Broadening the Range of Variable Reverberance

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ABSTRACT

Broadening the range of variable reverberance. Russell Johnson and Robert Essert (Artec Consultants Inc, 245 Seventh Avenue, New York, NY 10001) **PACS: 43.55.Br, 43.55.Fw.**

Variable sound absorbing banners, curtains and panels have been incorporated into many performing arts facilities over the past three decades. These passive systems allow the building users to **reduce** the level and/or length of the reverberance from what would be the basic decay of the room. These systems are typically used to provide a dry acoustical environment for sound system use and some portions of the classical repertoire. Recently several halls have been completed that make use of partially coupled reverberation chambers to **increase** the level and/or length of reverberance without changing the basic shape, dimensions or materials in the audience chamber. With operable shutters at the boundary between the audience chamber and reverberation chamber and with sound absorbing curtains in the reverberation chamber, the overall reverberant decay can be tailored to provide a long decay without significant decrease in clarity. Issues of volume, surface area, coupling area, materials, shape, and location of the reverberation chamber will be discussed.

Introduction

For so-called "dedicated" concert halls and theatres as well as for multi-purpose halls, a building owner's goals often include the need to provide excellent acoustics for a wide range of performance types and a wide range of repertoire. Today's concert halls and theatres are used for jazz and popular music, recitals, chamber music, lectures, product launches, and an ever-expanding range of musical repertoire. A hall built to accommodate a symphony orchestra will be called on to be excellent one day for early nineteenth music played by 14 musicians, and another day for Mahler's Fourth played by 96 musicians. And if a hall has an organ, people will want the hall (and the organ) to sound appropriate for the organ repertoire.

Today, social politics and operating economics dictate that the owner keep the hall as busy as possible. And since today's concertgoers and theatregoers have increasingly attractive alternatives in audio and video home entertainment, we as hall designers have to provide a truly special experience for the audience. Instead of designing a "best compromise" acoustic (which is, ultimately, still a compromise), we strive to stretch the acoustical capabilities of the space. We have been incorporating variable sound absorbing devices into performing arts spaces for more than three decades, now, in order to control reverberance, and sound reflecting panels and canopies to foster clarity.

As seating capacities have increased, we have had to concentrate on maintaining intimacy -- acoustical as well as visual intimacy. "Acoustical intimacy" seems to include elements of impact, warmth, envelopment and clarity. All of these elements can be better in a basically narrower, tighter, space. But we also know that one's sense of reverberance is another important aspect of listener preference.

For many years it has been generally accepted that clarity and reverberance are mutually exclusive, or at least negatively correlated. That is true if you look at a large number of traditional, single-volume rooms. It may not be quite so true if you look at only narrow rectangular halls. Such observation must be a consequence of the historical use of Reverberation Time -- T60 -- as virtually the only measure of reverberance. And whatever validity there is behind the use of T60 as a comparative metric is based on the assumption of simple exponential sound decay.

Over the past few decades we acousticians have begun to get more specific with respect to reverberation. We speak of "running reverberance" as distinct from "terminal reverberation". We use EDT, C80 and other measures to help illuminate the venerable, but often misleading T60. At Artec we sometimes use the term "audible tail" to refer to the subjectively significant tail of decay audible after a performer releases a note or a word and lets it die away, perhaps to silence. Think about it: we can hear a dynamic range greater than 60 dB; accomplished performers make use of a dynamic range greater than 60 dB; now we can make recordings and measurements with a dynamic range greater than 60 dB. There's no reason we should limit our consideration of the audible tail to the definition of T60. We have the capability to digitize and analyze the fine structure of the reflection sequence. It is only appropriate that we broaden our perspective on the character of the reverberation.

