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FIVE SENSITIVITIES OF A COUPLED VOLUME CONCERT HALL: A COMPENDIUM

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Abstract
In the execution of a coupled volume concert hall, a dynamic and kinetic architecture defines a space's acoustics. Wrapping a concert hall audience chamber with another room, or coupled volume, and connecting the two with adjustable apertures, creates the opportunity for a double sloped sound decay. The acoustic interaction between the primary and secondary volumes offers a level of variability and control to the sound field that is not possible in traditional, single volume halls. Most distinctly, the double sloped approach promises a measure of simultaneous clarity *and* reverberance (qualities long thought to be mutually exclusive). While some spaces achieve that promise, others probably do not. Measurements taken in a coupled volume concert hall, simulations of coupled volume concert halls, and listening tests suggest a fickle relationship between the architecture of the hall and its ability to provide both clarity and reverberance simultaneously. The two halls studied suggest five sensitivities of the system: (1) the coupled volume must be exceedingly more reverberant than the audience chamber, (2) the aperture linking the two spaces must be exceedingly small, (3) location within the hall relative to the apertures impacts what is heard, (4) the background noise level must be exceedingly low, and (5) it is unclear whether subjects of a listening test preferred the coupled volume system.

1. Introduction

The coupled volume concert hall and its signature sound decay—the double sloped acoustic—offer a tantalizing promise to designers. By attaching a reverberant coupled volume of space to a room for music making and listening, acousticians and architects hope to create an impulse response that rapidly decays at first, but later decays slower as sound that had been "trapped" in the coupled volume "leaks" out. Given that rapid sound decay is the hallmark of acoustic clarity, and given that slower sound decay is the hallmark of acoustic reverberance, and given that clarity and reverberance are each desired yet inversely related, the double slope undertakes to reconcile the two. In this impulse response model, the early rapid slope allows each note to decay and make room for the next (clarity) and the late gradual slope allows each note to linger and blend into the next (reverberance).

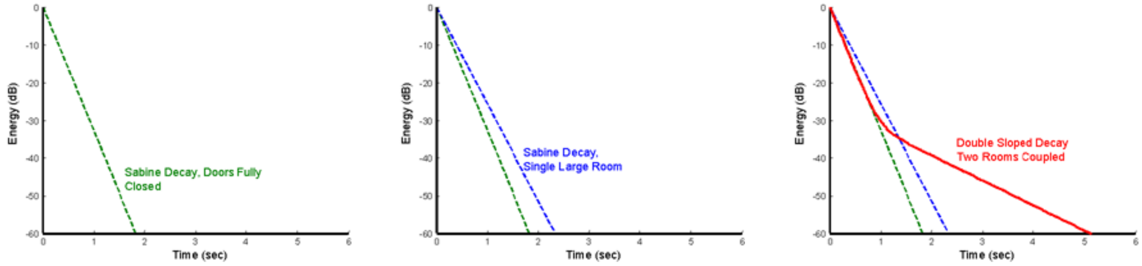

Figure 1. Left: Impulse response sound decay, based on the Sabine formula for diffuse sound fields, predicted for a concert hall (main hall only)l. Center: Sabine decay predicted for a single large concert hall of a size equal to a main hall plus a coupled volume. Right: Double sloped sound decay, based on Kuttruff's[1] formula for a non-diffuse, coupled volume condition where the two rooms are only partially connected through apertures.

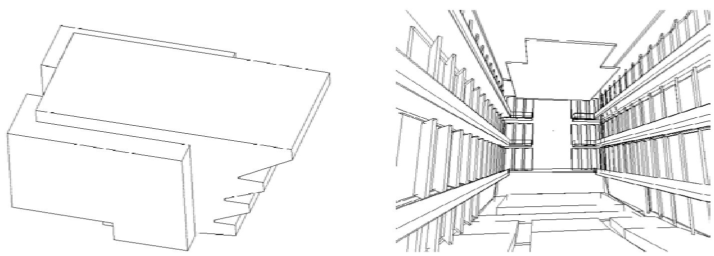

Figure 2. Left: Concert hall massing diagram of a main hall space, saddled by two coupled volume spaces. Right: Interior perspective of the main hall of a coupled volume concert hall, looking toward the stage; the partially open apertures lining the side walls and portions of the upstage wall acoustically connect the main hall space to the coupled volume space. The ray tracing software results presented in this paper utilize this model, which is based on a built U.S. concert hall.

Once anathema to good acoustics, the double sloped decay has received attention since the early eighties when a flurry of coupled volume concert halls began construction.[2,3] The process continues today with recent or upcoming coupled volume concert hall openings in Singapore, Miami, and Orange County, California. Cesar Pelli, Raphael Vinoly, I.M. Pei, Jean Nouvel, and the Finnish firm Arkkitehtityöhuone Artto Palo Rossi Tikka Oy have designed coupled volume concert halls, among others. Yet, anecdotal evidence, reputation, and room measurements suggest that of the approximately 20 concert halls built with dedicated coupled volumes designed to provide a double slope decay, perhaps only a handful deliver on that promise.[4,5,6,7,8] Why?

This line of research finds five sensitivities inherent in the design of concert halls based on architectural composition, haptic perception, background noise levels, listener sensitivity, and listener preference. Designers of concert halls, note: coupled volume systems are remarkably sensitive to these issues in a way not typical of other spaces designed for unamplified music listening.

2. Methods

This line of inquiry, spanning six years, draws on anecdotal evidence, statistical acoustics simulations, geometrical acoustics simulations, in-situ room measurements, and subjective listening tests. Two coupled volume halls have been examined and modeled to derive the results. “New Hall” is a coupled volume concert hall that has opened since the year 2000; “Old Hall” is a similar venue (though with fewer apertures connecting the main hall with the coupled volume) that opened in the 1990s.

