Coupled Volumes: Aperture Size and the Double-Sloped Decay of Concert Halls*

M. Ermann
Virginia Tech School of Architecture + Design
201 Cowgill Hall (0205), Blacksburg, Virginia 24061

Address for correspondence: Michael Ermann,
Virginia Tech School of Architecture + Design
201 Cowgill Hall (0205), Blacksburg, Virginia 24061, 540.231.1225
mermann@vt.edu

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ABSTRACT:

The coupled-volume concert hall and its signature double-sloped sound decay relate to the often-competing qualities of clarity and reverberance. By wrapping a room with another more reverberant room, and allowing for apertures to control the sonic transparency between the two rooms, designers use coupling to provide a sound field that is variable, longer, distinct, and performance-piece-specific. For this study a coupled-volume concert hall (based on an existing hall) is conceived with a fixed geometric volume, form, and materiality. Aperture size is established as variable. The simulated hall undergoes statistical and geometric (ray tracing software) analysis. Results show disparity in the absolute decay patterns projected by the two methods; however, both statistical and geometric relative analyses suggest a highly sensitive relationship between the aperture size exposing the coupled-volume and the double-sloped condition. To test the model, simulations are compared to real-room measurements taken in a coupled volume concert hall.

I. INTRODUCTION:

Researchers have established an inverse relationship between the important acoustical qualities of clarity and reverberance.[1,2] Once considered an anathema to quality acoustics,[3] the double-sloped sound decay has recently received attention as a possible method of simultaneously achieving clarity *with* reverberance in concert halls. By allowing a musical note to decay rapidly at first, each successive note may be perceived as a

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distinct event; by allowing a musical note to decay more slowly after the initial rapid decay, a sense of fullness may be perceived.

To effect the double slope, concert hall designers utilize a reverberant secondary space—a coupled volume—that is contiguous to the main concert hall. Operable apertures vary the acoustic connection between the two spaces, (see Figure 1). When the apertures are fully closed the system behaves like a conventional concert hall, with a less reverberant Sabine decay. When the apertures are ajar the two partially-connected subspaces may create a double-sloped acoustic.[4,5] When the apertures are fully opened the condition approaches a more reverberant Sabine decay, as would be found in a space with the combined size of the main hall plus the coupled-volume[5,6], (see Figure 2). This paper explores architectural composition and the thresholds of aperture size that separate (1) the less reverberant Sabine decay and the double-sloped decay and (2) the double-sloped decay and the more reverberant Sabine decay. Anecdotal evidence, statistical

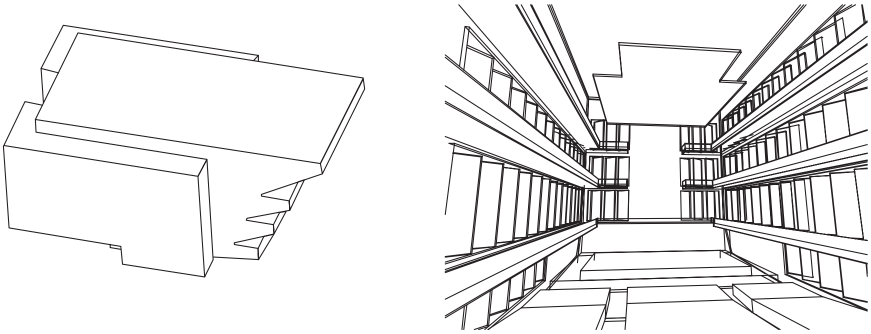
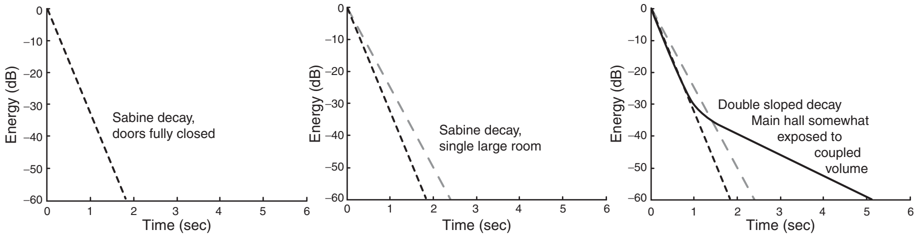


Figure 1. Schematic of a concert hall saddled by coupled volumes (left). Interior of the modeled hall (New Hall), towards the stage, with apertures lining portions of the walls (right).



