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Exposure and materiality of the secondary room and its impact on the impulse response of coupled-volume concert halls

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Abstract

How does sound decay when one room is partially exposed to another (acoustically coupled)? More specifically, this research aims to quantify how operational and design decisions impact sound fields in the design of concert halls with acoustical coupling. By adding a second room to a concert hall, and designing doors to control the sonic transparency between the two rooms, designers can create a new, coupled acoustic. Concert halls use coupling to achieve a variable, longer, and distinct reverberant quality for their musicians and listeners. For this study a coupled-volume shoebox concert hall is conceived with a fixed geometric volume, form, and primary-room sound absorption. Aperture size and secondary-room sound absorption levels are established as variables. Statistical analysis of sound decay in this simulated hall suggests a *highly sensitive* relationship between the double-sloped condition and (1) architectural composition, as defined by the aperture size exposing the chamber and (2) materiality, as defined by the sound absorptance in the coupled volume. The theoretical, mathematical predictions are compared with coupled-volume concert hall field measurements and guidelines are suggested for future designs of coupled-volume concert halls.

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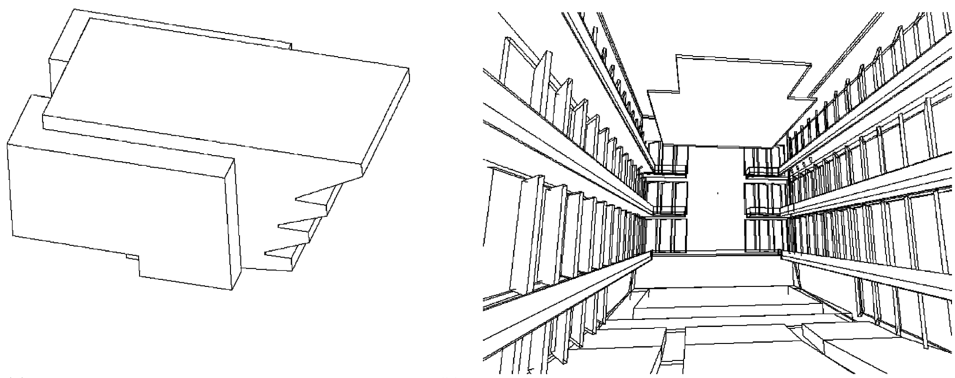
1. Introduction

The coupled volume and its signature acoustic—the double-sloped sound decay—are now part of the concert hall design lexicon. The double-sloped decay was once considered contrary to high-quality acoustic character [1]. Now it is receiving notice [2] as a method of providing a variable and performance-piece-specific sound environment. In the last quarter-century acousticians have built halls with coupled volumes in Philadelphia; Lucerne; Dallas; Birmingham, England; Tampa; Kitchner, Ontario; Hamilton Ontario; Regina, Saskatchewan; Syracuse; Macomb, Illinois; Washington DC; Ft. Worth, Texas; Magdeburg, Germany; Cedar Falls, Iowa; Columbus, Ohio; Denver and Singapore. More are planned or under construction in Miami, Florida and Orange County, California. In one building archetype, dedicated chambers are saddled on the sides of the house and/or behind the upstage wall of a concert hall as shown in Fig. 1. In another, multipurpose auditoria have been specifically outfitted to take advantage of the stagehouse cubage above acoustic shells and use it as a coupling volume. In each archetype a window or aperture connects the two volumes.

Designers are attracted to the double-sloped decay, and thus the coupled volume form, because it proposes a compromise between the sometimes-competing acoustic qualities of reverberance and clarity [3–5]. The rapid early sound decay of the double slope provides a measure of acoustic clarity; later, as the sound decay slows, a low-level reverberance lingers.

With a sound source (orchestra) and receiver (audience) in one room (main hall) and the aperture closed, the room will behave as a small space, as if the coupled volume was not present at all. If the aperture is large enough, the acoustic character will approach that which is found in a single large space encompassing the entire volume of both the main hall and the coupled volume [6,7]. With the aperture partially open, the two partially-connected subspaces can produce a third, double-sloped acoustic (see Fig. 2) [7,8]. This research will explore the thresholds of aperture openness between ''small space'' and ''double-sloped'' acoustic conditions and between ''double-sloped'' and ''large space'' acoustic conditions. Anecdotal evidence and statistical room acoustics



(a) (b)

Fig. 1. (a) Schematic massing model of a concert hall saddled on each side by coupled volumes. (b) Schematic perspective view of the interior of the concert hall looking toward the stage. The apertures to the coupled volume that line the sides of the house and portions of the upstage wall in this drawing are shown at 35% open.

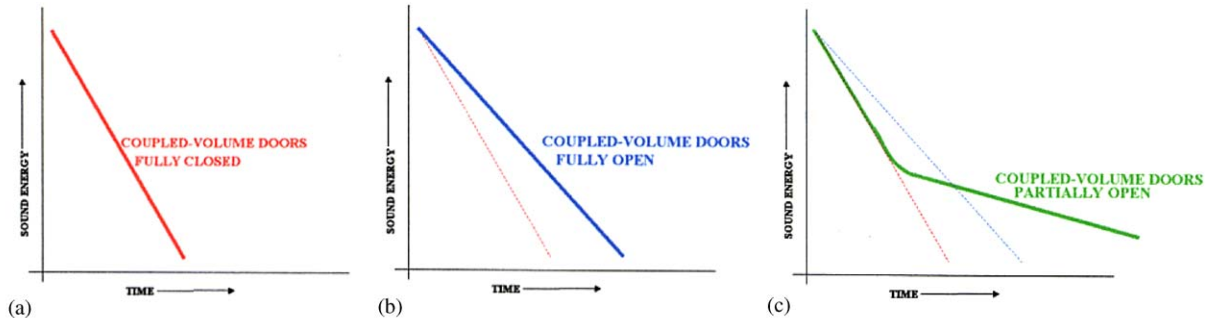


Fig. 2. Sound decays. (a) Small space acoustic. Schematic of sound decay for a coupled volume concert hall with its doors fully closed. Only the primary room is exposed to music. (b) Large space acoustic. Schematic of a slower sound decay for a coupled-volume concert hall with its doors fully opened, essentially enlarging the room. For comparison, the fully closed condition is ghosted in. (c) Double-sloped acoustic. Schematic of a double-sloped sound decay for a coupled-volume concert hall with its doors partially open. For comparison, the fully closed and fully opened conditions are ghosted in.

will, furthermore, suggest a fickle relationship between aperture openness and the double-sloped condition.