The author gathered anecdotal evidence from interviews with operators and designers of coupled volume concert halls, many from his year working for the architectural acoustics consulting firm that has designed a majority of the world’s coupled volume halls. He developed a software program, based on established statistical acoustics to model and compare varying architectural compositions of coupled volume concert halls.[1,9] Further models were created using the geometrical-acoustics-based software, CATT-Acoustic, which both simulates impulse response decays and auralizes the results so that a user may hear the room’s simulated impulse response convolved with an anechoic musical recording.

In-situ measurements were taken at 16 positions in Old Hall by binaurally recording an organist during rehearsal. All but one of the recording positions were unable to reveal a double sloped decay; one of the positions probably revealed a double slope. That measurement was compared to both the statistically based and geometrically based prediction methods to verify their efficacy as modelers. The results of that comparison neither confirm nor repudiate either model, but the statistically based model appeared to be more accurate.

Finally, listeners of varying experience were given paired comparison tests to determine perception of, and preference for, the double sloped decay. Experienced listeners volunteered at acoustics conferences, and generally-less-experienced student listeners volunteered from both architecture and architectural acoustics classes. In each case, subjects were given eleven pairs of CATT-Acoustic auralizations created from models with varying architectural compositions and for each pair were asked (1) if they heard a difference between the two recordings, (2) which one of the two is “more” double sloped or “more likely” double sloped, and (3) which one of the two they prefer.

Note that this paper is written with architects and designers of coupled volumes in mind as readers. Those wishing to learn more about the technical details involved in the statistical acoustics and geometric acoustics simulations, as well as the in-situ room measurements are directed to the publications referenced in endnote 5. Those wishing to inquire about the anecdotal evidence gathered, or the technical details of the listening tests (which will be published in an upcoming paper) are encouraged to contact the author.

3. Sensitivity I: coupled volume materiality and scale

To achieve a double sloped condition, sound must leave the main hall, move into the coupled volume, wait a bit for sound in the main hall to decay rapidly, then slowly leak back into the main hall to form the late gradual decay of the double slope. For this to work, the sound level in the coupled volume created by the impulse in the main hall must, over time, be louder than the sound level in the main hall. Clearly, then, the coupled volume must be reverberant. What has been found here, however, is that the coupled volume must be *exceedingly* reverberant to effect a double sloped decay.

Typically, when we speak of sound reflective materials, we are referring of those with absorption coefficients less than 0.2.[10] Using the geometrical volume of the coupled volumes found in Old Hall and New Hall as a baseline for size, the world of the double slope then requires an absorption coefficient of less than 0.02—a full order of magnitude more stringent. This limits the materials that can be used for coupled volumes of these sizes to: painted brick, smooth concrete, marble and glazed tile (on concrete). See Figures 3 through 5. Indeed, of the few halls that are reported as successful in achieving a double sloped decay, all have coupled volumes of concrete. Of the many more that are reported as less successful, the author knows of none that are constructed of concrete, but several which are dominated by wood or concrete block.

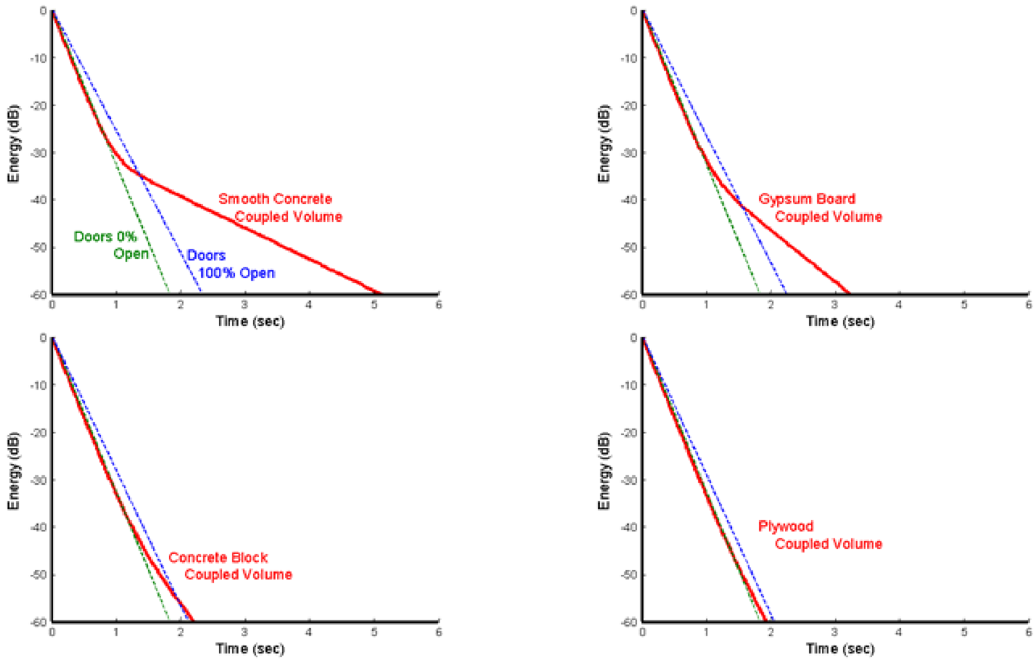

Figure 3. Statistical acoustics predicted decays at 1000 Hz for different material profiles of the coupled volume. Top left: smooth concrete (α=0.02). Top right: 1/2" gypsum board nailed to studs (α=0.04). Bottom left: concrete block (α=0.07). Bottom right: 3/8" plywood over airspace (α=0.09). The green dashed line indicates the predicted decay for the main hall only condition; the blue dashed line indicates the predicted decay for a single large volume equal in size to the main hall and coupled volume combined. For these simulations (in red) the apertures connecting the two halls were set to 0.5% of the total available surface area of the walls and ceiling of the main hall.