[SLIDE 1 - Basic considerations/questions]

This paper is about putting partially coupled chambers to use in an overall vocabulary of variable acoustics. By designing a hall with a variable, partially coupled reverberation chamber, we can allow a much greater independence of clarity and reverberance than is possible in a single-volume room. If a large, very hard volume is partially coupled to the main audience volume, the decay after a few hundred milliseconds will have a double slope -- faster at first, and slower later. If done properly, the double slope can provide clarity with a sense of reverberance. But it has to be done just right, so the tail is not too "disconnected" from the running reverberance, and so the loudness ot the "clarity" portion of the signal has a proper relation to the loudness of the decay portions of the signal.

Background

[SLIDE 2 - Vienna]

In the first half of this century, coupled chambers were an evil to be avoided in concert hall design. In retrospect, now we can see that the highly regarded 19th century shoebox halls have tall hard side walls, and what amounts to a reverberant volume above the top balcony. Our use of partially coupled chambers evolved from our study of the best of the old halls.

[SLIDE 3 - Flint, Michigan]

As auditorium design began to crawl out of its infancy in the 50's and 60's, we increased cubic volume in order to increase reverberance, and then added reflectors to promote clarity. The hall in Flint, Michigan dating from the late 50's for example, has "extra" volume above a wire mesh ceiling.

[SLIDE 4 - Tanglewood]

This is the reflector array at **Tanglewood**; the volume above the panels helps to provide some of the reverberance in this open shed. While at BBN, Russ worked on at least 15 or 16 other halls in Kalamazoo, Roanoake, Winnipeg, Regina, and other cities, and these halls all have "extra" volume that is decoupled from the main volume to a greater or lesser degree. However, none of these had means to control the opening between the principal volume and the "extra" volume.

[SLIDE 5 - Birmingham Jefferson]

Over the course of this experience we began to learn how useful it would be to have operable shutters between the two volumes. Russ's first rooms while he was at BBN with such shutters were at Penn State and in Birmingham Alabama. In the Birmingham Jefferson Center the design included operable panels to vary the opening between the ceiling void and the audience volume, but the panels were cut by the Owner for cost reasons. Consequently, the concept does not work in the Birmingham-Jefferson Center. At Penn State the Owner funded the hinged (manual) panels, but the porous wall surfaces of the secondary chamber were never adequately sealed.

Stagehouse reverberation chambers

[SLIDE 6 - Pikes Peak looking forward]

Starting the mid-70's we incorporated reverberation chambers into the stagehouses of several multipurpose halls: the Crouse-Hinds Theatre in Syracuse, Pikes Peak Center in Colorado Springs, and halls in Thunder Bay and Kitchener, Ontario. These facilities had the usual multi-purpose program, from symphony to musicals to ballet to pop music. This is a slide of the Pikes Peak Center.

[SLIDE 7 - Plan of reverb chamber - Concert mode]

In contrast to the usual shell, the concert towers in these designs are typically usually spaced apart a foot or two, and they stop 6 ft to 9 ft short of the ceiling.

[SLIDE 8 - Section of rev chamber]

In concert mode the ceiling panels shut off entirely the upper part of the flytower from the lower part. All the theatrical draperies are stored above the ceiling. The concert ceiling units are as heavy as was practical; they run on dedicated rigging, and store up at the grid. The finishes in the stagehouse below the ceiling are as hard and non-porous as possible. A portion of the sound energy travels over and between the towers back into reverberation chamber, which has a slower decay rate than the auditorium, and then feeds back into the hall. The level of the reverberated energy is lower and the duration is longer in the hall than if the extra stage volume were fully part of the auditorium.

While this design does not have dedicated shutters between the stage volume and auditorium, there are means to control the effects of the chamber:

(a)set up the towers closer together or farther apart to vary the coupling area

(b)tip the rear concert ceiling units to increase the effective absorption in the chamber.

(c)By moving the towers, the volume of the secondary chamber can be increased or decreased.

[SLIDE 9 - Plan - Theatre mode]

...And what makes this elegant is that it uses volume that is required anyway for theatrical events.

