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The Effect of Partially Diffuse Sound Fields on the Prediction of Absorption Coefficients

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Abstract

To enable accurate absorption coefficient measurements, materials are generally measured in a standardized reverberation chamber according to ISO-354. When these measurements are undertaken it is required that the sound field is diffuse so that the random angle of incidence for the absorbent materials are equal at all locations. With an even distribution of incidence the sound energy is optimally distributed and the most accurate measure of absorption can be obtained. It is known that the measured absorption values become inconsistent when they are used for prediction of reverberation time in non-diffuse sound fields as the sound waves are not equally incident upon the absorption. An attempt to isolate this problem and gain an understanding of the discrepancies between diffuse and non-diffuse fields will be attempted using a 1/10th scale reverberation chamber. Results of this experiment are able to recreate these inconsistencies and also focus on other issues with fundamental room acoustics problem, such as absorption coefficients that exceed 100%. Sabine and Eyring's equations are used primarily for calculating the absorption coefficients of both the diffuse and non-diffuse configurations of the scale reverberation chamber.

Acknowledgements

I would like to acknowledge, and thank, all of my friends that I met during my one-year adventure in England. Without them I could never have enjoyed my one-year abroad to such a great extent.

A warm thank you to Professor Bill Davies for providing insight and advice on this dissertation project.

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Literature Review

Modern room acoustics relies on several fundamentals that determine the behavior of sound in a room. These fundamentals stem from the studies undertaken by Sabine [1] in the early 20th century by defining a measuring technique that enabled him to mathematically describe an expression for a room's reverberation. Reverberation is referred to as the decay of sound energy after a short impulse sound [2]. Reverberation occurs when reflections of an impulse sound reflect off of boundaries until all sound energy has been either been absorbed or dissipated (and the room falls silent). An example of a room with noticeable reverberation would be a squash or racquetball court. Sabine used four organs as an impulse sound and measured the amount of time needed for the notes played to decay by a factor of one million (-60 dB's) [1, 3, 4] and this was defined as the reverberation time (RT). Sabine could determine the room's average absorption coefficient by comparing the RT of a room with absorption and a the same room without absorption, then determining the energy absorbed by deriving equations that utilized the difference in times. The work of Sabine has become the groundwork for much of acoustics studies and is still relied upon in modern architectural acoustics. Another fundamental that is important to acoustics is diffusion.

A diffuse sound field determines how evenly distributed sound energy is in a room. Waterhouse (1955) stated that constructive and destructive interference patterns at the boundaries of a room create a non-uniform distribution of energy in the room [5]. Interference caused by reflecting waves and incident waves is good evidence that a perfect diffuse sound field cannot be created in practice but in most sciences theoretical values are rarely achieved. Hodgson is able to validate diffuse theory based on the parameters of room shape, absorption, surface reflectivity and plane diffusers [6] enabling the possibility of a good approximate diffuse field. Sound waves incident on an absorbent material is referred to as the angle of incidence and in a room that is very diffuse the distribution of angles of incidence onto an absorber will be large. When the distribution is high a measurement of absorption taken will result in an accurate value because an even amount of sound energy will have been absorbed. With a lesser amount of diffusion the distribution of angles will be lower which means a greater or lesser amount of sound energy could hit the absorbers. In the case of parallel walls the lack of diffusers present can allow some sound energy to reflect back and forth between a pair of walls and avoid everything else in the room [7]. Though the amount of energy is the same in each situation, lop-sidedness in energy distribution results in a lower degree of accuracy for absorption coefficient. A lack of diffusivity in a room can also cause discrepancies if measurements are being done for reverberation time. Reverberation measurements are made from several microphone (receiver) locations in a room and averaged together. If there is not an even distribution of sound energy then some receiver locations might record a lower, or higher, reverberation time. A large emphasis is placed on reverberation time and diffusion because a room cannot be acoustically treated without an accurate description of either. A large number of studies have been done to better understand diffusions as well as Sabine's work in reverberation.