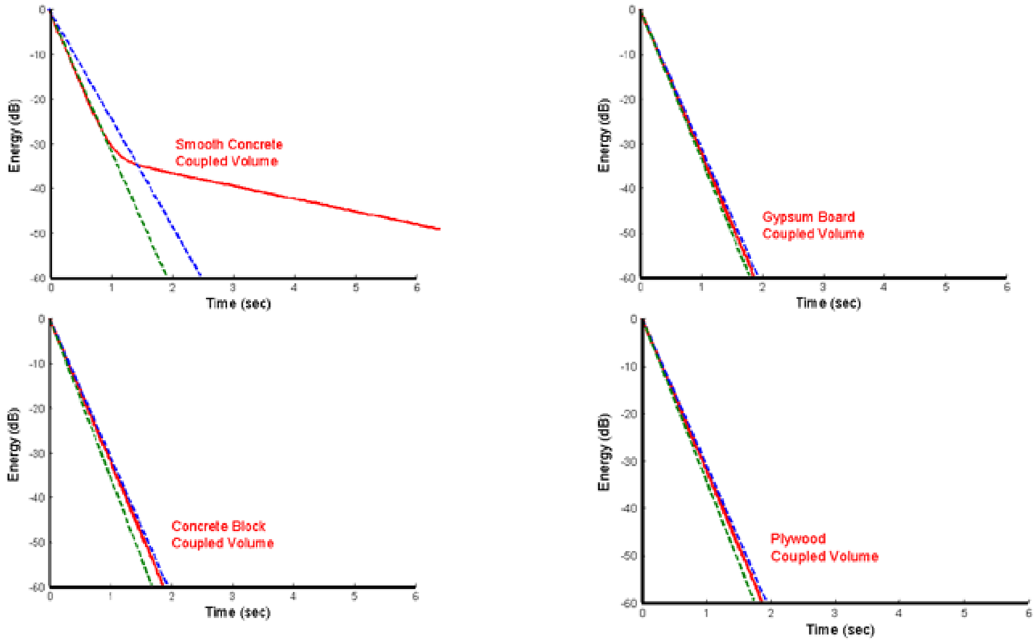

Figure 4. Statistical acoustics predicted decays at 125 Hz. Note the limited material palette available to effect a double sloped decay.

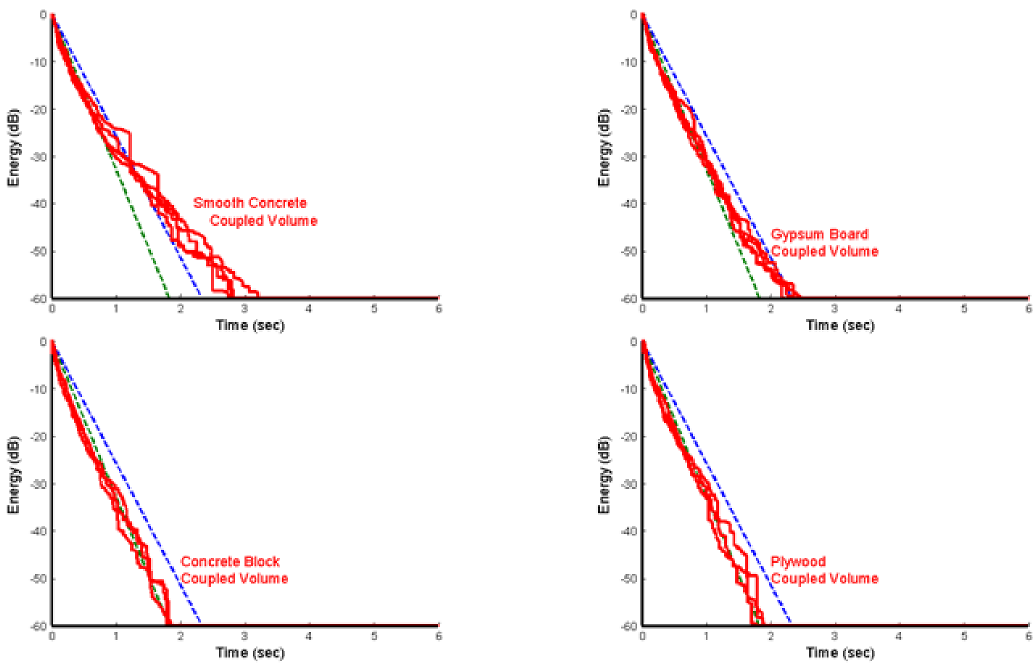

Figure 5. Geometric acoustics predicted decays at 1000 Hz. Top left: smooth concrete. Top right: 1/2" gypsum board nailed to studs. Bottom left: concrete block. Bottom right: 3/8" plywood over airspace. Multiple red lines indicate simulations at different receiver positions.

It is not enough, it appears, to simply specify an exceedingly sound reflective material in which to clad the coupled volume. The designer must also be wary of the typical residue of construction processes, fire and egress requirements, building systems, and end-user patterns if any of these elements are to be exposed to the sound energy that enters and later leaves the coupled volume. Spray-on fireproofing, metal ducts, air cavities behind plaster finishes, doors, miscellaneous items held in storage, grilles and diffusers, raceways, conduit, and lighting may affect performance. In a typical space, even one designed for unamplified music listening, many of these ancillary elements may not have a significant impact, but in the sensitive world of the coupled volume, small changes in materiality leverage large changes in the behavior of sound.