Models

We have used two computer models in the design and analysis of coupled chambers over the last decade: one based on coupled volumes and the other on coupled surfaces. Sam Berkow also did some measurements in a 1:7 scale model as part of his thesis.

A. Coupled Volume Model

[SLIDE 10 - Coupled volume model]

Our first and simplest mathematical model was based on energy transfer between coupled volumes. It is effectively a heat transfer model using coupled differential equations, and is accessible in acoustics texts such as Cremer & Muller and Pierce. There are five input parameters:

volume in the audience chamber
volume in the reverberation chamber
absorbing area in the two spaces
coupling area.

Diffuse fields in the two volumes build up to steady state levels determined by the absorbing area in each chamber. The two decay rates are coupled such that a change in one space affects the decay in both spaces.

[SLIDE 11 - Mathcad Plot: Hard-Hard]

This is a plot of the computer model results for the Pikes Peak Hall in its symphony setting -- both the auditrium and stagehouse chamber are in their hard conditions. The upper plot shows asymptotes for the decay of the audience chamber (green) and the stagehouse chamber (red) and their sum in blue, which is the double slope decay curve. The lower graph shows the instantaneous slope of the decay curve. The decay rate is approximately -27 dB/sec at the start, and reduces to -18 dB/sec later in time, by about 800 msec into the decay. The slopes of the asymptotes are given as RT equivalents in the lower left of the slide -- EDRATE and LDRATE, and for those of you comfortable with C80 and Center Time, they are shown as well.

The lower graph is the slope of the decay curve (smoothed with an 80-point running average). We were finding it hard to see the double slope decay on the measured data, but we were hearing them. The plot of instantaneous slope makes it easier to quantify the double slope.

[SLIDE 12 - Soft-Hard]

When we extend the sound-absorbing banners and curtains in the auditorium, but leave the reverberation chamber hard, the late decay remains fairly strong, but the early decay is more rapid -- approximately -35 dB per second.

[SLIDE 13 - Hard - Soft]

If, on the other hand, we add absorption to the stage chamber, and keep the audience chamber hard, the late decay is faster. The model confirms our field experience that a very small amount of absorbing material in the chamber will "kill off" the audible tail. The late decay here is about 23 dB/sec.

[SLIDE 14 - Soft-Hard - smaller coupling area]

We can also vary the coupling area by shifting the arrangements of the concert towers. Here we have reduced the coupling area to 150 sq.m. The **late decay slower and lower in level --** would expect greater clarity, and a tail that would sound too much "detached" from the main decay.

[SLIDE 15 - Soft-Hard - larger coupling area]

If we increase the coupling area, the two contributions merge and tend toward a single volume decay. The crossing of the asymptotes is quite close to the origin.

This model does not account for room geometry. It doesn't know what shape the volumes are or how far the sound source is from the opening. We have found that both of these effects are important in the "real world".

B. Coupled Surface (Markov Chain) model

[SLIDE 16 - Markov chain formulas]

John Walsh has developed an improved model using first-order continuous Markov chains to follow energy transfer among the surfaces of the room, in effect solving sets of differential equations similar to the coupled volume process, but much more involved. The coefficients are the transition intensities between each pair of surfaces, given by

$$q_{ij} = (1 - a_i)\ (c / l_{ij})\ (Y_{ij} / 2{*}PI),$$

where l_{ij} is the average distance between surfaces i and j, $alpha_i$ is the absorption coefficient of surface i, and Y_{ij} is the average solid angle subtended by surface j at surface i. We also introduce an "absorbing state" which receives energy from each surface in proportion to the product of that surface's absorption coefficient and the total rate of transition from it, and a "non-return state" which acts as a point source with the 2PI in the equation above replaced by 4PI (since the source can radiate omnidirectionally versus the hemispherical radiation from each planar boundary element). The solution involves computing the vector P at each time of interest, with its value given by

$P(t) = p(0)\ e^{Qt}$,

where p(0) is the initial distribution vector (usually having only one non-zero element for the source state), and Q is the matrix of transition coefficients.

