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*by*

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# Coupled Volumes: Secondary Room Reverberance and the Double-Sloped Decay of Concert Halls

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## ABSTRACT

The coupled volume concert hall and its signature double sloped sound decay aim to partially reconcile the often-competing qualities of clarity and reverberance. A concert hall is conceived with a fixed geometric volume, form, and aperture size. A coupled volume is attached and its materiality is established as variable. Both statistical and geometric relative analyses suggest a highly sensitive relationship between the coupled volume reverberation time and the double-sloped condition.

## 1. INTRODUCTION

The double slope decay has been well documented as a phenomenon, but under-documented as a design tool. It has recently received attention as a possible method of simultaneously achieving a measure of clarity *with* a measure of reverberance in concert halls. 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 sonic transparency between the two spaces. (See Fig. 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.[1,2] 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[2,3] (see Fig. 2). This paper explores the reverberance of the coupled volume room through models of two built coupled volume concert halls: “New Hall” and “Old Hall.” Though New Hall opened in the year 200X and Old Hall opened in the year 199X (specific dates are withheld for purposes of anonymity), both halls are similar in volume and form. Each hall was visited, examined through drawings, and modeled using both the geometry-based CATT-Acoustics software and the statistically-based Kuttruff[4] formula for predicting decays in conditions of acoustic coupling.

Additionally, stop chord recordings were taken in Old Hall in order to validate each of these models. Neither model predicted a marked double slope and the recordings failed to measure a marked double slope, leading to neither a confirmation nor a repudiation of the models’ validity at predicting double sloped decays.[5] This paper will

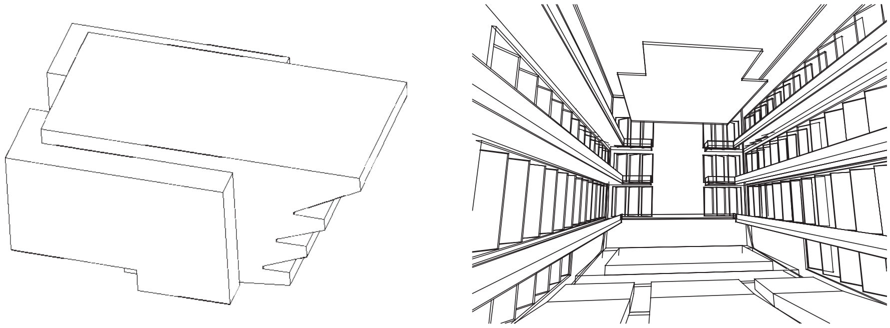

**Figure 1.** Schematic massing model of a concert hall saddled on each side by coupled volumes (left). Schematic perspective view of the interior of the simulated concert hall (New Hall model) viewed toward the stage with apertures lining portions of the walls (right). From Ermann (2005).

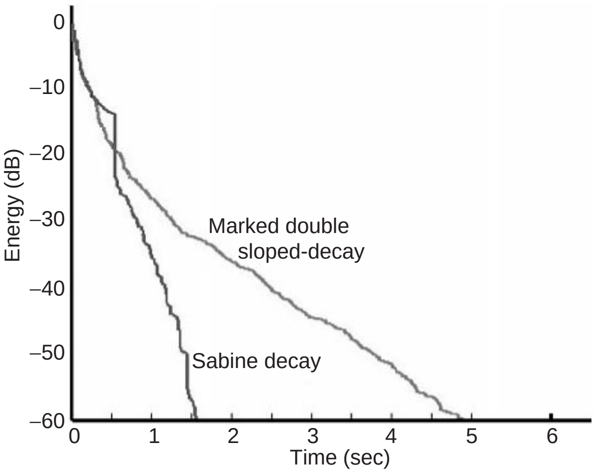

**Figure 2.** 1000 Hz impulse response generated by CATT-Acoustic. Both decays share a similar EDT, but the double sloped decay is the result of exposure to a coupled volume. The classic Sabine decay is generated by fully closing the apertures.

demonstrate that statistical acoustics and ray-tracing software suggest a fickle relationship between coupled volume reverberance and the absence, presence, and magnitude of the double-sloped sound decay.