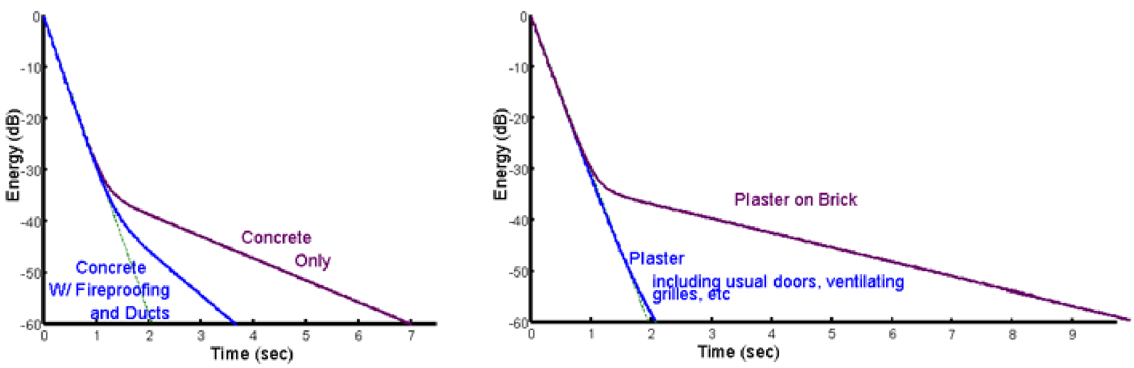

Figure 6. Residues of building processes make an impact on impulse responses in double sloped decay. Left: 1000Hz comparison of concrete coupled volume versus the same condition with 5% of the surfaces in sheet metal duct and 5% of the surfaces covered in spray-on fireproofing. Right: 125 Hz comparison of plaster on brick versus "typical" plaster condition.

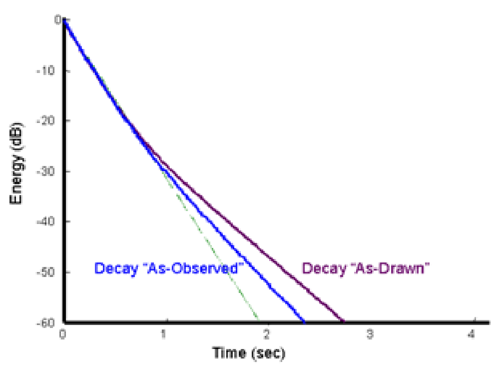

Figure 7. 1000 Hz comparison of Old hall as it is drawn and published[11] vs how it was observed on a visit. The visit revealed additional concrete structure, not apparent in the drawings (approximately 10% of total surface area), steel raceways, catwalks, pipes, roof truss structure and music stands in storage (2.5%), partially exposed velour drapes (1.1%), wood doors, organ stop cases, crates in storage (2.3%), sheet metal ducts, electrical panels (0.9%), cardboard tubes (0.1%), and rubber conduit (0.5%).

4. Sensitivity II: aperture size

In these systems, adjustable apertures control the sonic transparency between main hall and coupled volume. When the apertures are fully closed, the system operates as a single, smaller, room. When the apertures are partially open, the system may operate as a coupled volume, producing a double sloped impulse response sound decay. When the apertures are fully open, the system approaches that which would be found in a single, larger volume comprising the main hall plus the coupled volume. Where then, in this continuum from closed to open, lies the threshold when single smaller room becomes a coupled volume system, and, as we continue to open the apertures exposing the main hall to the coupled volume, where does the coupled volume system approximate a single, large room?

On this question, again, the anecdotal evidence, the statistical simulations and the geometric simulations generally agree. And again, the system is remarkably sensitive. Interviews with concert hall designers occurring before the quantitative portion of this research commenced suggested that a double sloped decay may be audible immediately, upon opening the doors a very small amount. The double sloped effect gives way to the single-large-room-decay when the doors connecting the two approach 3% to 5% of the total available wall and ceiling space. (For clarity, descriptions of apertures' degree of openness will be expressed as the percentage of New Hall's available main hall surface area, not including the floor.) The interviews indicated that the double sloped phenomenon peaks at approximately 0.5%. The statistical and geometric simulations bear this out: at 0.1% a discernable double slope emerges, at 0.4% it peaks, and at 3% to 5% it settles back to approach a classic, single (larger) volume Sabine decay. Again, we see the sensitivity of the system to the architectural composition of the spaces. When both aperture size *and* coupled volume reverberance are allowed to interact, the inherent fickleness of the double sloped decay emerges. To effect such a decay, the designer must work with the hall operator and target a limited "sweet spot," where both of the following conditions are met: the coupled volume is much more reverberant than the main hall and the apertures linking the two spaces are relatively small.

Note that "coupling constant" is used in the figures that follow. This term refers to the ratio of the time required for an impulse to decay by 60db relative to the early decay, extrapolated out to approximate the time it would take to decay by 60db, if the early decay was allowed to continue linearly (on a decibel scale). *A linear, Sabine, decay will have a coupling constant of 1.0; a higher coupling constant is suggestive of a double sloped decay.* For more on the coupling constant, refer to endnote [5].

