The Effectiveness of the Electro-Acoustical Simulator for Engineers (EASE) in Determining Room Acoustics

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July 30, 1995

Abstract

Proper room acoustics play an integral role in the effectiveness of a given chamber for aural communication. This investigation explored the effectiveness of the Electro-Acoustical Simulator for Engineers (EASE), a computer simulation, in determining critical properties of room acoustics by comparing data compiled with the computer model to measured physical data in a detailed case study. The study illustrated that the electronic model provides reliable reverberation time data through the Sabine reverberation formula. Sound decay plots and values obtained through reverse Schroeder integral formulas are inconsistent with measured data, however, due to the tracing module EASE uses.

Introduction

The room acoustics of a given chamber dictate the effectiveness of aural communication within it. The goal of architectural acoustics is to maximize this effectiveness through the study and manipulation of a room's acoustical properties. Most often, this process consists of the reduction of unwanted noise and the enhancement of deliberate sound through electronic amplification. Any noise which is present will counteract this signal, making it less audible and acoustically unsatisfactory. The ability to control this signal to noise ratio is therefore a necessity.

A critical element in improving the signal to noise ratio and the intelligibility of sound in an enclosure is its reverberation time (RT)[1], defined by the time it takes for sound waves of a given frequency to decrease in intensity by 60dB. Long RT values tend to create an echo-like atmosphere, making direct sound less audible. Bradley and Soulodre have found that these late arriving echos in an acoustically live chamber not only increase noise, but also affect the spatial impression of the listener, the apparent source width, and the degree of listener envelopment [4]. In situations where direct sound is desired, all of these reverberant effects can have a negative impact on the listener's ability to clearly distinguish sounds. To improve overall intelligibility, reverberance should therefore be decreased.

Theoretically, if air absorption is neglected, sound will propagate infinitely until it reaches a physical barrier. At this point, the sound waves are either reflected, absorbed, transmitted through the object, or some combination thereof. Logically, waves which are

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[1] Appendix A contains a complete listing of symbols used in this paper.

refracted or reflected off a barrier retain their amplitude and continue to propagate on a different course. In the alternate instance that a wave is absorbed or partially absorbed, its sound energy is transformed into heat and the amplitude is reduced. How a sound wave reacts to such an obstacle depends on the angle of incidence of the sound wave, the physical dimensions of the body, and the surface's absorptive traits. All of these variables can be controlled architecturally. However, in the case of noise reduction, because the source of noise is often indirect and the surface area of incidence is very large, it is usually most feasible to decrease reverberance by altering the absorptive traits of the surface.

The re-treatment of a surface for acoustical reasons normally entails its covering with a more absorptive material. To quantify the absorptive traits of such a material leads to the measurement of its seven octave band absorption coefficients (α). A more generalized measure of absorption is referred to as the Noise Reduction Coefficient (NRC), calculated as the arithmetic mean of the 250Hz, 500Hz, 1kHz, and 2kHz α values. Because the permeability of a surface as well as its surrounding air space can alter the total amount of absorption, the mounting of a material is equally critical in achieving maximum benefits. In general, increased air space between an absorber and a wall increases low-frequency absorption and improved permeability of the surface aids in the attenuation of high frequency waves. Consequently, the absorption of a particular frequency wave cannot accurately be predicted based only on the facing material of a surface.

While a simplified model of a room's reverberation time can be constructed from the makeup of its surfaces, only so much can be determined about its acoustics solely from this information. Other variables, including the room's geometry, climate, and the location of the sound's source have a marked impact on how sound will behave. While scientific advancements in acoustics have led to a better understanding of sound propagation and transmission, they have also indicated the vast number of such factors that must be considered. For this reason, the ability to theorize quantitatively the behavior of a three-dimensional space undergoing natural sound transfer becomes extremely complex.

One factor to be considered in forecasting this behavior is the sheer number of waves that propagate to make up a single tone. While it is possible to follow the paths of individual waves to a small degree of error, it is humanly infeasible to attempt to consider the quantity necessary to attain a true model of sound decay at any given point of a room.