Cremer and Müller[2] found that both the coupled-volume *and* the main room need to be highly reverberant to produce a double-sloped decay, Eyring,[1] Anderson and Bratos-Anderson[3], and Harrison and Madaras[6] 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.

## 2. DATA AND ANALYSIS

Models suggest the sound field's sensitivity to small changes the coupled volume's architecture. A software tool was created in Matlab, based on Kuttruff's formula, to simulate the decay in Old Hall.[7] Data derived from published drawings of the hall were inputted 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, miscelaneous items in storage, etc. These additional observed items—residue from the construction process and byproducts of building usage—become significant factors in the realm of the double-sloped decay. Figure 3 suggests that in the domain of these double-sloped decay models, small changes in secondary room absorbtion leverage larger changes in the impulse response.

A space, based on New Hall was conceived and modeled in both the statistical acoustics Matlab software and in the ray-tracing CATT-Acoustics software.[5] The data that follow are derived by varying the coupled volume reverberance in the New Hall models by substituting the painted concrete block used on the interior of the coupled volume with alternate room finish materials.

Figure 4 uses both statistical and geometric acoustics to reveal a sensitive relationship between secondary room sound absorption levels and the double-sloped decay. The two models predict significantly differing sound fields, with the statistical method predicting a more marked double-slope than the geometric method. However, while the two predictions' methods vary in amplitude, they *are* in phase: both indicate that for the double slope to appear in earnest, the secondary volume must be exceedingly sound reflective. In this model, some materials that would traditionally be considered sound reflective at 1000 Hz (those with an $\alpha<0.20$) are not capable of effecting a marked double slope decay.

In the data that follow, refinement of the "coupling constant" developed by Harrison, et al.[6] quantifies the sag of the double-sloped decay. The more marked the double slope—the more it varies from a classic Sabine exponential decay—the higher the coupling constant. (See Fig. 5.)

$$\text{Coupling Constant} = \frac{RT^{*}}{T_{15}^{*}} \tag{1}$$

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

Figure 6 compares coupling constant to the coupled volume absorption coefficient for both the statistical and geometrical models of New Hall. Again, the statistical model