Similarly, this research will suggest a sensitive relationship between the existence of the double-sloped condition and the quantity of sound absorption present in the coupled volume. This study will propose that traditionally held understandings of what constitutes "sound reflective" materials [9] need be tightened when speaking of the double-sloped condition. The double-sloped condition requires a very sound reflective coupled volume.

While the double slope has been extensively studied as a *phenomenon*, it has been under-researched as a *design tool*. Using established formulae, this paper aims to identify two areas (aperture size and coupled-volume materiality) to which concert halls may be especially sensitive. It further means to give the coupled-volume concert hall operator a basis for setting the appropriate sizes of apertures, and to give the coupled-volume concert hall designer the wherewithal to make material and spatial decisions essential to effect a double-sloped sound decay.

2. Literature review

Cremer and Müller [7] and Kuttruff [10] published room acoustics formulas to account for double-sloped decay in coupled volumes. Eyring [8] and Anderson and Bratos-Anderson [6] showed favorable comparisons between theoretical calculations and experimental results. Harris et al. [11], Thomson [12] and Summers [13] questioned these formulas' ability to account for frequency modes, spatial particulars, and non-diffuse sound fields.

In looking at the relationship between aperture size and sound field in coupled-volume concert halls, Eyring found the effect of a small aperture on the double-sloped decay to be negligible. However, Kuttruff and Anderson and Bratos-Anderson determined that in order to produce a double slope, the area of the coupling aperture must be substantially small as compared to the total surface area of the coupling room.

Cremer and Müller and Kuttruff related aperture size to materiality, observing that a distinct double-sloped decay is only possible when the equivalent absorption area in the coupled volume is small relative to the aperture size. In one of the few papers examining coupled volumes as a design tool, Johnson [1] surmised that coupled volumes must be large and sound reflective to produce a double-sloped sound decay.

While Cremer and Müller found that both the coupled volume *and* the main room needed to be highly reverberant to produce a double-sloped decay, Anderson and Bratos-Anderson, and Harrison and Madaras [14] compared the reverberant qualities of the main room with that of the coupled volume and found that a double-sloped decay occurs only when the source and receiver are located in a more sound absorptive room, and the coupled volume is a sound reflective room by comparison. Eyring went farther, varying coupled-volume absorption levels. He found (1) a pronounced double-slope decay with a coupled-volume average absorption of 0.01, (2) a significantly less-pronounced double-sloped decay with a coupled-volume average absorption of 0.05, (3) a barely observable double-sloped decay with a coupled-volume average absorption of 0.10, and (4) no observable double-sloped decay with a coupled-volume average absorption of 0.20 or greater. This is in strong agreement with the data presented in this paper.

Qualitative anecdotal evidence, gleaned from discussions with designers of coupled-volume concert halls, follows in close agreement to the findings of this paper. Most discussions were conducted casually among colleagues, while one of the authors was employed by the acoustician-designer of most of the world's coupled-volume concert halls. All such discussions were conducted before the onset of a formal inquiry into the relationship between the double-sloped decay and architectural composition—they in fact gave birth to this inquiry. Thus the results are truly anecdotal and have not undergone rigorous survey or analysis. Even with these shortcomings, they are worthy of note because of the dearth of published research written by *designers* of coupled-volume concert halls and because of the striking similarity between designers' observations and the quantitative studies undertaken here. One acoustician reported that subjectively, the transition from small-space acoustic to 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 45–50%. Similar numbers are reported here (see Figs. 6 and 7). Another described the need to guard against attempts by architects and mechanical engineers to introduce items that could add absorption, such as ductwork, to the interior of the coupled volume. The halls that were considered successful in creating a double slope were more likely to have coupled volumes constructed of concrete; those that were less successful were more likely to have coupled volumes constructed of (more-absorbent) concrete block or wood. Likewise, the formulas explored in this paper suggest a high sensitivity of the double slope to the addition of small quantities of sound absorption in the coupled volume.

3. Formulas

Kuttruff developed his coupled-volume energy decay formula as a method of predicting average sound levels for complex, interconnected subsystems. While it simplifies sound decay predictions in coupled volumes, it fails to take into account frequency distributions within each octave band or spatial distribution of sound energy within a space. This leaves it ill-equipped to predict sound decays in situations with low-frequency sound or non-uniform wall absorption [12].

The formula used in this paper accounts only for aperture size and does not address the haptic nature of listener location nor the geometry of aperture door configuration. This is of particular concern because there is a spatial component to the coupled-volume system. Field measurements conducted in Old Hall show a discernable difference between decay patterns in measurements made near the doors and those made far from the doors (see Fig. 4). Those made near the doors are more similar to the Sabine decay predicted for a large room of volume equal to the main hall plus the coupled volume. Moreover, if the aperture doors are of similar size and the openings are of similar size, there may be a risk of tonal coloring due to diffraction, for which this formula does not account. Finally, in practice, the acoustically-driven need for massive, low-frequency-reflecting doors with tight seals conflicts with architecturally-driven concerns inherent in a heavy, hinged, door with tight gaskets at the door's perimeter.

Nevertheless, this paper uses established equations to derive its data. The authors feel that it is a valid tool given that the comparisons made here are (1) relative to one other rather than absolute, (2) not concerned with frequency distribution within an octave band, (3) not concerned with spatial sound distribution within a space, and (4) used to glean general correlations rather than predict behavior in a specific concert hall.

This analysis follows the coupled room theory outlined by Kuttruff [10]. The objective is to couple together two lightly damped rooms using a small open area such that the effect of room damping and open area can be investigated. The assumptions made are: (1) that the sound field in each room is diffuse and therefore the intensity I is independent of angle and position; (2) the power flow through the open area between the rooms is proportional to the intensity times the open area.