To calculate a room's acoustical properties is therefore restricted by the capacity to perform large numbers of calculations with multi-variable equations. With the evolution of computer technology and the ability to perform millions of calculations per second, it may be possible to accurately predict the acoustical behavior of a room.

Materials and Methods

Tools of Study

Acoustical measurements were made with a Techron model TEF-20 time delay spectrometer. The spectrometer is set up with a small loudspeaker which produces a synchronized time sweep over a defined frequency range. The resulting direct and echoic sound is captured by a nearby microphone with a tracking filter that measures the arriving energy. This spectrometer internally calculates the reverberation times and produces sound decay printouts using a reverse Schroeder integral [2].

The Electro-Acoustical Simulator for Engineers (EASE) was developed by Dr. Wolfgang Ahnert and Dr. Rainer Feistel and distributed by Renkus-Heinz, Incorporated as a software package to perform the necessary calculations in order to create an accurate model of a room. The program uses manually entered coordinates and planes to create a three-dimensional model of an enclosed room in which all sound origin, propagation, and transmission are to occur. To further delineate how sound originates and reverberates in the model, the software is equipped with a pre-defined library of loudspeakers and common room materials with their respective absorption coefficients from which to choose. It also supports user-defined values for these data.

From these inputted variables, EASE makes calculations internally to determine the room's volume, surface area, and total absorption (in Sabines). From this data, the program then finds RT values for the seven octave band frequencies by using the Sabine reverberation formula:

$$\mathrm{RT} = 0.163 * (\mathrm{V}/\mathrm{A}) \tag{1}$$

and an average α for the room is calculated. Because the Sabine method of determining reverberation time, to which EASE has been configured, does not account for air absorption,

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[2] Schroeder's derivation of this integral can be found in Appendix B.

decay due to air is not figured in deriving total absorption. In order to achieve maximum accuracy, particularly in high frequency ranges, air absorption should be addressed. This is done according to the delay formula:

$$\mathrm{D(x)} = \mathrm{D_0 e^{-mx}} \tag{2}$$

and then used with the Sabine formula to update the reverberation times calculated by EASE [3].

Due to the large amount of time required to figure propagation and transmission calculations for waves, the EASE simulator treats individual sound waves as vectors, or rays. As a result, it is possible to trace rays produced by a single loudspeaker or group of loudspeakers, and to determine the impacts of the sound with a particular point in the space. By analyzing the intensity of impacts and the elapsed time between rays, the program can then describe a plot of the sound decay versus time for that particular point. This ray function is therefore useful in providing a specific acoustical model for various locations of a room.

Methods of Study

Experiment One

The test subject used to verify the accurateness of an EASE model was The Pyramid, a 22,000 seat sports and entertainment facility in Memphis, Tennessee. This site was chosen

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[3] A full listing of the calculations used in this process appears in Appendix C.

because of the vast amounts of accessible measured data for the project. The original design of The Pyramid resulted in a highly reverberant atmosphere in which the clarity of amplified sound was minimal. For the entertainment setting, these poor acoustics due to low signal to noise ratios and long reverberation times were unacceptable. To qualify these properties, sound decay data was measured using a TEF-20 time delay spectrometer placed in the center of the arena.

To explore the accuracy of the computer model, the original conditions were extrapolated from the arena's architectural blueprints and then replicated using the EASE program. For acoustical purposes, the Pyramid's design called for the placement of approximately 56,600 square feet of vinyl, ceiling-hung baffles slightly above the audience seating areas along the metal decking of the arena. In EASE, these baffles were modeled with the *Original Panels* surface whose α values were defined by test data accumulated at the Riverbank Acoustical Laboratories [10]. The remainder of the ceiling and side panels were covered with the *Metal Deck* surface; *Glass* and *Concrete* data were extracted from the EASE materials library; and the *Scoreboard* coefficient was designed with low absorptive coefficients due to its reflective nature. Because data for the specific chairs used in The Pyramid's spectator regions was not available, the *Arena Seats* α values were determined from the high and mid frequency absorption values for similar arena seats, and low frequency absorption was derived according to Barron's theory of bass attenuation due to grazing incidence over audience seating [3] [4].