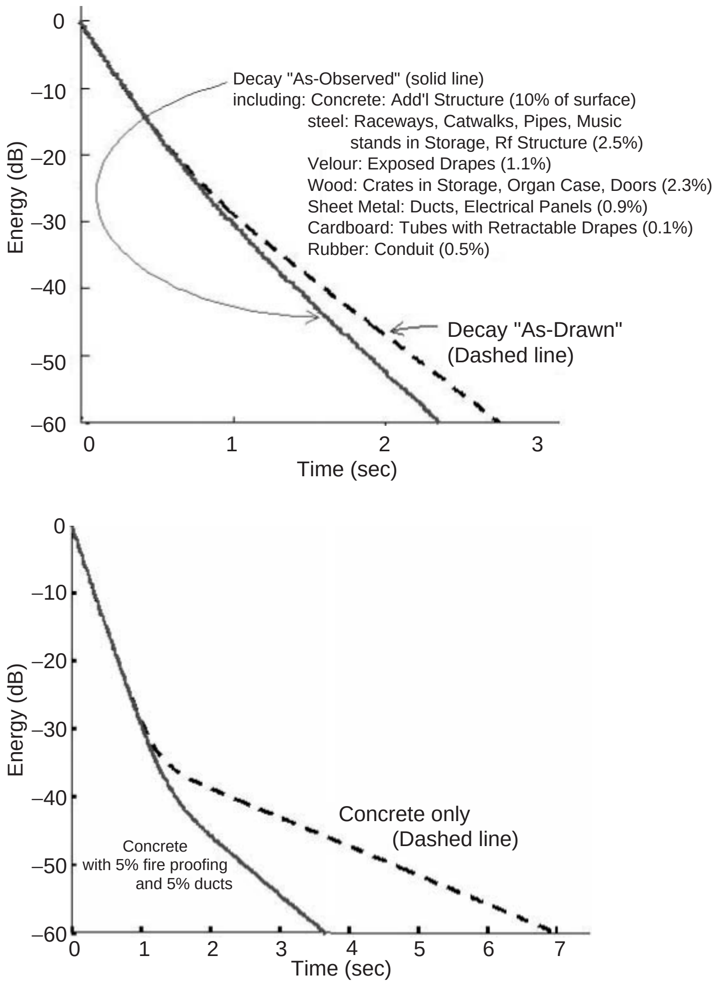

**Figure 3.** 1000 Hz. Above: Statistical-acoustics-based predicitons of double-sloped decays in Old Hall. The “As-Oberserved” decay (solid line) includes the residue of building occupancy not included in published drawings of the hall—as observed on a visit. The “As-Drawn” decay (dashed) is based on published drawings of the hall. Below: Statistics-based predictions of double sloped decays in New Hall. The solid line indicates the predicted decay for a coupled volume constructed of concrete with spray-on fireproofing covering an area equivalent to 5% of the coupled volume surface and sheet metal ducts covering an area equivalent to 5% of the coupled volume surface. The dashed line indicates the predicted decay without the fireproofing and ducts.

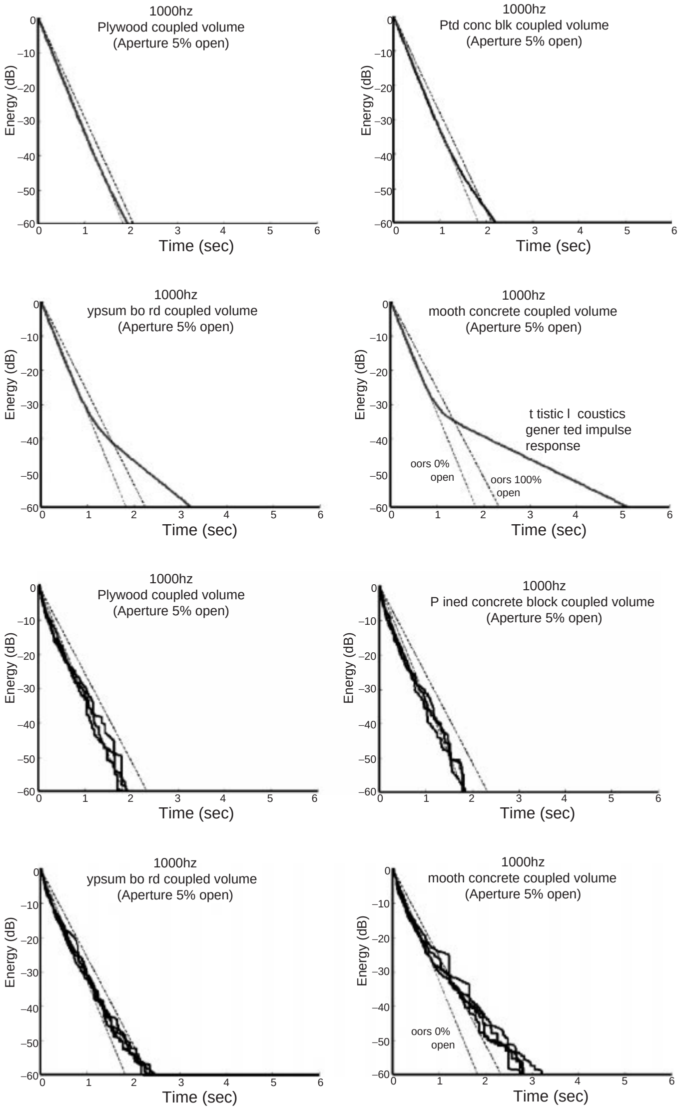

**Figure 4.** 1000 Hz octave band New Hall simulations. Top two rows: statistically-based Kuttruff formula predictions. Bottom two rows: geometrically-based CATT-Acoustic software predictions for multiple receiver positions. Calculated decay curves for halls with coupled volumes made of 3/8″ plywood over airspace ($\alpha = 0.09$), unpainted concrete block ($\alpha = 0.07$), 1/2″ gypsum board nailed to studs ($\alpha = 0.04$), and smooth concrete ($\alpha = 0.02$). For reference each graph includes ghosted Sabine decay predictions for the conditions of aperture doors-fully-closed and aperture doors-fully-open. For these calculations, the apertures are assumed to be 5% opened, an area equal to 0.55% of the total surface area of the main hall, which was determined to be a configuration that produced a marked double slope (See Fig. 7).