The energy density in a room w is defined as

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

where c is the speed of sound (taken as $343\,\mathrm{m\,s^{-1}}$). Following Kuttruff the energy change in the first room can be written as a first-order differential equation,

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

This equation states that the rate of change in energy in the first room is equal to the energy absorbed per second by the damping in the first room (δ_1 is the damping constant for the first room), the energy lost per second to the second room through the open area A, the energy gained per second through the open area from the second room and the power P_1 injected into the room due to some noise source. The volumes of the first and second rooms are given by V_1 and V_2, respectively. Equivalently the energy density in the second room is given by

$$\frac{\mathrm{d}w_2}{\mathrm{d}t} = -\left(2\delta_2 + \frac{cA}{4V_2}\right)w_2 + \frac{cA}{4V_2}\,w_1. \tag{3}$$

It is assumed here that there are no noise sources acting directly into room 2. Eqs. (2) and (3) are coupled and can be combined into a single equation to determine the effect on the energy in room 1 due to a power source P_1. To do this, a Laplace domain approach will be used. After some rearrangement the transfer function between the input power to the energy density in the first room can be written as

$$\frac{W_1(s)}{P_1(s)} = \frac{s + 2\delta_2 + \frac{cA}{4V_2}}{V_1\left[\left(s + 2\delta_1 + \frac{cA}{4V_1}\right)\left(s + 2\delta_2 + \frac{cA}{4V_2}\right) - \frac{c^2A^2}{16V_1V_2}\right]}, \tag{4}$$

where s is the Laplace variable, $W_1(s)$ is the Laplace transform of the energy density in the first room and $P_1(s)$ is the Laplace transform of the power input into the first room. This equation shows that the coupled system has two poles, each having a different rate of exponential decay. This transfer function also has a single zero. It can be seen that as $A \Rightarrow 0$ the two poles in the system tend to the pole positions for the two uncoupled rooms at $s = -2\delta_1$ and $-2\delta_2$. In this scenario the zero also tends to $s = -2\delta_2$, canceling the effect of the second pole and simplifying the equation to the uncoupled equation for the energy in the first room. The above equation for the coupled system has two poles and can be re-written as

$$\frac{W_1(s)}{P_1(s)} = \frac{s + 2\delta_2 + (cA/4V_2)}{V_1[(s + 2\delta_1^*)(s + 2\delta_2^*)]}, \tag{5}$$

where each pole ($s = -2\delta_1^*$ and $s = -2\delta_2^*$) has a different rate of exponential decay $e^{-2\delta_1^* t}$ and $e^{-2\delta_2^* t}$, where δ_1^* and δ_2^* are the *coupled* damping constants for the *coupled* rooms. As the open area between the rooms vanishes (i.e. $A \Rightarrow 0$) the two poles in the system tend to the pole positions for the two uncoupled rooms ($\delta_1^* \Rightarrow \delta_1$ and $\delta_2^* \Rightarrow \delta_2$) as would be expected. It should also be noted that this transfer function has a single zero and with no coupling ($A \Rightarrow 0$) the zero tends to $s = -2\delta_2$. Therefore, the zero cancels the second pole and the equation simplifies to the uncoupled equation for the energy in the first room.

For any given choice of variables the change in the energy density $W_1(t)$ can be determined by finding the residues for the two poles (using the partial fraction expansion in Eq. (6)) and then taking the inverse Laplace transform (in Eq. (7)). For the sake of simplicity, the input power $P_1(t)$ is assumed to be an impulse (i.e. $P_1(s) = C$) whose amplitude C is chosen such that the initial energy density is unity (i.e. $A+B=1$ or 0 dB).

$$W_1(s) = \frac{s + 2\delta_2 + (cA/4V_2)}{V_1[(s + 2\delta_1^*)(s + 2\delta_2^*)]}\, C = \frac{A}{(s + 2\delta_1^*)} + \frac{B}{(s + 2\delta_2^*)}, \tag{6}$$

$$W_1(t) = Ae^{-2\delta_1^* t} + Be^{-2\delta_2^* t}. \tag{7}$$

Fig. 3 shows how the poles and zero of this system change position as the coupling between the rooms increases. The assumption made is that room 2 is more lightly damped. With very low coupling the zero is very close to the pole associated with the slowly responding pole (i.e. one with

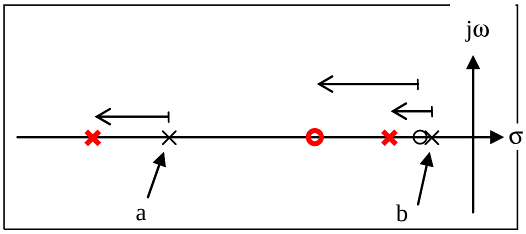


Fig. 3. The pole zero map for the coupled room system with large and small coupling. xo = small coupling, **xo** = large coupling: (a) identifies the pole associated with the more heavily damped room 1; (b) identifies the pole associated with the lightly damped room 2.

long decay time) resulting in a very low level of response from that pole. As the coupling increases the poles shift left becoming faster but this effect will be more pronounced on the pole associated with room 2. As the coupling increases the other main effect is that the zero moves away from the pole associated with room 2 increasing the effect of this pole on the response.

4. Verification

Field measurements were taken in ''Old Hall'', a coupled volume concert hall built approximately 10 years ago. Organ stop chords were recorded on a portable DAT recorder in 16 locations in the hall while a performer rehearsed.

A software tool was created, based on Kuttruff's formula, to simulate the decay in Old Hall. Data derived from published drawings of the hall were input into the software, as was a second set of refined data based on the *observed* condition of the coupled volume. The ''observed'' data includes absorption provided by items not depicted in the published drawings: concrete structure, metal raceways, catwalks, pipes, roof trusses, ducts, music stands in storage, wooden doors, organ stop cases (7 organ stops are housed inside the coupled volume), retractable drapes that were not fully retracted, and miscellaneous items in storage.

Fig. 4 compares the predicted decays for Old Hall with the actual measured decays. There is good agreement between the two, though this should not be read as verification (nor indictment) of the Kuttruff formula. The formula predicted a decay with little double slope, similar to a classic Sabine condition. This is what was measured in the hall. According to the formula, there was not enough reverberence in the coupled volume of Old Hall to predict a dramatic double slope: one with a sharp visual distinction between the initial rapid sound decay and the later, slower rate of decay (see Fig. 15). In most of the measurements taken, neither the quantitative impulse response nor the qualitative impressions of the researcher were able to definatively identify a double-sloped decay. Note that in many of the receiver positions, background noise obscured the later portion of the decay curve—important in evaluating double slopes.

While inputting the Old Hall data as shown in Table 1 returned a predicted sound decay curve used for verification, the analysis portion of this study was derived using data from ''New Hall'', an existing coupled-volume concert hall which opened in the past few years. New Hall's construction drawings are archived in Virginia Tech's Architecture Library.