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[4] Plots of the exact absorption coefficients used are located in Appendix D.

Upon completion of the model, RT values were recorded with air absorption taken into effect [5]. To acquire a readout of sound decay, the ray tracing module was then configure to produce 20,000 rays from a speaker located at the center of the arena and to record all impacts with a listener directly beside the speaker. Once impacts were found, the EASE reflectogram was used to visually describe the sound decay that occurred.

Experiment Two

Due to the long RT values and poor intelligibility of The Pyramid, architectural acoustical enhancements were suggested by Acentech Incorporated and constructed in the arena [1]. Approximately 130,000 square feet of high efficiency sound absorbing treatment was placed along the interior sidewalls of The Pyramid and hung an average of four inches from the steel decking. The material used was five-inch thick fiberglass insulation enclosed in a perforated vinyl shell to allow sound penetration. Laboratory test data on the absorption of this material based on its installation in The Pyramid was performed at the Riverbank Acoustical Laboratory [9].

Once acoustical improvements had been completed, representatives from Acentech again tested the RT of the arena using a Techron TEF-20 time delay spectrometer as described in Experiment One.

In the EASE model, The Pyramid geometry input for Experiment One and the materials used were preserved. A new material, NEWPANELS, was defined according to the

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[5] The differences in data as a result of these calculations are recorded in Appendix E.

laboratory test data. The old acoustical treatment of the sidepanels was then removed, and the new fiberglass treatment was placed according to the recommendations made by Acentech. After a modified model had been created, EASE was allowed to calculate RT data, and the effect of air absorption was manually calculated into these values.

Results and Data

To assure optimal accuracy, the EASE model was programmed with the arena's actual settings at the time of measurement. The EASE program then produced data that was charted and compared with the actual measured data for each test simulation.

Comparisons made between the measured RT values for The Pyramid before acoustical renovation and the simulator data are shown in Figure 1. The data were found to be in relative accord, particularly in the low and high frequency ratings. On an equal comparison in the acoustically re-treated arena, reverberation times compiled with EASE correlated with the actual data but were not as precise as those in the previous experiment, as illustrated in Figure 2. Whereas the EASE prediction in this case for RT versus frequency was basically linear, the measured data shows a greater fluctuation of slope around the 2 kHz range.

Sound decay plots obtained through ray tracing, however, did not correlate well with measured data. EASE RT data using this method was imprecise with measured values by over 65%.

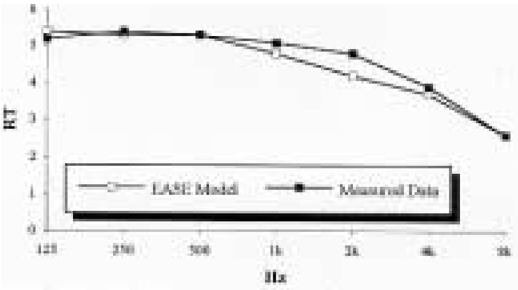

Figure 1: Reverberation time data before acoustical enhancements

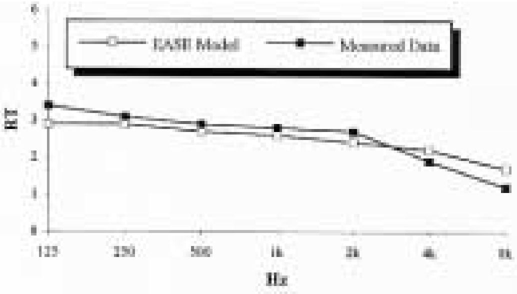

Figure 2: Reverberation time data after acoustical enhancements

Discussion

The data suggest that the EASE model may be a useful tool for predicting approximate RT plots, but does not create a truly precise model of sound decay.

It is difficult in such a case to pinpoint exact areas of error due to the numerous variables included and the inability to create genuine control and experimental groups. Contributing factors to inaccuracy can be located, however, by exploring the means which EASE uses to model sound propagation and transmission.