Small Space Acoustic. Schematic of sound decay for a coupled volume concert hall with its doors fully closed. Only the primary room is exposed to music.

Large Space Acoustic. Schematic of a slower sound decay for a coupled volume concert hall with its doors fully opened, essentially enlarging the room from an acoustic point of view. For comparison, the fully closed condition is included on the graph.

Double Sloped Acoustic. Schematic decay for a concert hall with its doors partially open. For comparison, the fully closed and fully opened conditions are included on the graph.

Figure 2. Sound decays.

acoustics, and ray-tracing software suggest a non stable relationship between aperture size and the absence, presence, and magnitude of the double-sloped sound decay.

In pursuit of the double slope, designers have built coupled-volume concert halls in Philadelphia; Lucerne; Dallas; Tampa; Syracuse; Washington DC; Denver; Ft. Worth; Singapore; Birmingham, England; Kitchner, Ontario; Hamilton Ontario; Regina, Saskatchewan; Macomb, Illinois; Magdeburg, Germany; Cedar Falls, Iowa; and Columbus, Ohio. More are planned or under construction in Miami and Orange County, California. In some cases the existing stagehouse is envisioned as a serendipitous coupled volume and apertures are incorporated into the performance shell. In others, dedicated rooms are saddled to the volume of the main concert hall. This paper will focus on the dedicated room type of coupled-volume concert hall.

II. LITERATURE REVIEW:

A. Methodology: statistical room acoustics and ray tracing software

For this paper, a statistics-based formula is used to compare the effects of aperture size. Cremer et al.[5] and Kuttruff[7] published statistical room acoustics formulas to account for double-sloped decay. Eyring[4] and Anderson et al.[6] showed favorable comparisons between statistical theoretical calculations and experimental results. Harris et al.,[8] Thomson[9] and Summers[10] questioned the ability of statistical acoustics to account for frequency modes, spatial particulars, and non-diffuse sound fields. Burroughs[11] defended the use of statistical room acoustics for most coupled-volume applications, citing it as an “ideal tool.”

Harris[8] warned that statistical acoustics is often inappropriate for modeling coupled rooms. Ricol and Junker[12] found data derived from computer models to be similar to that in measured rooms with coupling. Similarly, Njis[13] demonstrated agreement between measured and computer-modeled data, provided that diffusion coefficients were well-defined. CATT-Acoustic, the software employed in this study, uses a hybrid of ray tracing, image source modeling, and cone tracing to simulate impulse responses in computer-modeled rooms. Ayr et al.[14] found agreement between a CATT model and measurements taken in a church with a coupled chapel, provided that a high number of rays per octave were emitted from the source. Though the two rooms used in Ayr’s study were coupled, a double-sloped condition was not found either in the model or in the actual rooms. In contrast, Anderson et al.,[6] using the image source model ODEON to represent St. Paul’s Cathedral, found substantial *disagreement* between modeled and measured data.

B. Aperture size and the double slope

Qualitative evidence from consultations with designers of coupled volume concert halls (of similar size, material, and proportions to those modeled here) closely agrees with the findings of this paper. One acoustician reported (before this study was undertaken) that subjectively, the transition from a small-space acoustic to a double-sloped acoustic occurs when the apertures are opened 5% or less; he added that the transition from double-sloped acoustic to large-space acoustic occurs when the apertures are opened approximately 45% to 50%. Similar values are reported here.

