusions of pilasters and other plaster relief work; and statues or large niches that lined the walls. The diffusing surfaces would break-up or scatter the sound that hit them. This would cause the sound to actually reach the listeners' ears from many different directions. A sense of acoustic spaciousness was achieved by the distinctly different reverberant sound fields that arrive at the left and right ears of people listening in the rooms (Beranek, 1996; Chiang, 1994; Schroeder, 1974).[9]

EXTENDING THE ACOUSTICAL QUALITIES OF THE PRECEDENT HALLS

The Concert Hall of the 21st century returns to these precedents as its basic parti. It extends the acoustic potential of performance and the architectural envelope of space by adapting the form of the precedent halls to the needs and desires of the future. Massive, moveable canopies are placed over the stage to improve the sense of ensemble among the performers and to provide variability in the response of the room to accommodate various types of orchestral performances. The sensation of reverberance can be increased rather dramatically by coupling large adjacent volumes to the hall itself through a series of operable openings. These reverberation chambers have been extremely successful in the new halls at Dallas and Birmingham. Acoustical banners can be lowered to cover portions of the side walls of the room to allow the room to change from very reverberant to extremely dry. The design features of these rooms are summarized below (Johnson, 1990; Siebein, 1994).

1. Canopy. A large sound reflecting canopy is constructed to float above the orchestral platform and the front rows of seats to enhance several of the acoustical qualities of the precedent halls. The height of the canopy can be adjusted in many rooms to accommodate a variety of performance types. Early sound reflections from the orchestra will strike the canopy and arrive at listeners' seats shortly after the direct sound. These early reflections will contribute to an enhanced sense of acoustic intimacy, increase the loudness level at main floor seats and increase the perception of clarity in the room. Some of the early sound reflections from the canopy will also be directed back to the musicians across stage increasing the sense of ensemble or support.

   The canopies can also be raised and lowered to change the acoustical qualities of the room for different types of performance. For romantic symphonies with full orchestra, chorus and organ, the canopy will be located very high in the room. This allows the full organ sound to propagate into the room. It also allows the sound of the large source (orchestra, chorus and organ) to mix or blend somewhat in the vicinity of the platform before it moves into the room. The high canopy location also provides the maximum access of sound to the reverberation chambers allowing extremely long reverberation times to be achieved in the rooms.

   When smaller groups such as chamber orchestras perform, the canopy can be lowered. This allows the strongest sound reflections from overhead to move towards the audience and arrive at listeners' locations closer in time to the arrival of the direct sound. This will enhance the sensations of intimacy and clarity of string passages for example and increase the relative loudness level of the weaker source.

2. Reverberation chambers. Large, sound reflective volumes are acoustically coupled to the main room volume to increase the sense of reverberance, spaciousness and warmth in the rooms. Large, massive doors can be opened or closed allowing more or less sound to move into the reverberation chambers. The sound will reflect off surfaces within the chambers and then move back into the main room volume. Recent concert halls in Tampa Bay, Dallas and Birmingham incorporate reverberation chambers with volumes that are equal to more than one half or more of the volume of the main house. Designs for newer halls in Singapore and Kobe have even larger reverberant chamber volumes that are equal to or greater than the volume of the main house.

   The doors that couple the chamber volume to the main house can be opened and closed in a variety of configurations to extend the rich reverberant sound up to six seconds in some cases. The sound from the chambers enters the main room at a lower sound level than the decaying sound field in the room. This creates a decay curve with two slopes. First is an early decay that falls off relatively quickly in the main room volume. This provides clarity and loudness for the music. Second is a later decay at a more gentle slope as sound from the chambers continues for quite some time. This adds a rich, but clear reverberant quality to the sound in the room.

   The extent to which the chambers have become an integral part of the design of many concert halls has increased over time as well. In Tampa Bay, the chambers covered only the upper portions of the room. The reverberant sound was perceived as coming from above or hovering above the room. Beginning with the Dallas hall and continuing through the halls currently under design in Singapore and Kobe, the chambers not only surround the upper portion of the room, but also extend down the side walls. This allows the reverberant sound to be heard as coming from all parts of the room, immersing the audience in the fullness of the music. The reverberant chamber concept and the resulting double sloped decay have allowed the apparently paradoxical conditions of clear and reverberant sounds to coexist in the same room. This series of architectural experiments has contributed a new acoustical condition to the palette of designers.