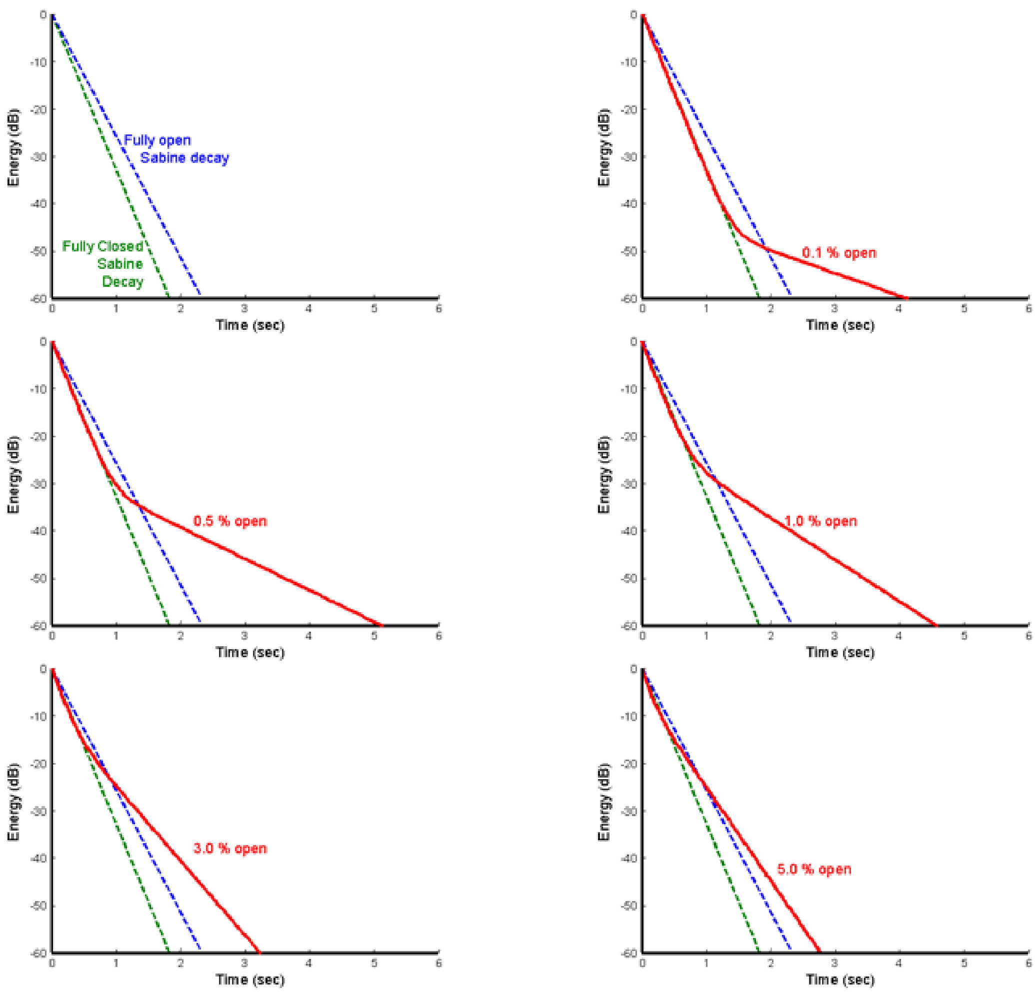

Figure 8. 1000 Hz statistical acoustics comparison of different aperture sizes. Based on New Hall with a concrete coupled volume.