The double slope has been little studied as a *tool*, but the concept has been well documented as a *phenomenon*. Eyring[4] found the effect of a small aperture on the double-sloped decay to be negligible. However, Kuttruff[7] and Anderson[6] determined that in order to produce a double-slope, the area of the coupling aperture must be substantially small , compared with the total surface area of the coupling room.

III. METHODS:

Despite the deficiencies of statistical models in accounting for differential spatial distribution of sound energy, low frequency sound decay, and non-diffuse sound fields, this paper uses a well-established statistically-rooted formula to characterize the double-sloped decay. It is a valid tool given that the comparisons made here are (1) relative to one another rather than to absolute values, (2) focused on middle frequency octave bands and therefore are not concerned with frequency distribution within an octave band, and (3) used to glean general relationships between aperture size and the double-slope rather than predict behavior in a specific concert hall.

The equations put forth by Cremer and by Kuttruff are used to form tools in Matlab.[15] The two formulae produce distinct, but very similar, decay curves. The Kuttruff formula results are depicted exclusively in the data section that follows. He defines the energy density in a room w as

$$w = \frac{4\pi I}{c} \tag{1}$$

where c is the speed of sound in air.

With the source of an impulse located in the main hall (*room 1*) exposed to a coupled volume (*room 2*) with an aperture of size A, the energy exchange between the rooms is written as a first order differential equation

$$\frac{\mathrm{d}w_1}{\mathrm{d}t} = -\left(2\delta_1 + \frac{cA}{4V_1}\right)w_1 + \frac{cA}{4V_1}w_2 + \frac{P_1}{V_1} \tag{2}$$

where δ_n is the damping constant for room n and V_n is the volume of room n.

For this study, a space is conceived and modeled using both this Matlab-Kuttruff software and in CATT-Acoustic software based on a recently built coupled-volume concert hall. The drawings of this hall, referred to here as “New Hall,” are available in Virginia Tech’s Architecture Library. The coupled volume, which is constructed of painted concrete masonry units, is modeled instead with smooth concrete to facilitate the existence of the double slope. The CATT model was run with a single source location on stage and a total of 13 receiver positions scattered throughout the audience planes (seven that are in close proximity to the aperture doors, six that are not). In this study, the model uses the program-default value (10%) for all surface scattering coefficients and a relatively large number (250,000) of rays per octave. The version of CATT (v.8.0b) is the first to offer users the option of deactivating the tail correction, which is used to extrapolate the later part of the decay in ray tracing software. By deactivating the tail correction in the simulations used for this study, it is believed that the software is better able to model the double-sloped decay.

IV. MEASUREMENT

A. Percentage opening

It should be noted that the total available aperture area is only 11% of the area available for apertures (the surface area of the main hall, including the area covered by audience seats). Unless stated otherwise, in the data that follows the phrase "10 percent open" refers to that portion of the available *aperture* that is exposed to the coupled volume. (See Table I.)

B. Coupling constant

In the data that follow, refinement of the "coupling constant" developed by Harrison, et al.[16] quantifies the sag of the double-sloped decay. The more dramatic the double slope—the more it varies from a classic Sabine exponential decay—the higher the coupling constant, (see Figure 3).

$$Coupling\ \ Constant = \frac{RT^{*}}{T_{15}} \tag{3}$$

RT* is the time required for the sound to decay by 60 decibels without extrapolation, as measured from 0dB to –60dB, and T15 is the time required for the sound to decay by 15 decibels—and extrapolated to produce a 60 decibel decay—as measured from 0dB to –15dB.

C. Validation

The data and analysis, for this paper, are based on a concert hall opened in 2000 (termed New Hall). To validate both the statistically based predictions and the geometrically based predictions on which this paper is based, recordings were made in a similar coupled-volume concert hall constructed approximately 10 years earlier (termed Old Hall). The same acoustical consultant designed both buildings; the main halls of each

Table I. Input data for simulated "New Hall"