5. Percent open

It should be noted that the total available aperture area in New Hall is only 11% of the area available for apertures (the surface area of the main hall, not including audience seats) and it is only 9% of the main hall's total area (including audience seating). Unless otherwise stated, the

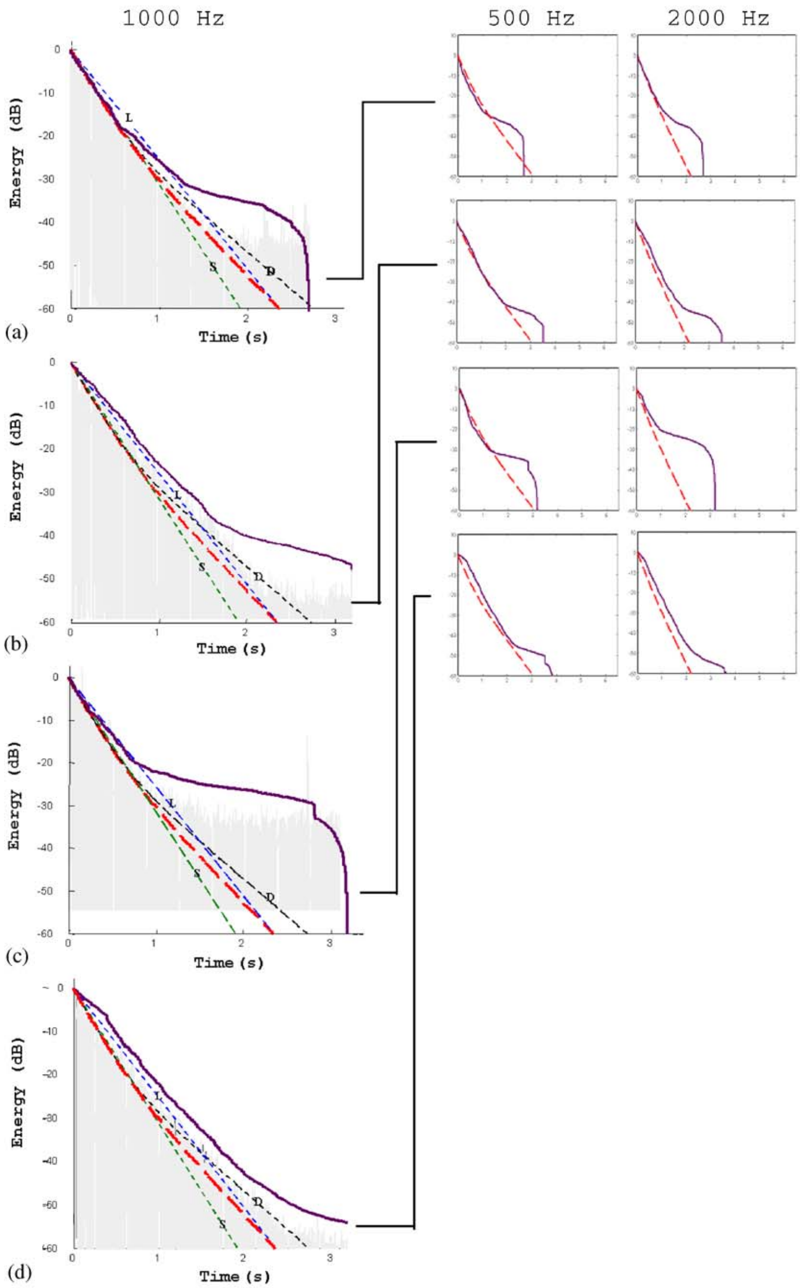


Table 1
Inputted data

Variable	New Hall	Old Hall (as-observed)
Geometric volume of the main hall	25,017 m^3 (884,000 ft^3)	25,014 m^3 (883,000 ft^3)
Geometric volume of the coupled volume	7811 m^3 (276,000 ft^3)[a]	10,453 m^3 (369,000 ft^3)[b]
Audience seat area	1500 m^2 (16,200 ft^2)	1032 m^2 (11,100 ft^2)
Percent of seats occupied	80%	0%
Metric sabines of the main hall,	125 Hz:1497 250 Hz:1367	125 Hz:1353 250 Hz:1579
	500 Hz:1171	500 Hz:2098
not including seats	1 kHz:1459 2 kHz:1376[c]	1 kHz:2264 2 kHz:2223
Total available aperture area	738 m^2 (7940 ft^2)	195 m^2 (2100 ft^2)
Total surface area of the coupled volume	3000 m^2 (32,300 ft^2)	6437 m^2 (69,261 ft^2)
Percent of aperture open	Variable	100%
Average α of the coupled volume	Variable	125 Hz:0.01 250 Hz:0.02
		500 Hz:0.04
		1 kHz:0.06 2 kHz:0.08

[a]The total size of the coupled volume is 31% of the size of the main hall.
[b]The total size of the coupled volume is 42% of the size of the main hall.
[c]From the average α of 15 halls, not including audience or seats [3].

phrase "10 percent open" refers to that portion of the *available* aperture that is exposed to the coupled volume.

6. Coupling constant

When the initial rapid decay of the double-slope shifts to the later, slower decay, the impulse response appears to sag. In the data that follows, refinement of the "coupling constant" developed by Harrison et al. [14] 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 Fig. 5).

$$\text{Coupling constant} = \frac{RT^*}{T_{15}}, \tag{8}$$

Fig. 4. Comparison of measured and predicted decays for "Old Hall", a coupled volume concert hall built approximately 10 years ago. All measurements were taken from DAT recordings of stop-chords as a solo organist practiced in the unoccupied hall. The apertures were fully opened. In some of the scenarios, the backwards-integrated field measurement appears to have a *very* dramatic double-slope—this is a residue from the background noise present in the hall and not evidence of a double-sloped decay. (a) Top tier, front row (co-planar with the apertures). (b) Second tier, house front-right (very near a fully opened aperture). (c) Orchestra level, center (high background noise). (d) Top tier, rear row (view to apertures partially obscured by a soffit). The measured decay is represented with craggy gray shading; ———, backwards integrated measured decay; - - -s- - -, Small single room Sabine prediction (main hall only); - - -L- - -, Large single room Sabine prediction (main hall plus coupled volume); - - -D- - - Kuttruff formula coupled room prediction, based on published Drawings of the hall; - - - - - - - Kuttruff formula coupled room prediction based on the published drawings and supplemented by observations made upon visiting the hall.