For example, it is quite possible that precision was lost in the definition of materials despite the use of laboratory-tested data. In a laboratory setting, the material under testing is subject to waves of random incidence from which absorption coefficients are defined. In practice sound waves strike a surface at specular incidence at which the α value may differ from the one determined in tests. Such a discrepancy could be reduced if sound allowed to strike the surface being tested was produced from a point correlating to the source of sound in the actual enclosure rather than a random locator. Tamura and Lafarge have evaluated the effectiveness of the spatial-Fourier transform (SFT) method of measuring absorption coefficients at varying angles of incidence [2]. Although the SFT technique was not applied in this study, experimental verification alludes that its use could produce a more precise model.

The inaccuracy of common absorption data for audience seating has been widely noted [6, 8]. RT in an arena environment is largely dictated by the absorption of seating though no standard exists for this measurement. Davies, Orlowski, and Lam propose the optimized barrier method of measuring seat absorption due to its superiority in predicting accurate reverberation time [5]. By using this method in our experimentation, some of the discrepancy in RT, particularly around mid-frequencies, could likely have been eliminated.

Another justification for inaccuracy in an EASE-generated computer model is the possibility of refraction. In the natural setting, sound waves will occasionally refract when encountered with a surface, and in effect, travel around the obstacle loosing very little sound energy. The EASE simulation, however, forces all sound to either be reflected, partially absorbed, or completely absorbed, so that refraction does not occur. This simplification for the purposes of the model could also explain some of the inaccuracy of the ray tracing calculations.

Limitations of computer resources and time also limit the degree of precision to which sound decay can be simulated. In a large, complex space, such as The Pyramid seating bowl, a very large number of rays is required to achieve a significant number of impacts at a certain point to generate any worthwhile data. Though 20,000 rays were drawn in our tests, the results point to the conclusion that a more realistic tracing model of a large building would require at least 100,000 rays and over two days of calculation time. Such detractors limit the effectiveness of sound decay simulation in large, reverberant enclosures. In 1994, Murch discovered that combining an interpretation of ray propagation with a representation of scattering produces acute data at both high and low frequencies [7]. The inferior performance of the Born ray tracing method that EASE uses suggests that algorithmic improvement should be made to include Murch's formulation.

Much of the work done by the EASE program does indicates a great potential for electronically forecasting building acoustics. Given a detailed model and accurate material data, the simulator can produce RT values that are extremely close to those measured. While the uses of computer simulators such as EASE are not well established, we find that they are attainable, and potentially an economic means of acoustical measurement and prediction.

Conclusions

This study has developed the current efficacy of a computer acoustical simulator in modeling sound behavior in an enclosure. We have found the advantages and drawbacks of EASE modeling in predicting reverberation time and sound decay plots. From an architectural acoustics standpoint, it is more reliable at this stage of simulator development to depend on field measurements due to the nebulous nature of predictions generated electronically. Experimentation results indicate that the possibility of a confident computer model is very real, and given a continued development of software, could become widely practiced. Using today's technology as a basis, with the proper improvements, electro-acoustical simulators would. among other benefits, be cost-effective, time-efficient, and precise with observed sound behavior. Most importantly, such advances would allow for acoustical problems in architecture to be easily detected before the construction of a building, saving projects such as The Pyramid from large expenditures on future acoustical enhancements.

Acknowledgements

I extend much gratitude to my mentor, Mr. Carl Rosenberg, Director of Architectural Acoustics at Acentech Incorporated, for his suggestion of the problem and guidance during the project which proved essential in attaining the final result. I would also like to thank Mr. Stephen Siegel, Director of Audio and Visual Design, for his assistance with the EASE program and Pyramid project, and for allowing the use of his personal computer. Continued thanks to Mr. David Homa, Mr. Tom Horrall, and the remainder of Acentech for their assistance in my research. None of this experience would have been possible without the Center for Excellence in Education's sponsoring of the 1995 Research Science Institute, and I am deeply indebted to this body and its sponsors for their services.

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[10] Riverbank Acoustical Laboratories. "Report on test number A92-239," (1992).