Variable	Value used
Geometric volume of the main hall	25,306 cu m (894,215 cu ft)
Geometric volume of the coupled volume	8,231 cu m (290,837 cu ft) equal to 33% of the main hall volume
Audience seat area (with edge effect)	1,737 sq m (18,696 sq ft)
Percent of seats occupied	100%
Surface area of main hall, not including seats	8,147 sq m (87,692 sq ft)
Average main hall α (not incl. audience)	500Hz:0.08 1000Hz:0.06 2000Hz:0.06
Total available aperture area	1056 sq m (11,368 sq ft)
Total surface area of the coupled volume	4728 sq m (50,895 sq ft)
Coupled volume surface	Smooth concrete
Percent of aperture open	Variable

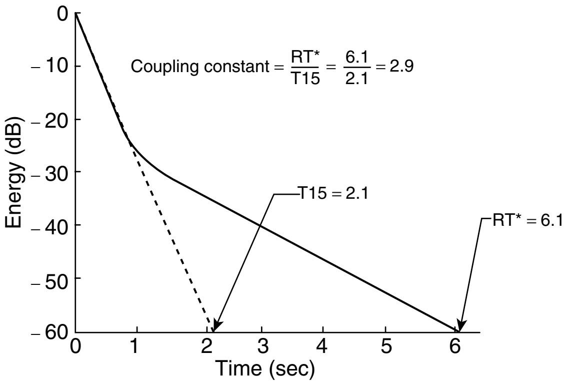


Figure 3. Coupling constant.

facility have approximately equal geometric volumes (within 1.5%), and forms (shoebox shape, three tiers). The location and quantity of aperture is the primary difference between the two halls: New Hall has nearly five times the available aperture area as Old Hall, with multiple door locations extending the height of the transverse section. The apertures of Old Hall are concentrated along the upper portions of the room.

Conditions during the recording were as follows: All of the available apertures were fully opened and the room was unoccupied. A pair of electret-condenser microphones binaurally recorded an organist rehearsing onto a DAT. Background noise, presumed to be emanating from a mechanical system, was audible. Stop bars, derived from 16 receiver locations, were isolated, imported into Matlab, and frequency-filtered. The data, used for creating the statistical and geometric-based models, was obtained from published drawings and photographs, augmented measurements and observations taken on-site. The measured results are compared with that predicted using the model in Figure 4.

None of the models predict a dramatic double-sloped decay and none of the recorded positions produces a dramatic double-sloped decay. This, of course, is neither a confirmation nor a repudiation of the model's validity in predicting double slopes. If the phenomenon occurs, it is most clearly defined in the front of the top balcony. This corresponds to qualitative observations made by interviewed hall officials who, though they make no claims to have heard a double slope, maintain that the front of the top tier is the best place to hear the effects of the chamber. This is logical because the majority of the open apertures connecting the main hall with the coupled volume are coplanar with the top tier. In this location the statistical prediction shows good agreement with measured results. In other locations, neither the presence of the double slope, nor agreement with a prediction method is as easily determined. It is also notable that (1) the impulse response recorded on the second tier, house-front-right, resembles the Sabine decay that we would expect if the two coupled rooms where merged in to a single larger space. This particular location is adjacent to a fully open aperture, exposing it to both the main hall and the coupled volume and suggesting a spatial sensitivity to the double-sloped condition. (2) The presence or absence of the impulse response