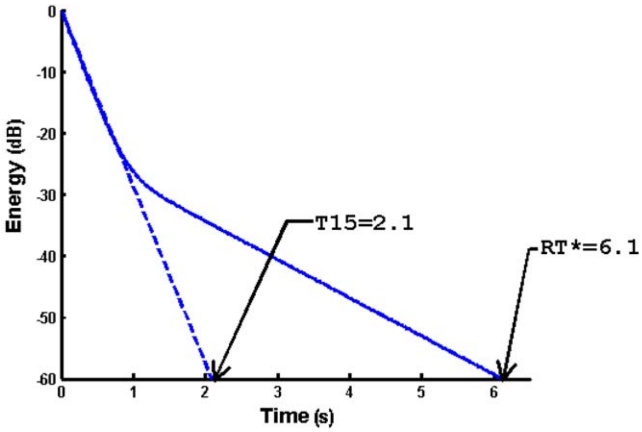


Fig. 5. Example coupling constant calculations. The higher the coupling constant is the more marked the double slope is. In this example, the coupling constant $= RT^{*}/T_{15} = 6.1\,\mathrm{s}/2.1\,\mathrm{s} = 2.9$.

where RT^{*} is the statistically predicted time required for the sound to decay by 60 dB as measured from 0 to -60 dB and T_{15} is four times the statistically predicted time required for the sound to decay by 15 dB as measured from 0 to -15 dB. Traditionally, reverberation measurements of normalized impulse responses are made beginning at -5 dB, but in the formula-predicted, double-sloped context, measuring decays beginning at 0 gives a clearer picture of the coupling constant.

7. Aperture size and sound decay

Figs. 6 and 7 illustrate the sensitive nature of aperture size as it relates to the double slope. The apertures, themselves a small portion of the total surface area in the main hall, have a dramatic effect on the slope of the calculated sound decay when opened only 1%. As measured by the coupling constant, the aperture's effect peaks at 4% and trails off rapidly as the aperture is opened further.

8. Materiality of the coupled volume and sound decay

As suggested in Figs. 8 and 9, the double-sloped decay requires exceptionally hard, heavy, and smooth surface materials in the coupled volume. Moderately sound reflective materials such as plywood offer little sag in the predicted impulse response.

Figs. 10 and 11 reveal the extreme diligence required of coupled-volume concert hall designers in ensuring that sound reflective surfaces are not "contaminated" by derivative materials inherent to construction. Items that may under typical circumstances have a negligible effect on the impulse response of a space—such as doors, ventilating grilles, air ducts, exit signs, curtains and spray-on fireproofing—may acquire relevance in the realm of the coupled volume.

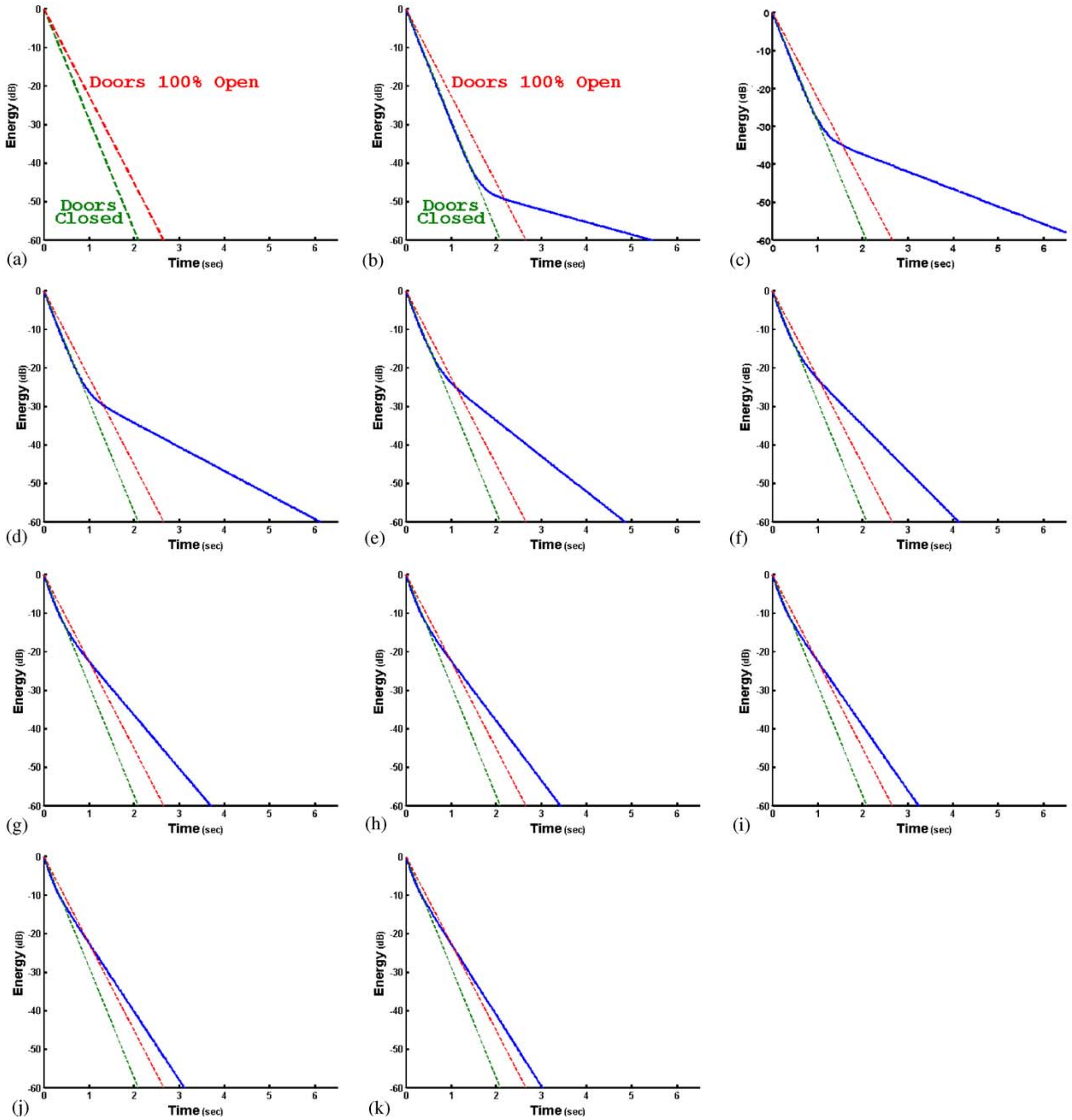


Fig. 6. Calculated decay curves for apertures of varying sizes at the 1000 Hz octave band. For reference, the graphs include ghosted Sabine decays for the conditions of aperture doors-fully closed and aperture doors-fully open. For these calculations, the coupled volume is assumed to be constructed of concrete. (a) Sabine decays; (b) 1% open aperture; (c) 5% open; (d) 10% open; (e) 20% open; (f) 30% open; (g) 40% open; (h) 50% open; (i) 60% open; (j) 70% open; (k) 80% open.