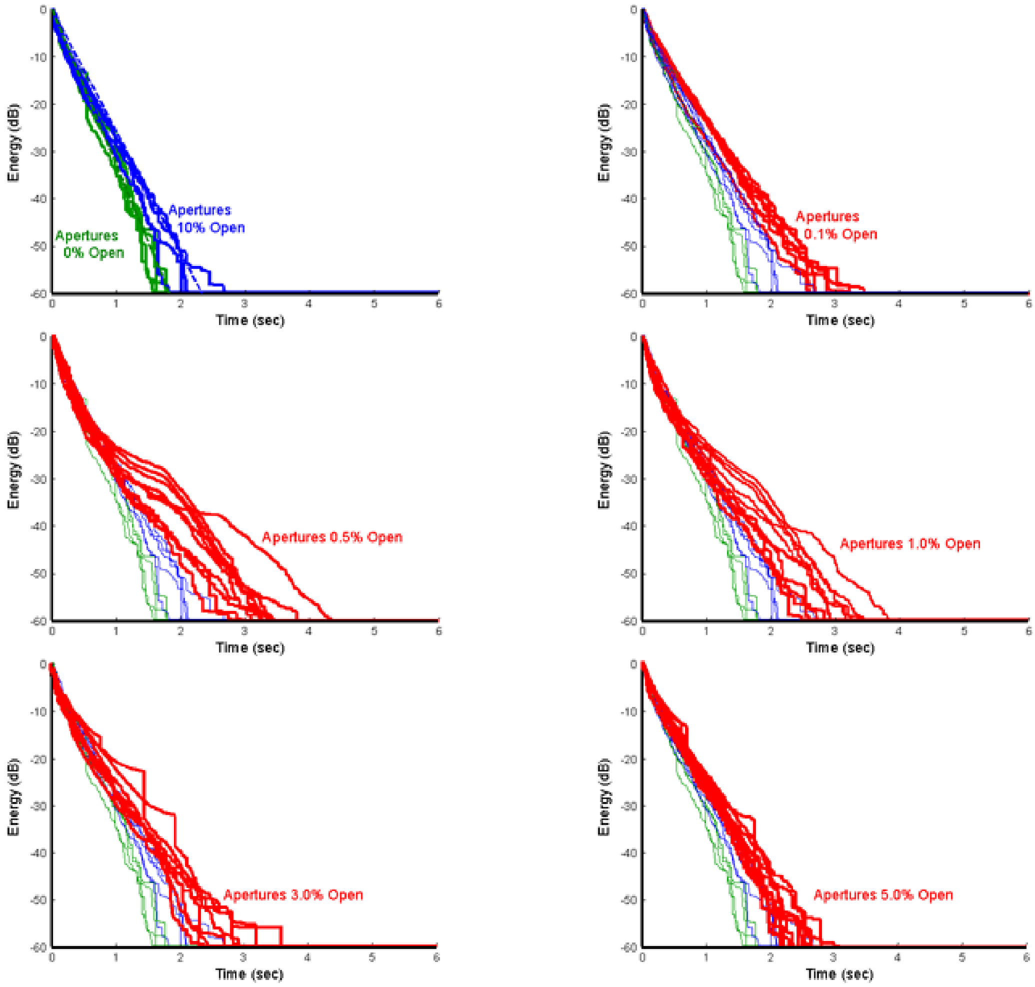

Figure 9. 1000 Hz geometric acoustics comparison of different aperture sizes. Each decay line is associated with a different location within the hall. Based on New Hall with a concrete coupled volume.

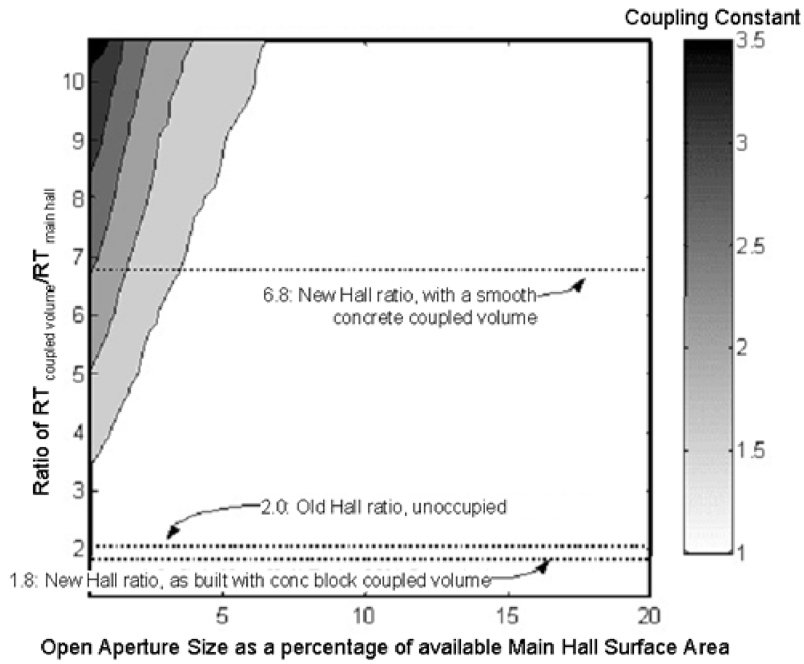

Figure 10. 1000 Hz statistical acoustics comparison of reverberation ratios (coupled volume/main hall), aperture sizes, and coupling constant. The higher the coupling constant, the more likely the impulse response will be heard as having a double slope.

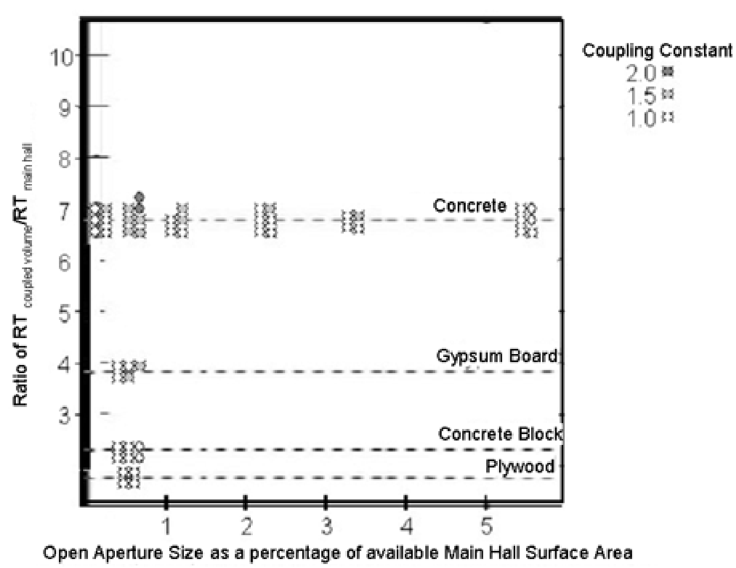

Figure 11. 1000 Hz geometric acoustics comparison of reverberation ratios (coupled volume/main hall), aperture sizes, and coupling constant. Note that Figs. 10 and 11 identify a narrow "sweet spot," with very reverberant coupled volumes and very small apertures, in which double sloped decays can be created.

5. Sensitivity III: aural haptic perception

Haptic perception involves one's sense of where one is in space. Anecdotal evidence, geometric acoustics, in-situ measurements, and listening tests suggest that a listener's proximity and view to the apertures connecting the main hall to the coupled volume space may impact the character of what is heard. When visiting Old Hall, the staff alerted the author to the location—the front of a balcony with excellent acoustic lines-of-sight to the apertures—from which the double sloped decay is most likely to be reported. This was the only location of the 16 measured where the author heard a double slope, and the impulse response taken there seems to indicate that a "mild" one may be present. In contrast, impulse responses taken from organ stop chords at seats very near the apertures themselves appear closer to the predicted linear Sabine decay for the single-large-room condition than they do to the double sloped condition—hardly surprising given that the listener is in, or close to, both spaces simultaneously.

Geometric acoustics predictions suggest that while there is no discernable difference in the coupling constant between locations that vary along the height axis or length axis, something different may be heard along the width axis when listeners move within two meters of an aperture. Not only do the graphically plotted impulse responses look different, but listeners to a paired comparison of two recordings auralized from different locations had a relatively easy time identifying the difference between them. Both simulations were created in what is believed to be the easiest to identify as a double sloped condition (1% open aperture and smooth concrete coupled volume). One, taken at orchestra level, house center, was by far preferred to the other, taken at orchestra level, house left, near the apertures.