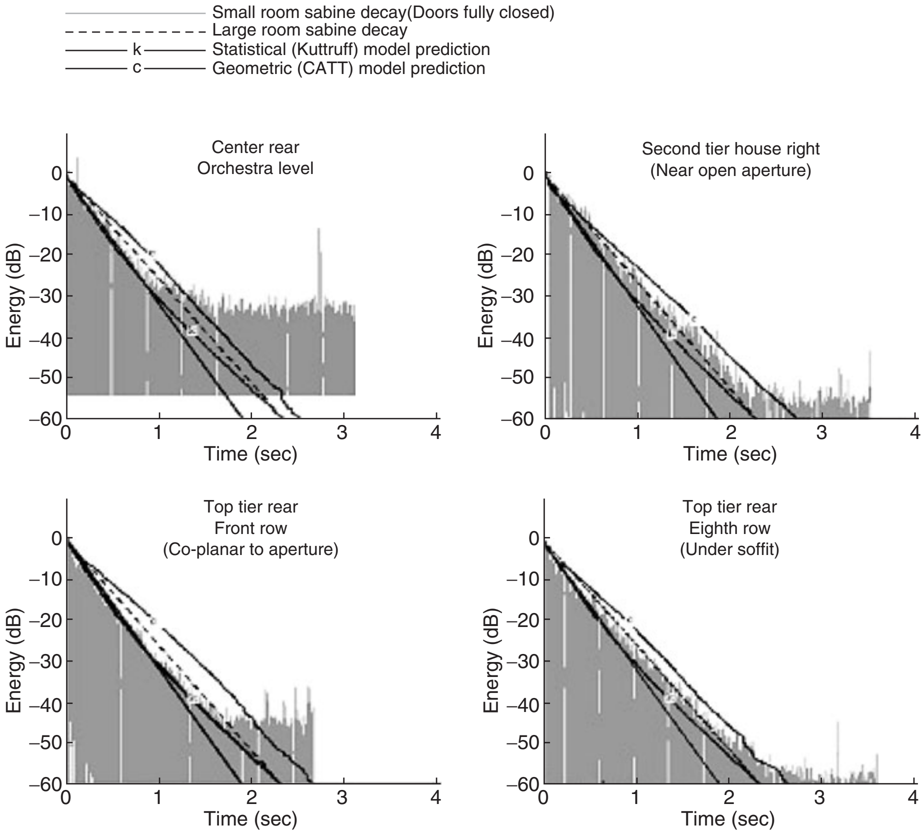


Figure 4. Measured and predicted data for Old Hall at 1 kHz. Left to right, top to bottom, (a) Orchestra level: Background noise obscures the search for a double slope. (b) Second tier: In close proximity to a three-metre wide aperture; (c) Front row of the top-rear balcony: Clear acoustical line of site to all aperture doors; (d) Near the rear of the top-rear balcony: Co-planar with the apertures but obscured by a soffit.

recorded on the main level is fully masked by background noise suggesting that noise-always of major importance in the design of a space for unamplified music listening-plays an important role in the perception of the double-sloped decay.

V. DATA AND ANALYSIS

A. Aperture size and sound decay

The data presented in Figures 5 through 8 suggests that in the New Hall model, coupled volume concert hall operators who wish to affect a double-sloped decay have a relatively small range of acceptable aperture sizes with which to work. Figures 5 and 6 present the predicted impulse responses for different aperture sizes for the statistical