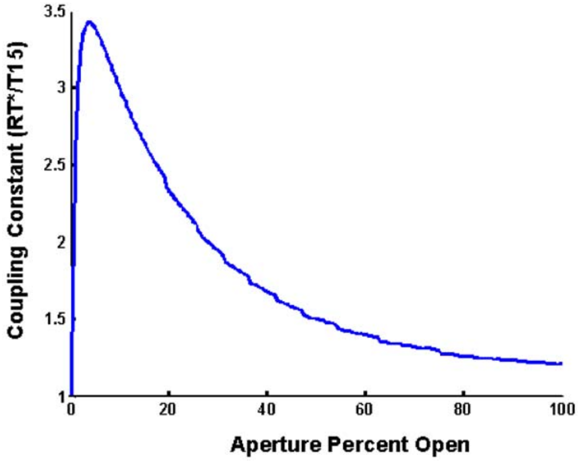


Fig. 7. Coupling constant, associated with the degree of "sag" of a double-sloped decay, plotted against the percentage-open of the apertures exposing the main hall to the coupled volume. 1000 Hz octave band.

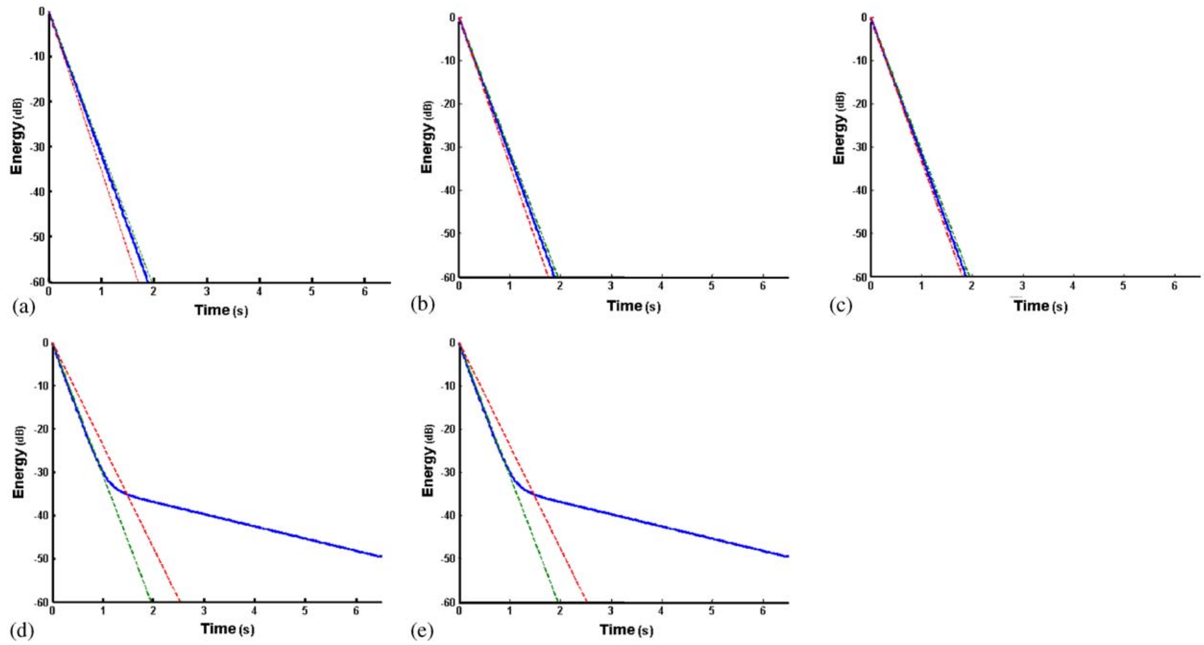


Fig. 8. One hundred twenty five hertz octave band. Predicted decay curves for halls with coupled volumes made of (a) unpainted concrete block ($\alpha = 0.36$); (b) 3/8″ plywood over airspace ($\alpha = 0.32$); (c) 1/2″ gypsum board nailed to studs ($\alpha = 0.07$); (d) plaster on brick ($\alpha = 0.01$); and (e) smooth concrete ($\alpha = 0.01$). For reference each graph includes ghosted Sabine decays for the conditions of aperture doors-fully-closed and aperture doors-fully-open. For these calculations, the apertures are assumed to be 4% opened. Questions exist about the appropriateness of using statistical room acoustics for predicting sound decay in low frequencies.