A simple sound source (monopole-type) has an initial intensity that creates a sound pressure wave containing a direct part and later a reverberant part [8]. After the direct sound has reflected from a surface the reverberant part of the wave and the initial intensity is affected by the absorption and the diffusivity of the room/surface. Measuring the reverberant part of the wave has been attempted by directly measuring diffuse wall reflections [9, 10]. These involve computer simulations and ray-tracing methods applied in empty rooms, scale models, and large empty factories [9].

Of the numerous studies done on Sabine's work the research done by Carl Eyring is most notable. Eyring's equation is based on Sabine's but it attempts to improve the accuracy of highly absorbent rooms and differently shaped rooms [4] by tracing each sound wave as it decays. Using the image source method Eyring is able to view each wave front as a ray reflecting around a room in space. A distance can be determined from ray tracing and by averaging a large number of rays' mean free path (MFP) can be determined. Eyring's new equation was successful in giving better predictions in high absorption rooms, but he also stated that "…no one formula without modification is essentially all inclusive" [4]. Sabine and Eyring's equations have been studied numerous times for prediction reliability [6, 11-15] and although both equations are fairly accurate there are cases that create theoretically invalid data. It is common for Sabine and Eyring's equations to produce coefficients of absorption that exceed unity [13] because of edge diffraction created by objects [16] as well as lack of diffusion. This has led to more attempts at an all inclusive reverberation time equation.

When a room is quasi-cubic the use of Eyring's and Sabine equations are particularly accurate. When parameters such as uniform surface absorption and diffuse surface reflections are present [6] the accuracy of these equations increase. These characteristics only apply to a small percentage of rooms and studies by Millington, Fitzroy and Puchades, and [2, 13, 17] aimed to deal with rooms that do not have those ideal parameters or diffusivity. Kuttruff's equation defines diffuse surfaces that reflect in accordance to Lambert's law (total energy reflection when absorption is absent) for rooms with non-uniformly distributed absorption[2, 13]. An attempt is made to correct Eyring's equation by including the variance of MFP. Millington attempts to correct the problem of absorption coefficients exceeding 1 by introducing a new absorption coefficient but suffers from high absorption areas and gives a reverberation time of 0. Ducourneau covers the reverberation works of many authors in his comparison of different formulas in an industry room [13]. The industrial room is used because of the heterogeneous walls and is able to find a correlation between the absorption coefficient and the distance of the source from absorbers [2, 13, 18-20]. This relationship is important in pointing out that the absorption coefficient of an object will behave accordingly with its distance to the source. Furthermore if the first reflections from a source are off of an absorption panel then the normal Sabine equation will no longer be correct. It is important to keep the source, receiver, and absorption at a consistent distance to avoid such discrepancies. In the following study regarding absorption measurements made in a 1:10 scale reverberation chamber, the noted objects are kept at a consistence distance.

In several references a comment can be found regarding absorption measurements in real rooms and how further research on the matter is required. This comment is leading to the idea that absorption coefficients in real rooms is not fully understood due to the differences found in reverberation times. These differences can occur because of different room sizes rooms, lack of diffuseness, or positioning of the absorbers and this creates problems with predictions. This study will use a 1:10 scale reverberation chamber and will focus on the effects that diffuseness plays on absorption coefficients. This scale chamber is setup according to ISO-354 standards and explores different configurations of absorption and diffusivity as well as changing locations of the receiver and source in each configuration. A major goal of this experiment is to discover how the absorption in a diffuse field changes when the diffuse field is removed.

Introduction

The study of room acoustics has seen a large increase in measurement accuracy over the past 100 years due to the interest of quality sounding rooms and advances in computing power. Sound response in a room has become more important as increasingly modern requirements are desired by industries that have a primary focus on audio reconstruction and presentation such as recording studios and large concert halls. W.C. Sabine is largely responsible for the basis of modern acoustics as his research and eventual acoustic mathematical expressions pushed past the previous concepts of room dimension ratios and semi-circular room shapes being the only thought acoustic parameters. The questions proposed by Sabine dealt also with the materials that are present in a room and their distribution on the surfaces in the room. Eventually Sabine was able to loosely define standards that could be applied to any enclosed space that enabled acousticians to take aim at a unit of measurement to manipulate. From this place in time (early 1900's) the study of acoustics has undergone a leap in understanding but there still remain many unknowns in the field.