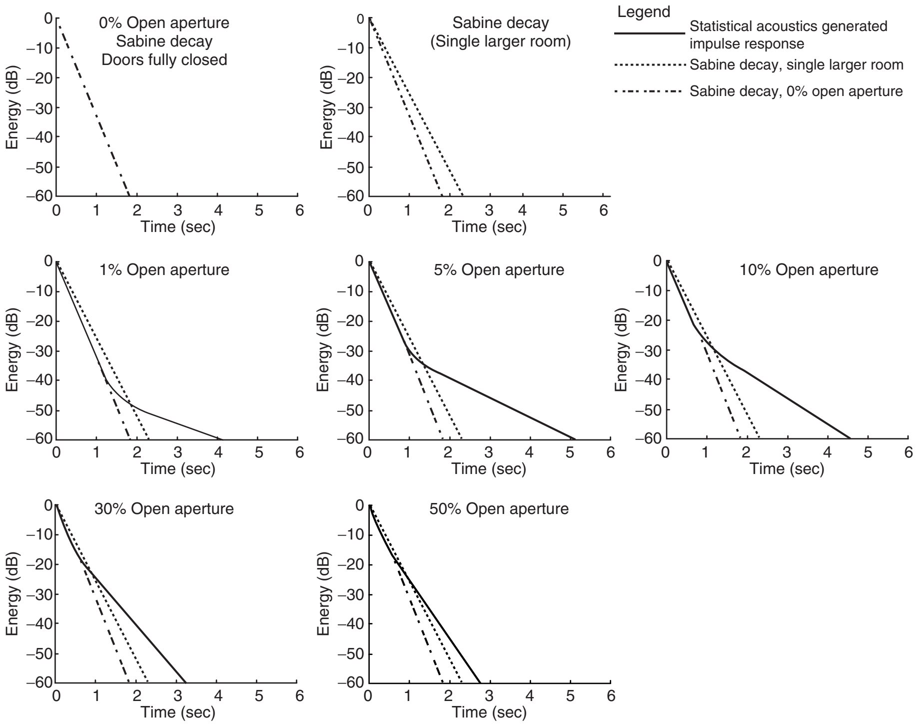


Figure 5. Statistically predicted sound decays for the simulated New Hall in the 1kHz octave band.

model and CATT model, respectively. From these figures we see the sensitive nature of aperture size as it relates to the double slope. In this spatial and material composition, apertures, which are a small portion of the total surface area in the main hall, have a dramatic effect on the slope of the calculated statistical *and* geometric sound decay when opened only 1% (0.1% of the total surface area available in the main hall). As measured by the coupling constant, this effect peaks at approximately 5% according to both the Kuttruff formula and CATT software, and diminishes as the aperture is opened further. As the aperture size approaches 30% (3.3% of the total surface area available in the main hall) the decay approaches that which would be expected for a single, larger room of a volume equal to the combined volumes of the main hall plus the coupled space.

The graph in Figure 7 translates the “degree” of double slope into the coupling constant and compares it to the aperture size for both the statistically based model and the CATT model. The two models are inconsistent in amplitude; the statistically based model predicts a markedly higher coupling constant than the CATT model for all aperture sizes greater than zero. However, both models predict a sharp increase in the coupling constant with the introduction of a small aperture size, followed by a sharp decrease in

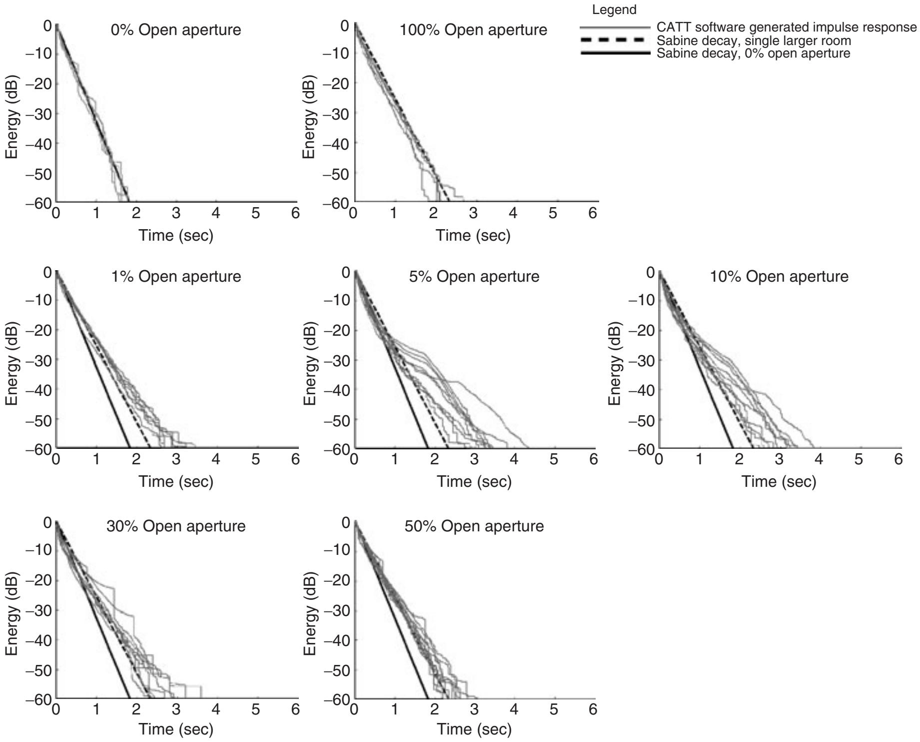


Figure 6. Geometrically predicted sound decays, derived from 13 receiver positions, in the simulated New Hall for the 1kHz octave band.