A few additional notes are required to adapt this method to coupled chambers. We introduce a mechanism for varying the coupling area between the enclosures, using two "surfaces" on the coupling wall, one inside and one outside the chamber. These surfaces allow a portion of the energy incident upon them to be returned to the enclosure from whence it came; the remainder passes through to the boundaries.

[SLIDE 17 - Markov room diagram]

The synthetic room used for this initial series of experiments is shown here, and is a highly simplified version of the configuration adopted for Dallas. The coupling wall is shaded in the figure. In the actual hall, the chambers surround the audience. Where audience absorption was to be emulated, and absorption coefficient of 0.85 was used; where drapery within the audible tail chamber was used, an absorption coefficient of 0.6 was used. All other surfaces were given absorption coefficients of 0.05. Transition intensity matrices were constructed for the configuration shown. Draperies can be drawn along surface 7, and the open area coupling the two enclosures could be either 60% or 20% of the vertical wall element. Audience absorption was placed on surface 1 in all cases, and also on surface 3 in many. The sound energy emanated from either the center of surface 1 or a point 15 feet in front of the coupling wall of the chamber, at its center.

[SLIDE 18 - Markov curves 1]

The upper curve shows the decay for the 60% open area case with curtain retracted; the next curve shows the decay for 20% open area and curtain retracted; the next shows the decay for 20% open area and curtain extended, while the bottom curve shows the decay for 60% open area and curtain extended. John Walsh did an in-depth comparison of the Markov Cahin model and the coupled volume model in a paper presented to the Canadian Acoustical Association, and found that the Markov chain model did indeed take better account of the inter-face visibility issues.

<u>Measurements</u>

[SLIDE 19 - Measurement schematic]

We have made measurements in some of the halls with coupled chambers. We'll look at some data taken in the Pikes Peak Center. Impulse responses were captured on digital tape, 4 tracks at a time. Our source was a modified .38 caliber pistol. Omnidirectional microphones were located in 3 places in the auditorium and in the reverberant stagehouse. The hall was empty for these particular measurements.

Various settings were investigated.

-Reverberation chamber as hard as possible,

- Reverberation chamber deadened somewhat by tipping concert ceiling panels 3 & 4

-Reverberation chamber deadened even further by dropping in a velour backdrop and legs.

[SLIDE 20 - COS with Banners]

-Audience chamber banners and curtains extended (soft) and retracted (hard).

[SLIDE 21 - Hard-Hard 912_10h]

This slide shows the decay for the audience chamber hard and the reverberation chamber hard (the normal setting for symphony). Except where noted, data presented here was filtered digitally through a 1kHz octave band filter. The first few slides are for various settings as measured in the center of the main floor, with the source at the concertmaster's position. The upper plot is the decay curve computed from the filtered echogram by backwards integration, and the lower plot is decay <u>rate</u>. Note that decay rate starts at -25 dB per second, and between about 400ms and 1 sec it makes a transition to -19 dB per second. EDT and T60 are not very different. This hall has excellent clarity, even in its most reverberant setting. Seats farther back in the hall show somewhat greater difference between the early and late slopes.

[SLIDE 22 - Soft-Hard 1217_10h]

When the banners and curtains are fully extended in the audience chamber, and the stage chamber remains hard, the audience chamber dries up more than the reverberation chamber, as one would expect. There is now a greater difference between the early decay rate and the late decay rate. This setting is not used to our knowledge.

[SLIDE 23 - Soft-Soft 1257_10h]

When the rear two concert ceiling units are tipped to absorb sound in the chamber, with the banners still extended in the audience volume, the late decay rate increases almost to the early decay rate. EDT and T60 are almost equal at 1.7. Note, on this slide the measurement noise floor has influenced the computation beyond about 1.2 sec.