3. Acoustical banners. Sound absorbent panels or retractable banners are also used in the new concert halls. At times when the room should be acoustically dry, such as during a rehearsal or during a speaking function, the banners or panels can be extended to cover most of the wall surfaces in the room. This will reduce the loudness and reverberance in the room. It will provide a suitable environment for amplified speech for a lecture or debate. Some smaller areas of banners may be used when chamber groups or renaissance music is played in the hall where clarity is more important than reverberance and fullness. When the hall is used for concerts, the absorbent materials are usually stored behind the walls where the sound from the orchestra can not strike them.

CONCLUSIONS

The Concert Hall of the 21st Century is emerging as an exciting acoustical and architectural building type. The acoustical qualities of these rooms have been developed through careful studies of historic precedents, modeling, simulating, listening and designing in a hybrid design method. The impulse response has been the catalyst that has fused current knowledge in music, electrical engineering, computer simulation, virtual reality, architecture, acoustics and statistics in a highly successful approach to design rooted in knowledge that is emerging from all of these constituent disciplines (Beranek, 1996; Johnson, 1990; Siebein, 1994).

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Fig. 5. The new symphony hall in Birmingham, england by Artec Consultants, Inc. represents one of the interim steps in the emergence of the Concert Hall of the 21st Century.

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ENDNOTES

[1] The impulse response test method was borrowed from digital signal processing. It is a basic premise of linear systems theory. If a system under test is subjected to an impulse, the response obtained is a result of the properties of the system plus the characteristics of the impulse.

[2] Impulse responses were originally recorded from a hand clap, a bursting balloon, a gun shot or an electronic pulse played through a loudspeaker. They were recorded on oscilloscopes and photographed for analysis. Currently sophisticated pseudo random noise signals such as maximum length sequences and complex sine sweeps are programmed in signal processing software in a portable computer, sent through a digital to analog converter, amplified and played through loudspeakers into the room. The pseudo random noise signals are more repeatable than the actual impulsive sources such as the hand clap or gun shot.

[3] The lateral fraction is an acoustic measure that relates the amount of sound that is received at a seat from the sides to the total sound energy that arrives at the seat. The lateral fraction has been related to the acoustical quality of envelopment and source width in laboratory studies where simulated sound fields were constructed to isolate the acoustic effects of early lateral sound reflections.

[4] Reverberation time is the amount of time it takes for the sound to decay to a level that is 60 dB less than the original level. It is derived from a least squares fit of the reverse integration of the impulse response of a room.

[5] The relative strength or relative early loudness are acoustic measures of loudness. Many of the precedent halls have remarkably consistent loudness levels throughout the rooms.

[6] The hearing conditions on stage are currently evaluated by an acoustical measure called support. The energy of reflected sounds heard on stage are recorded over short time intervals. The time intervals were chosen based on interviews with musicians regarding stages where adequate support for their listening was provided by the room.

[7] The sense of intimacy is related to the initial time delay gap. This is the difference in arrival time between the direct sound and the first reflection from the room surfaces.

[8] The bass ratio is an indication of the relative warmth or the support of bass or low frequency sounds in the room. It is a ratio of the reverberation times in the lower frequencies to the reverberation times in the middle frequencies. The bass ratios were usually high in the precedent halls.

The treble ratio is an indication of the relative brilliance or support of higher frequency sounds in the rooms. It is a ratio of the reverberation times in the higher frequencies relative to the reverberation times in the middle frequencies. The treble ratios tended to be fairly high in the precedent rooms as well.

[9] The interaural cross correlation or IACC is a physical measure that is intended to indicate the relative dissimilarity of the sounds that arrive at the left and right ears of people. In laboratory studies it has been found that seats in rooms that have low IACC values are generally preferred by listeners. This would mean that people prefer listening to music where the sound that arrives at the left ear is different than the sounds that arrive at the right ear. Most of the precedent halls have relatively low IACC values.