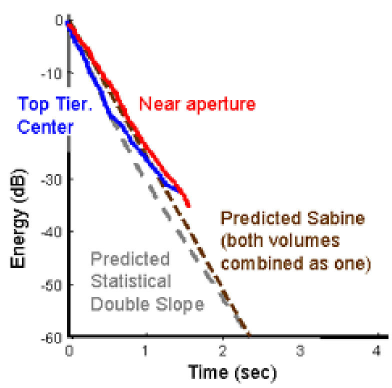

Figure 12. 1000 Hz in situ room measurements, derived from recordings of organ stop chords. The house center measurement impulse response, with clear acoustic lines-of-sight appears to be closer to the double slope prediction, while the impulse response associated with the measurement location immediately adjacent to an aperture appears to be closer to the prediction for a single-large-volume linear Sabine decay.

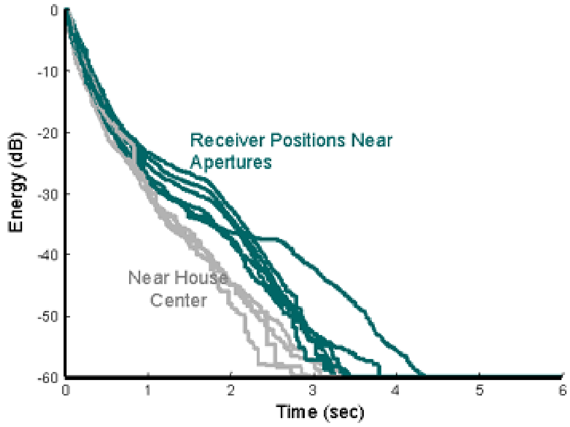

Figure 13. 1000 Hz geometric acoustics New Hall simulations (0.5% open apertures, smooth concrete coupled volume condition) . The receiver positions near the apertures, as a group, are notably different from the group of receiver positions farther from the apertures. This split was evidenced only in the simulated hall conditions that created the most dramatic double sloped decays (the ones with the highest coupling constant).

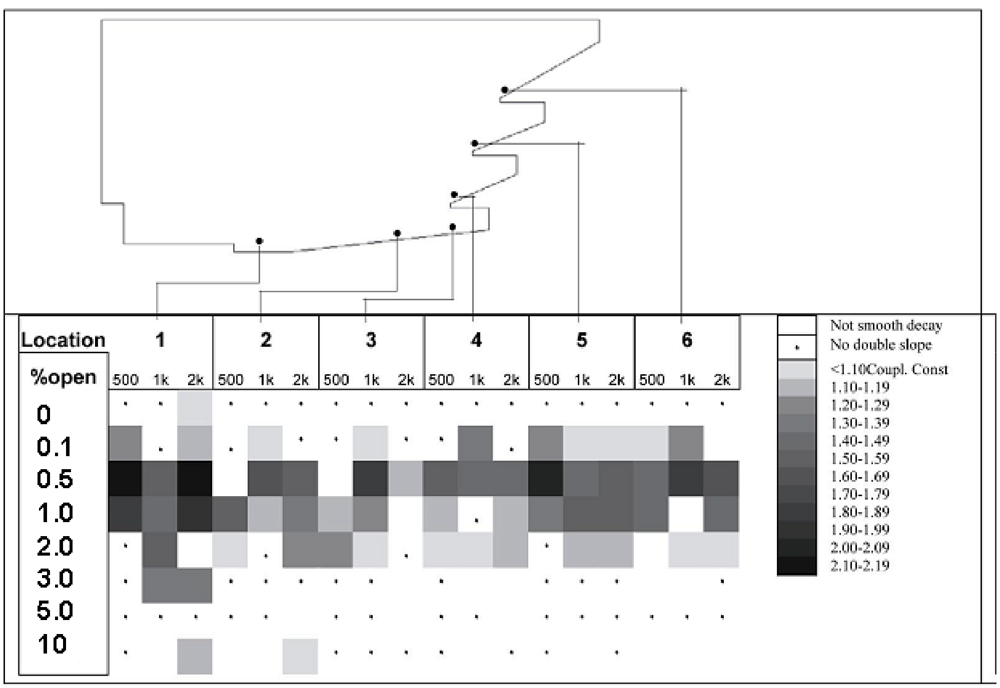

Figure 14. 1000 Hz geometric acoustics New Hall simulations. Coupling constant does not vary between locations along length of room.

6. Sensitivity IV: background noise

Maintaining low levels of background noise is paramount in any space for unamplified listening, but in the realm of the coupled volume, double sloped perception requires exceptionally low background noise. This is because if the crossover point—the elbow in the impulse response where the initial rapid decay gives way to the later-arriving slower decay—falls below the noise floor, the double slope can not be heard. To account for this, the designers of coupled volume concert halls interviewed for this line of research, target the threshold of hearing as a maximum acceptable background noise level.

Anecdotal evidence, in situ noise measurements, and both statistical and geometric acoustic simulations suggest that a low signal-to-noise ratio will likely eliminate perception of the double slope. However, absolute levels of background noise are not solely responsible for determining if a cross-over point falls below the noise floor. Obviously, the sound level of the music being played impacts the location of the crossover point relative to the noise floor. Less obvious is the impact of aperture size. With increasing aperture size comes a crossover point that is “sooner” or “higher” in the impulse response and, therefore, less likely to fall below the noise floor. See Figure 8 and note the location of the crossover point relative to the size of the aperture.