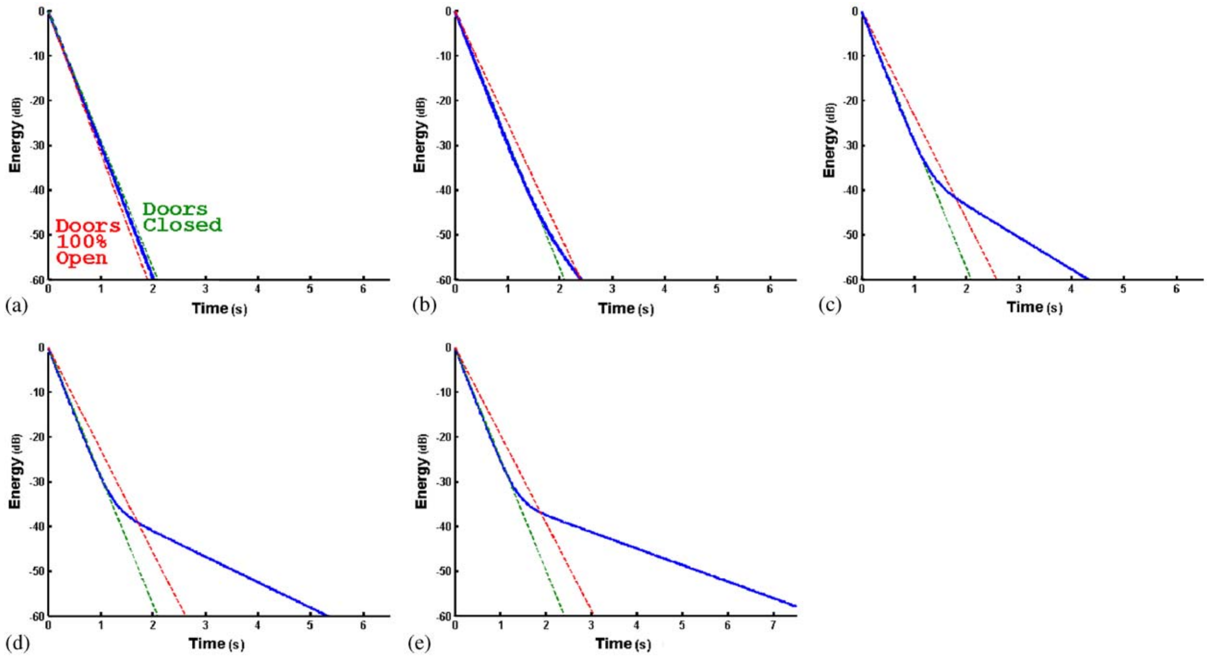


Fig. 9. Thousand hertz octave band. Calculated decay curves for halls with coupled volumes made of (a) unpainted concrete block ($\alpha = 0.36$); (b) 3/8″ plywood over airspace ($\alpha = 0.09$); (c) 1/2″ gypsum board nailed to studs ($\alpha = 0.04$); (d) plaster on brick ($\alpha = 0.03$); and (e) smooth concrete ($\alpha = 0.02$). For reference each graph includes ghosted Sabine decays for the conditions of aperture doors-fully-closed and aperture doors-fully-open. For these calculations, the apertures are assumed to be 4% opened.

Figs. 12–14 reveal the overarching influence coupled-volume absorption levels seem to possess. Materials with $\alpha < 0.02$ have a significantly higher coupling constant than those with $\alpha > 0.05$.

Fig. 15 is of particular use to the designer of a new coupled-volume concert hall. It assumes that the geometry and size of the coupled volume have not been fixed, nor has the total size of the apertures. It relates the coupling constant both to the ratio of reverberation times (coupled-volume-only reverberation time to main-hall-only reverberation time) and to the aperture size (as a percentage of the *total available surface area of the hall*, in contrast to previous measurements based on the percentage of available aperture area in New Hall). The graph demonstrates the fickleness of the system: according to Kuttruff's formula, only a limited set of architectural compositions is capable of creating a double-sloped impulse response.

9. Conclusions

The study of coupled-volume concert halls suggests a hegemonic relationship between the built environment and the presence of the double-sloped decay. For this decay to materialize apertures connecting the main hall with the coupled volume must be *very* small and the coupled volume itself must be *very* sound reflective. Small variations in either aperture size or coupled volume sound absorption levels can produce dramatic changes in the calculated sound decay of a space.

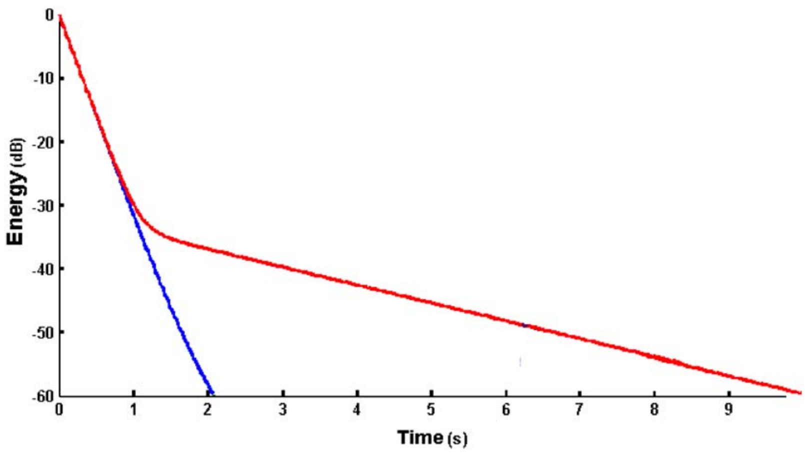


Fig. 10. One hundred twenty five hertz octave band. Predicted sound decays comparing a coupled volume of (top curve) plaster on brick ($\alpha = 0.01$) and (bottom curve) plaster application with typical byproducts of the design process, including doors, ventilating grilles, etc. ($\alpha = 0.11$) [3]. For these calculations, the apertures are assumed to be 4% opened. Questions exist about the appropriateness of using statistical room acoustics for predicting sound decay in low frequencies.

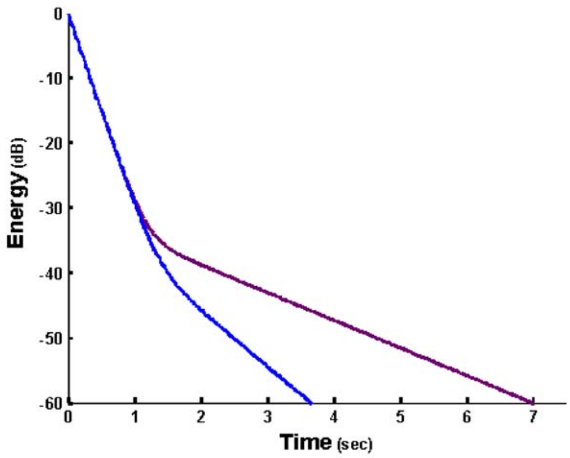


Fig. 11. Thousand hertz octave band. Calculated sound decay rates comparing a coupled volume of (top curve) smooth concrete and (bottom curve) smooth concrete with 5 percent of the room's surfaces covered by spray-on fireproofing and 5% of the room's surfaces covered by sheet metal duct.