[SLIDE 24 - Hard-Hard in chamber 1007_20h]

1kHz decay measured in the reverberation chamber with the source in the chamber as well. The decay rate is essentially flat in the range of -18 to -20 dB/sec.

[SLIDE 25 - Hard-Hard 912_20 flat]

This is a detail of the unfiltered response measured in the chamber with the source at the concertmaster's position. It shows the delay in the build-up of the sound field in the chamber.

A few more recent examples

After completing several working reverberation chambers, we began to understand more of the subtleties. We felt the reverberance should come more from all around the listeners (stagehouse reverb is somewhat frontal for people sitting in the rear of the hall). Also, we felt that the chamber boundaries needed to be even more solid to provide better low end to the tail.

We were achieving PNC-15 background noise levels as a matter of course, but since noise was audible, it was still too noisy... so we began to design for even lower noise levels. This helps to increase both one's sense of clarity and sense of reverberance, to say nothing about the nature of the sound of ppp passages in the score.

[SLIDE 26 - Tampa Model]

In the Tampa Bay PAC (designed 1981-82, opened 1987) the Owner insisted on an approach to the concert setting where the stagehouse is fully shut off from the audience chamber. We designed a reverberation chamber around the top of the room, using the same ratio of chamber volume to audience volume as had been successful in Kitchener. This chamber gives a more surrounding reverberation than the stagehouse chambers do, a definite plus. This is the first chamber with mechanically activated shutters to vary the coupling area plus dedicated sound absorbing curtains in the chamber. We learned how the chamber could be used as a net absorber as well as a reverberation extender.

[SLIDE 27 - Dallas Front]

The Meyerson Center in Dallas is the first "pure concert hall" to have a dedicated reverberation chamber. Like Tampa, the chamber and other aspects of the hall are adjustable in many ways. This chamber, like Tampa, has operable shutters and curtains. It embodies the best of both the stagehouse approach (openings near the performers) and the Tampa approach (surrounding the audience).... Musicians near the rear of the platform like the ambience they get back from the chamber openings at the front of the hall. And since there is a regular orchestra user in Dallas and they have made the effort to learn what the chamber can do for them, they use it in a variety of configurations for various types of music and non-music events.

[SLIDE 28 - Dallas looking back]

The architect decided to hide the shutters behind a sound transparent screen. This is a shot looking back in the architectural model.

[SLIDE 29 - Dallas 3-D wire frame diagram]

This slide shows the Dallas chamber from above, as if sliced open with a can opener. The doors are in the vertical inner face.

[SLIDE 30 - Symphony Hall, Birmingham, Model]

Symphony Hall in Birmingham, England opened last spring. It has a chamber similar in many ways to the Dallas chamber.

[SLIDE - Birmingham, looking forward]

Conclusion

Musicians and audiences are responding with enthusiasm to the sound of these new halls. Of course, ten years from now, these halls may not be rated as highly as they are today. But based on these reactions, we believe there will continue to be a justifiable role for partially coupled chambers in the future. However, we must caution that the overall success of these latest halls is due to the combination of controllable reverberance chambers with many other aspects of the acoustics.

PARTIALLY COUPLED REVERBERANT CHAMBERS

<u>Some Basic Considerations/Questions</u>:

- Volume of Reverberation Chamber (RC)

- Absorption in RC

- Coupling Area:
  - Total Area
  - More smaller openings or fewer larger openings?
  - Shape of openings

- Location of openings
  - High or low level?
  - At sides or ends of hall?

- Shape of RC: compact or stretched out
  -Ratio of surface area to volume (intrinsic absorption)
  -waveguide effects

- Materials
  -How hard is hard enough?
  -Variable absorption in chamber

- Double Duty
  -Stagehouse
  -Audience circulation
  - Technical gallery
  -HVAC duct zone

- Other architectural design considerations

SLIDE 1