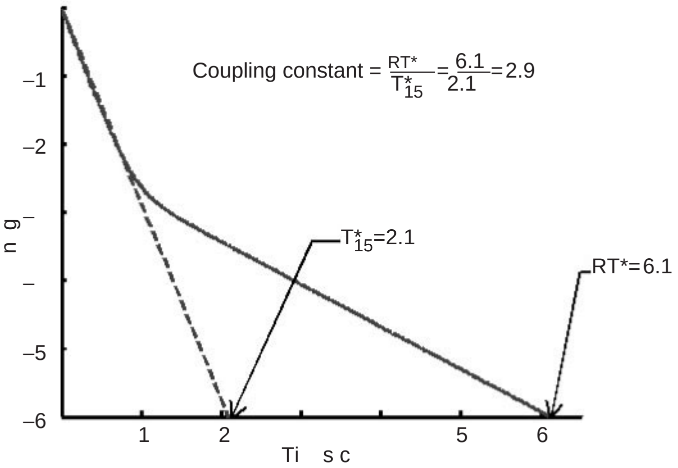

**Figure 5.** Coupling Constant. The more marked the double slope, the higher the coupling constant.[5]

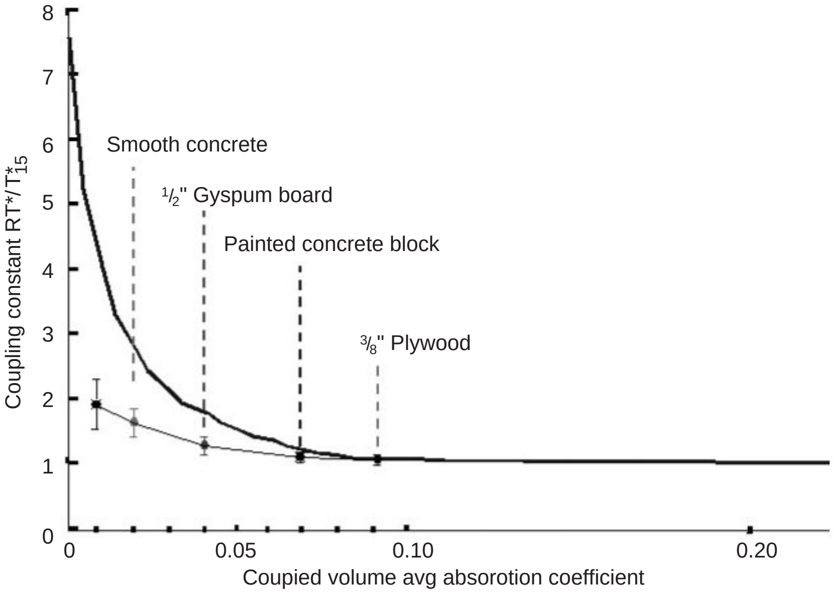

**Figure 6.** 1000 Hz octave band simulations for New Hall. The higher the coupling constant, the more marked the double slope decay. Statistical analysis is shown with a thick line, geometric CATT-Acoustic Analysis is shown with a thin line. Error bars denote one standard deviation.