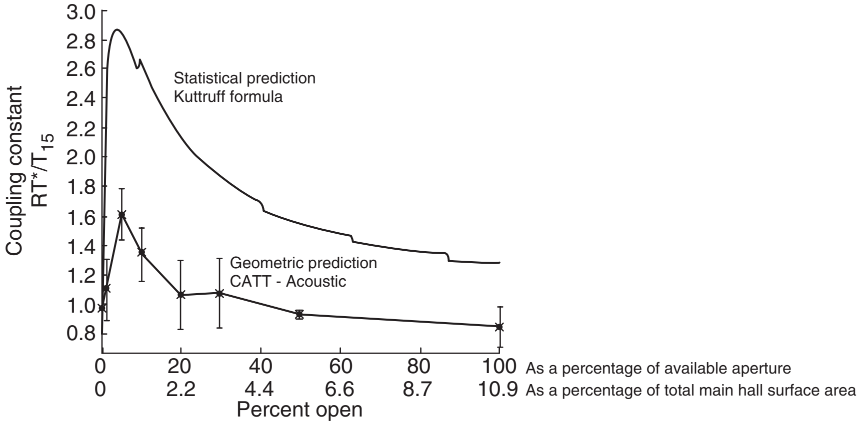


Figure 7. Coupling constant vs. aperture size at 1kHz for New Hall. The geometric predictions are limited to receiver positions that are not immediately adjacent to open apertures.

the coupling constant as the aperture size expands. This underscores the predicted fickleness and sensitivity of the New Hall coupled volume system.

The size of the aperture also influences the location of the point where the early rapid decay and the late slow decay intersect. This “crossing point,”[10] as measured in decibels on the y-axes of Figures 5 and 6 tends to move up as the apertures open wider. While this change is noticeable in the CATT-based decays of Figure 6, it is particularly apparent in the statistical analysis presented in Figure 5. The crossing point associated with the 1% open condition is located at –45dB, while the crossing point associated with the 30% open condition is located at –15dB. The crossing point most likely affects the balance of clarity and reverberance sought after by designers looking to employ the double-slope, and is therefore a strong candidate for future study. Importantly, if the crossing point sound level falls below the background noise level, the double slope may not be discernable by the listener.

B. Listener location and sound decay

Kuttruff observed that the strength of the perceived coupling depends on the location of the receiver. Figure 8 expands the investigation into other mid-frequency octave bands and includes the effect of location on the CATT model longitudinal section as a variable. Again, we see the sharp peak in coupling constant at one to ten percent open aperture and thus, the sensitivity of the system as a whole. The study fails to reveal significant correlation between the coupling constant and the listener location with respect to the longitudinal or height vector. Figure 9, however, suggests a marked shift when the receiver position is near the sidewalls, and thus the apertures. In the crucial 5% open and 10% open simulations, receiver positions on the side balconies were given a distinct triple-sloped decay; rapid at first, then slower, then more rapid again.