As the coupled-volume concert hall and its signature double-sloped sound decay are under-researched as a design tool, this line of inquiry may give rise to further study. The following topics are particularly in need of research. (1) Verification: the compositional and material sensitivity suggested by statistical room acoustics may be verified through computer ray tracing models, to-scale physical models, and real-room measurements in other coupled-volume concert halls. (2) Qualification: the relative value (or insignificance) of the coupled-volume listening condition may

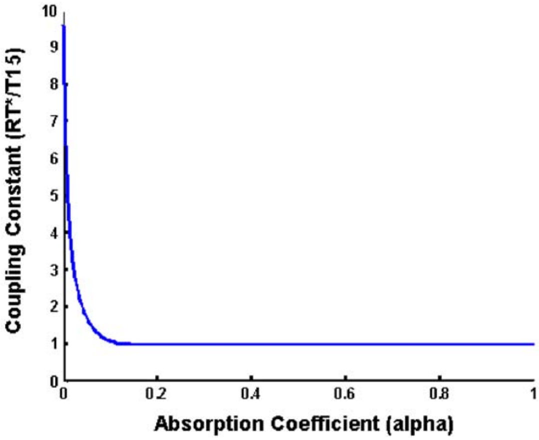


Fig. 12. Thousand hertz. coupling constant vs. coupled-volume average absorption coefficient. For these calculations, the apertures are assumed to be 4% opened.

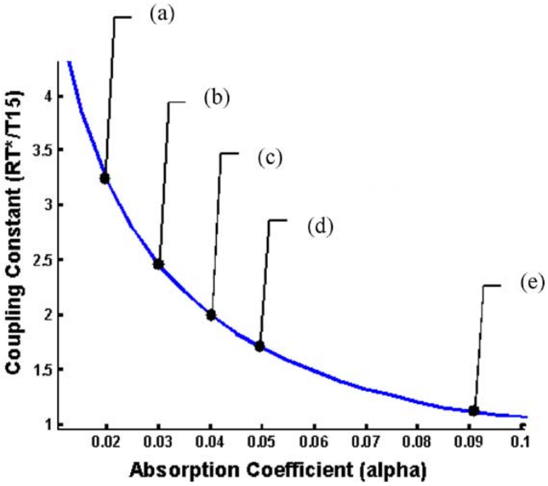


Fig. 13. Thousand hertz. Coupling constant vs. coupled room surface material: (A zoomed-in window of a portion of the graph depicted in Fig. 12.) (a) Smooth concrete; (b) plaster on brick; (c) plaster including usual doors, ventilating grilles, etc; (d) smooth concrete with 5% of the room's surfaces covered in spray-on fireproofing and 5% of the room's surfaces covered in sheet metal duct; and (e) plywood over airspace. For these calculations, the apertures are assumed to be 4% opened.

be established. Auralization and experiences listening to concerts in coupled-volume halls may yield qualitative analysis, uncovering levels of human perception of the double-sloped decay and addressing the appropriateness (or inappropriateness) of constructing coupled-volume concert halls. (3) Metrics: because different sound decay curves are capable of producing the same coupling constant, a supplementary or complimentary system of measuring the sag of a double-sloped decay may be necessary. (4) Haptic perception: by moving away from space-averaging room acoustics formulae—and into the realm of computer ray tracing models, to-scale physical models, and real-room measurements—research may add a location function to the data

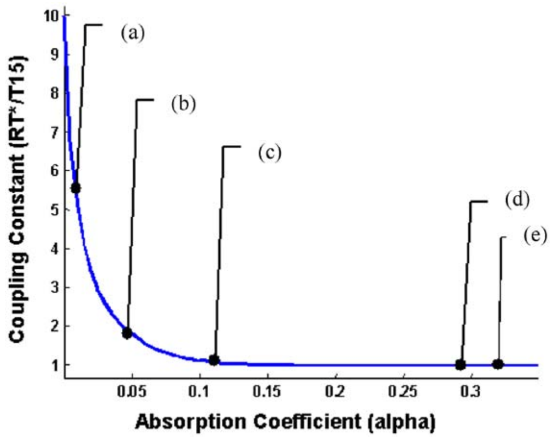


Fig. 14. One hundred twenty five hertz. Coupling constant vs. coupled-volume surface material: (a) Smooth concrete or plaster on brick; (b) concrete with 5% of the room's surfaces covered by spray-on fireproofing and 5% of the room's surfaces covered by sheet metal duct; (c) plaster, including doors, ventilating grilles, etc.; (d) gypsum board; and (e) plywood over airspace. For these calculations, the apertures are assumed to be 4% opened. Questions exist about the appropriateness of using statistical room acoustics for predicting sound decay in low frequencies.

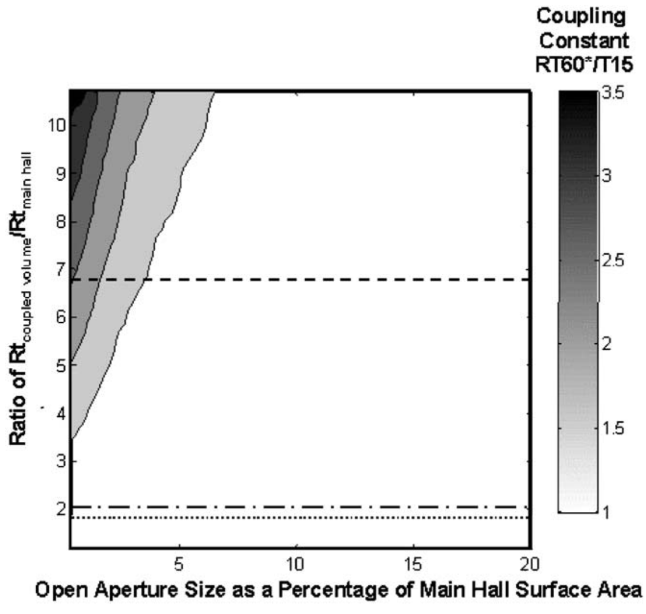


Fig. 15. Thousand hertz. Relates the coupling constant both to the ratio of reverberation times (coupled-volume-only reverberation time to main-hall-only reverberation time) and to the aperture size (as a percentage of the *total available surface area of the main hall, including audience area but not including audience edge*, in contrast to previous measurements based on the percentage of *available aperture area*). Ratios of coupled volume reverberation time to main hall reverberation time: - — - — -, Old Hall; · · · · · · · · · ·, New Hall as it is built, with a painted concrete block coupled volume, $\alpha = 0.07$; - - - - - - -, New Hall, as predicted with a smooth concrete coupled volume, $\alpha = 0.02$. Per Kuttruff's formula, there are limited sets of design conditions that will allow for a double-sloped decay.

presented here. Which seats receive which kind of double-sloped sound decay? Cremer and Müller [7], Kuttruff [10], Anderson and Bratos-Anderson [6] and Summers [13] have shown that coupling includes a spatial component.

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