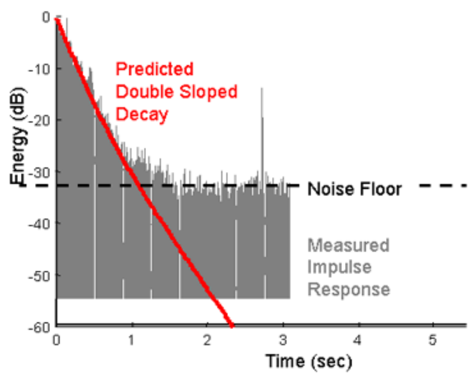

Figure 15. 1000 Hz in-situ room measurement at orchestra level of Old Hall. Note the elevated level of the background noise relative to the predicted double slope of the curve. In this situation, even if the hall’s architectural composition were favorable to the creation of a double sloped decay, it likely would be drowned by the background noise, which was clearly audible to the researcher.

7. Sensitivity V: perception and preference

The larger question, of course, is “Who Cares?” In other words, are listeners able to perceive the double slope decay? And if they are, are they able to perceive it during music, or only at stop chords? Finally, if they can perceive it, do they prefer it? For this study, listeners were given auralizations of pairs of recordings and asked about perception and preference. Through analysis of the data, trends appeared.

First, many of the listeners were “liberal responders.” That is, even when each member of the pair of recordings were identical, the subjects often identified them as different from one another. For this reason, a group of “proficient” listeners were identified who recognized the control groups of pairs that were identical and were teased out as a separate category. The other two categories of respondents were (1) student volunteers and (2) professionals attending acoustics conferences. Generally the proficient listeners were more successful at correctly identifying those recording pairs that were indeed different relative to the non-proficient professionals, and the non-proficient professionals were generally more successful than the students.

Second, listeners generally were not able to “correctly” identify the “more” double sloped recording with any consistency when the impulse responses associated with the two recordings were more similar to one another (0% open apertures versus 0.1% open apertures, for instance). Listeners were, however, more able to “correctly” identify the recording that was “more” double sloped when the impulse responses differed greatly from one another (0% open apertures versus 1.0% open apertures, for instance). Again, here, proficient listeners performed the best.

Finally, on the question of whether listeners prefer the “more” double sloped recording, the evidence is not as conclusive. It does appear that proficient listeners prefer the recording that is *less* double sloped, while non-proficient professionals and students were split or unsure of which they prefer. In other words, it may be that, when given a choice, listeners do not prefer the double sloped decay!

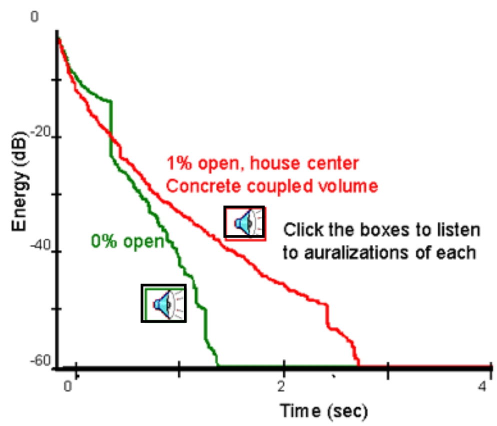

Figure 16. Pair of auralizations used to detect perception and preference of the double sloped decay. Click on the icon to hear each decay. Subjects were asked (1)if they could detect a difference between the two recordings, (2) if a difference exists, which one is more likely to be double sloped or is more dramatically double sloped? and (3) which one is preferred?

It should be noted that the listening test portion of this inquiry is ongoing and only preliminary results are reported here. The latest listening test administered involve those with truncated decays so that in identifying perception and preference, listeners must rely on running music and are denied the stop chords at the end of musical passages. It should be noted that the perception and preference results published here are consistent with others reported in separate studies.[12,13,14]

8. Conclusions

Simply designing a coupled volume concert hall is not enough to ensure that the space will produce a double slope decay; producing a double slope decay will not ensure that it will be heard everywhere in the space, nor will it ensure that it will be heard above the background noise; and hearing a double slope decay will not ensure that it will be perceived or even preferred. As a rule of thumb for purposes of schematic design, to achieve a double sloped decay in the concert halls modeled here, a designer should (1) create a coupled volume that is at a minimum, four to seven times as reverberant as the main hall, and possibly much more, (2) maintain small aperture sizes, less than 1.5% of the available surface area of the main hall, (3) keep background noise to the level of the threshold of hearing, and (4) inform the client that the double sloped effect, sought after as a way to reconcile the competing qualities of reverberance and clarity, may not be able to be perceived and may not be preferred.

The idea of a kinetic architecture, where spatial composition, materiality, and haptic perception may profoundly impact the aural environment is an exciting one to many acousticians and designers. This natural excitement is credited with the genesis of the studies outlined here. However, the fickleness of the system, where small changes in architecture leverage large changes in acoustics, and the unconvincing value of the double slope itself, assuming it is successfully achieved, should give pause. This is not to condemn the entire arena of music-piece -specific adjustable acoustics, nor does it dismiss the other possible uses of a coupled volume (absorptive chamber when velour banners or drapes are deployed, place for lighting effects, auxiliary stage for performance, giver of added reverberance when doors are opened). This line of research simply frames the double slope decay itself as fickle-at-best and unwanted-at-worst.

8. Acknowledgements

As this is a compendium, many of the images are based on those found in references 6, 7, and 8. Thanks to Marty Johnson, Bill Yoder, Rebecca Stuecker, and Chiss Yoder for their help researching this paper.

9. Endnotes

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