Appendix A: Listing of Symbols

A - total absorption, in Sabines

$\mathbf{D_0}$ - initial energy density, in watt-seconds/meters^3

m - air energy attenuation constant, in meters^{-1}

NRC - Noise Reduction Coefficient, calculated as the arithmetic mean of the absorption coefficients for the 250Hz, 500Hz, 1kHz, and 2kHz octave bands

$\mathbf{p_{diff}}$ - sound pressure in the reverberant sound field

$\mathbf{p_{dir}}$ - sound pressure in the direct sound field

RASTI - Rapid Speech Transmission Index

RT - reverberation time, in seconds

S - total surface area, in meters^2

STI - Speech Transmission Index, a weighted average of the middle five octave band reverberation times to determine intelligibility of sound

V - volume, in $meters^3$

x - distance of propagation, in meters

α - absorption coefficient

Appendix B: Derivation of Reverse Schroeder Integral

Schroeder's derivation of his reverse reverberation time integral is as follows:

Let n(t) be a stationary noise whose autocovariance function $< n(t_1) \cdot n(t_2) >$ depends only on the time difference $t_1 - t_2$. This function is zero everywhere except where $t_1 = t_2$. Thus, one may write

$$< n(t_1) \cdot n(t_2) >= N \cdot \delta(t_2 - t_1) \tag{3}$$

where N is the noise power per unit bandwidth and $\delta(t_2 - t_1)$ is the Dirac delta function. The signal received at a receiving point in the enclosure is then

$$s(t) = \int_{(-\infty)}^{0} n(\tau) \cdot r(t - \tau) d\tau \tag{4}$$

where r(t) is the combined impulse response of the system. The upper limit of the integral is the time at which the noise was switched off($\tau = 0$), and the notation of the lower limit $(-\infty)$ is meant to indicate that the noise is switched on sufficiently before the onset of the decay for the sound to have reached a "steady state."

The square of the recieved signal may be written as a double integral as follows:

$$s^2(t) = \int_{(-\infty)}^{0} d\tau \int_{(-\infty)}^{0} d\theta n(\tau) \cdot n(\theta) \cdot r(t - \tau) \cdot r(t - \theta). \tag{5}$$

By averaging the squared received signal over the ensemble of the noise signals and applying Equation(3), one obtains

$$< s^2(t) >= \int_{(-\infty)}^{0} d\tau \int_{(-\infty)}^{0} d\theta N \cdot \delta(\theta - \tau) \cdot r(t - \tau) \cdot r(t - \theta). \tag{6}$$

Since $\delta(\theta - \tau)$ vanishes, except when $\theta = \tau$, and since the integral over the delta function equals unity, the integration over θ yields

$$< s^2(t) >= N \cdot \int_{(-\infty)}^{0} r^2(t - \tau) d\tau, \tag{7}$$

or, after substituting the new integration variable x for $t - \tau$,

$$< s^2(t) >= N \cdot \int_{t}^{(\infty)} r^2(x) dx, \tag{8}$$

and $s^2(t) >$ is the ensemble average of the squared noise decay.

Appendix C: Adding Air Absorption to RT

The Sabine RT data may be manipulated to take into account the effects of air absoprtion. Working backwards from the computer model and the Sabine reverberation formula, the total absorption at any particular octave band before the inclusion of air can be found:

$$A = .163 * V/RT \tag{9}$$

using the data generated by EASE. The room's overall absorption coefficient, without respect to air, can then be generated with:

$$\alpha = A/S \tag{10}$$

where S is the total surface area as calculated from the room geometry in the EASE model.