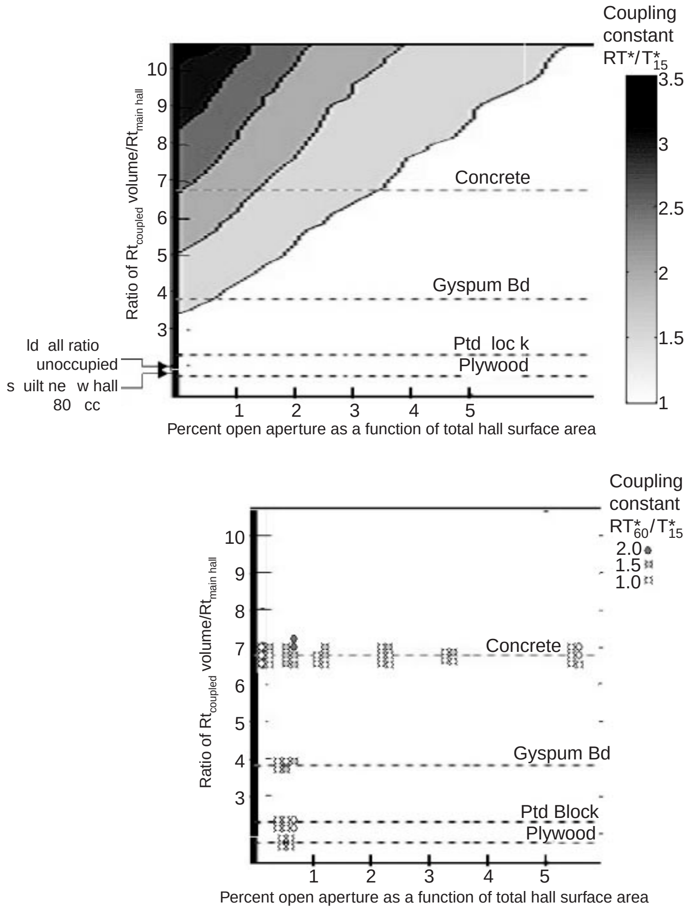

**Figure 7.** 1000 Hz New Hall simulations—statistical model (top) and CATT-Acoustic ray-tracing software model (bottom)—suggest a limited set of design conditions that will allow for a double-sloped decay. These graphs relate the coupling constant both to the ratio of reverberation times (coupled-volume-only 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). In each case, it is assumed that the entire coupled volume (approximately 1/3 the geometric volume of the main hall) is clad in the surface indicated.

indicates a more robust coupling constant than the geometric model. Again, both models suggest that for New Hall to effect a double-sloped decay, the coupled volume must be *highly* reflective.

Figure 7 is of particular value to the designer of a new coupled-volume concert hall. It is created with both a statistical model and a geometric CATT-acoustic model and assumes that the geometry and size of the coupled-volume have not been fixed, nor has the total size of the open apertures that sonically connect the two volumes. 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). From the graphs, one can see that neither Old Hall nor New Hall (as-built with a concrete block coupled volume) has a sufficient reverberation ratio to effect a marked double slope prediction. The figure demonstrates the fickleness of the system: in both of these models, only a limited set of architectural compositions is capable of creating a double-sloped impulse response.

## 3. CONCLUSION

In simplified computer models of a built coupled volume concert hall, both statistically based analysis and ray-tracing analysis suggests a hegemonic relationship between the reverberance of a coupled volume and the "double-slope-ness" of a impulse response. The two methods however are not in agreement as to the absolute form of the decay—the statistics based model produces significantly higher coupling constants than the ray-tracing model for the same inputted parameters. The statistical model suggests that to effect a coupling constant of at least 2.0 at 1000 Hz, the designer must ensure that the coupled volume is at least five times as reverberant as the main hall, and the operator must ensure that the apertures are small relative to the total surface area of the room; the geometric model suggests that to effect a coupling constant of at least 2.0, the designer must ensure that the coupled volume is more than fifteen times as reverberant as the main hall, and the operator must ensure that the apertures are small relative to the total surface area of the room. Measurements taken in a real coupled volume concert hall fail to validate or invalidate either of the modeling methods employed in this paper.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Eyring, C.F., "Reverberation Time Measurements in Coupled Rooms," J. Acoust. Soc. Am. **3**, 181-206 (1931).

[2] Cremer, L. and Müller, H., *Principles and Applications of Room Acoustics.* (Applied Science, London, 1978).

[3] Anderson, J.S. and Bratos-Anderson, M., "Acoustic Coupling Effects in St. Paul's Cathedral, London," J. Sound and Vib **236(2),** 209-225 (1997).

[4] Kuttruff, H., *Room Acoustics* (Elsevier, New York, 1991).

[5] Ermann, M., "Coupled Volumes: Aperture Size and the Double Sloped Decay of Concert Halls," Build. Acoust. **12**, 1-14 (2005).

[6] Harrison, B., Madaras, G., and Celmer, R. “Computer modeling and prediction in the design of coupled volumes for a 1000-seat concert hall at Goshen, College, Indiana.” (From the meeting 141 Meeting of the ASA, Chicago) J. Acoust. Soc. Am. **109**, 2388 (2001).

[7] Ermann, M., and Johnson, M., “Exposure and Materiality of the Secondary Room and Its Impact on the Impulse Response of Coupled-Volume Concert Halls,” J. Sound and Vib., **284**, 915-931 (2005).