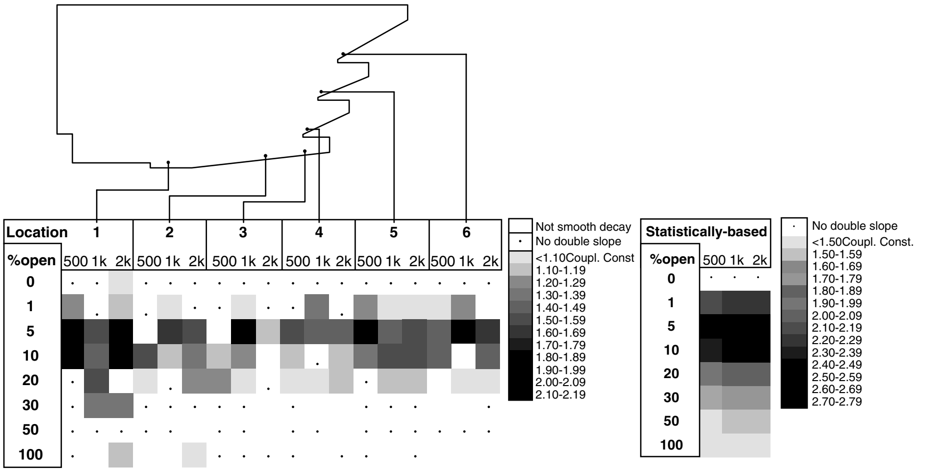


Figure 8. Coupling constant gradient for the simulated New Hall. CATT-based analysis (left) for six receiver locations approximately 6.5 metres from the sidewalls. Statistically based analysis (right).

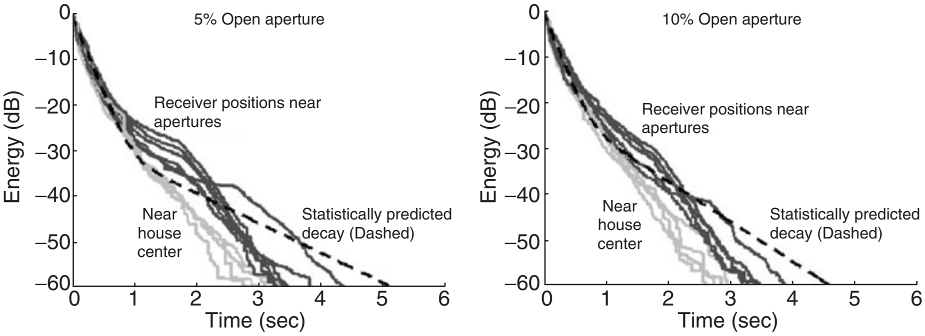


Figure 9. CATT-generated sound decays for the 5% and 10% open condition, for New Hall, in the 1kHz octave band.

C. Modeling method comparison

The two systems of modeling, geometric and statistical, while indicating similar trends, with regard to sensitivity of the double slope to aperture size, do not agree in terms of amplitude. This is especially evident in the 1% open to 10% open range, the conditions that both models predict dramatic double-sloped decays. The measurements taken in Old Hall fail to resolve this inconsistency because the 100% open aperture was effectively equivalent to a 20% open aperture in New Hall (New Hall has a greater area covered by apertures), and is well outside of the range in question.

VI. CONCLUSIONS

In the study of middle frequencies in a coupled volume concert hall, statistical room acoustics and ray tracing software indicate a hegemonic relationship between architectural composition and the double-sloped decay. In a simulated concert hall of 25,306 cubic metres (894,215 cu ft), high values of coupling constant are obtained with aperture sizes in the range of 0.1% to 1.0% of the total area available within the main hall. Maximum values are obtained with aperture sizes at or near 0.5% of the available area in the main hall. The coupling constant approaches unity (no double slope) when the aperture size is larger than 3.5% of the area available in the main hall. Small variations in aperture size produce dramatic changes in the calculated sound decay of a space. For designers and operators of coupled–volume concert halls, seeking the double-sloped decay to reconcile the often competing qualities of reverberance and clarity, this suggests that the size and openness of doors, connecting the main hall to the reverberation chamber, requires careful consideration.

While predictions, from statistically based formulae and ray-tracing software (CATT), indicate aperture hegemony, the two methods are not in agreement in predicting the absolute decay associated with aperture size. In predicting coupling constants, statistically based values significantly exceed geometric based values at all aperture sizes. CATT echogram predictions fall into two distinct categories: receiver positions near (2 metres) the open apertures, and receiver positions far (6.5 metres) from the apertures. This discrepancy was especially evident in the range of aperture sizes that produce the most dramatic double slopes and, therefore, the highest coupling constants.

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