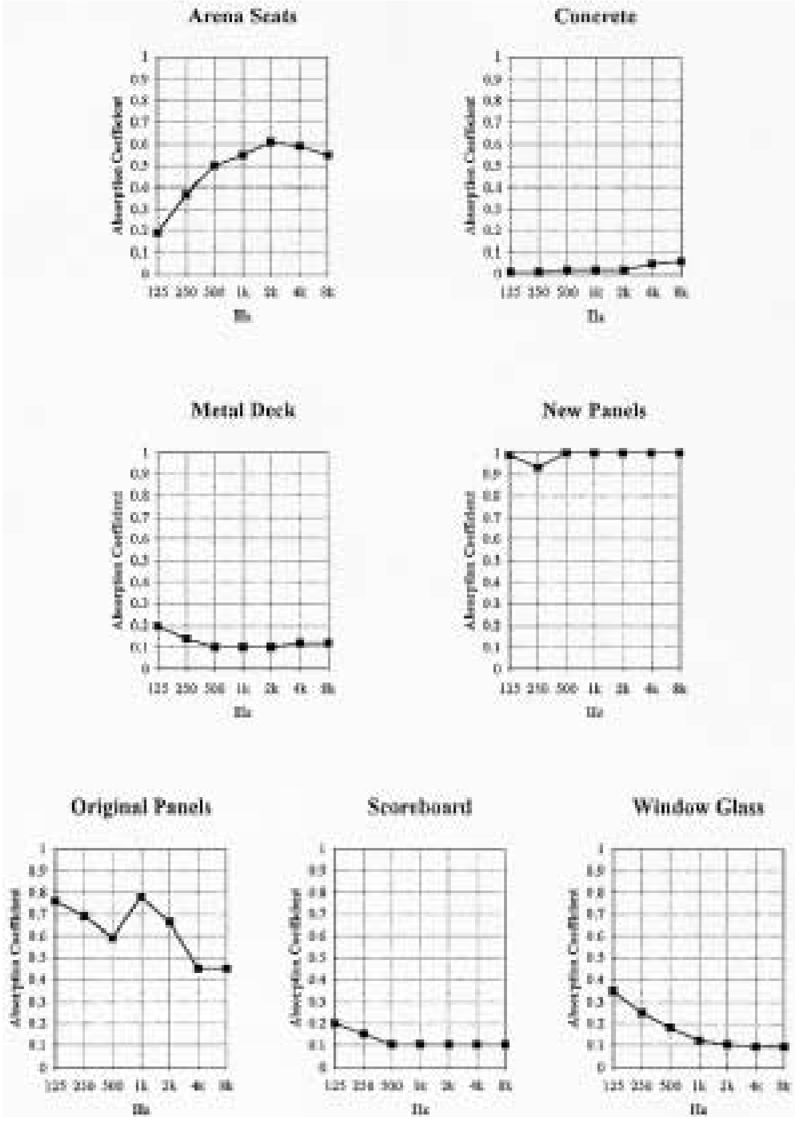
From this point, we must determine the effect the absorption coefficient for the air will have on the sound decat of the space, according to the equation:

$$\alpha_T = \alpha + (4mV/A) \tag{11}$$

with the resulting absorption coefficient being the modified coefficient for the entire room. This is finally used to calculate the adjusted RT for the room:

$$RT = (S * \alpha_T)/(1 - \alpha_T) \tag{12}$$

Appendix D: Absorption Coefficients used in Model



Appendix E: Effects of Air Absorption on RT Data

freq.	sabins per 1000 $ft.^3$	RT w/o air	Rt w/ air	measured RT	precision gained
2kHz	.9 Sabines	4.6 sec	4.2 sec	4.8 sec	-8%
4kHz	2.3 Sabines	4.5 sec	3.7 sec	3.9 sec	21%
8kHz	7.2 Sabines	4.1 sec	2.6 sec	2.6 sec	58%

Table 1: Changes in RT for Experiment One due to the inclusion of air absorption in EASE-generated data.

freq.	sabins per 1000 $ft.^3$	RT w/o air	Rt w/ air	measured RT	precision gained
2kHz	.9 Sabines	2.4 sec	2.5 sec	2.7 sec	-4%
4kHz	2.3 Sabines	2.2 sec	2.4 sec	1.9 sec	11%
8kHz	7.2 Sabines	1.7 sec	2.3 sec	1.2 sec	50%

Table 2: Changes in RT for Experiment Two due to the inclusion of air absorption in EASE-generated data.