Different aspects of a room can affect the behavior of sound based on the dimensions, objects in the room (absorbers), and the way sound is distributed in a room. These basics can cause discrepancies that often lead to a room with 'good' or 'poor' acoustics. The definitions of these terms are often considered subjective to layman's that only use what they hear as the only discerning point of reference to decide on a room's acoustics. There are only rare moments when simply listening can be counted upon to accurately define the acoustics of a room, and these moments tend to happen in extreme cases such as a noisy squash court (poor) or a quiet room in a library (good). Although the noise levels in the two rooms are different it does not justify perfect acoustic conditions. Final judgments on a room will be decided by the ears of it's listeners and even if the acoustical properties applied create a theoretically perfect room it will still be labeled as flawed if a listener is not happy the room's sound. To analogize with a perfectly designed automobile, it may have the best engine and suspension characteristics but if it is uncomfortable to its driver then how could it be considered 'perfect'? The same can be applied to a well-planned room.

This is not to give the impression that room acoustics is based on an artistic touch, but rather the impression warranted is to understand the complex behavior of sound waves in a room and manipulate this sound to produce a good listening environment.

A goal to be discussed here is to move beyond a layman's subjective definition and to delve into what makes a room have certain characteristics and not others. Ultimately a question to be reviewed thoroughly, and possibly resolved, is where errors in reverberation time predictions occur based on the rated absorption in the room.

Chapter 1 Room Acoustics Theory and Fundamentals

To appreciate the results of this study the groundwork of acoustics must be overviewed to understand what portions of this study are most important. The fundamentals of room acoustics can be described mathematically in the forms of Sabine's and Eyring's reverberation time equations as well as several theories regarding energy density distribution (diffusivity). The derivation of these equations is deemed necessary so that there is an explanation of how these methods have become the modern standards of acoustics, and also to explore the physical aspects (outside of measurements) that are incorporated. Reverberation time has several representative equations and yet only one remains to be used considerably more often than others.

1.1 Room Modes of an Arbitrary Room

Calculating the room modes of an arbitrary sized room is determined by finding an expression that incorporates the mode integers that were discussed in the introduction above. The Helmholtz equation introduces the three dimensions of the room as differential equations:

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} + k^2 p = 0 \qquad (3.1)$$

With boundary conditions applied to the Helmholtz equation, new values can be used:

$$\frac{d^2 p_1}{dx^2} + k_x{}^2 p_1 = 0 \qquad (3.2)$$

The differential for the pressure is now set to equal zero. The other part of the equation has the general solution:

$$\begin{gathered} k_x^2 + k_y^2 + k_z^2 = k^2 \\ p_1(x) = A_1 \cos(k_x x) + B_1 \sin(k_x x) \end{gathered} \qquad (3.3)$$

The general solution gives the boundary condition for $A_1=L$ and $B_1=0$. So that the boundary of $x=L_x$ must be represented by $cos(k_xL_x)=+/-1$ and by this being true k_xL_x must be integers of π. So that the expression for k_x could now be given as:

$$k_x = \frac{n_x \pi}{L_x} \quad (3.4)$$

This same expression can be used for the y-axis and z-axis. Now (3.3) can be rewritten to find the wave number (also called the eigenvalue) of the mode integers (*l, m, n*):

$$k_{xyz} = \pi \left[\left(\frac{n_x}{L_x} \right)^2 + \left(\frac{n_y}{L_y} \right)^2 + \left(\frac{n_z}{L_z} \right)^2 \right]^{1/2} \quad (3.5)$$

And the frequency (also called the eigenfrequency) can be found by the expression:

$$f_{xyz} = \frac{c}{2\pi} k_{xyz} \quad (3.6)$$

Using (3.5) and (3.6) the room modes and frequencies can be calculated for an arbitrary rectangular room.

Room modes pose a problem with small to semi-small rooms (volume between 150m^3 – 300m^3) because the modal frequencies will occur at audible frequencies. This will create a sound wave in the room that changes in intensity as a function of location in the room; this is referred to as a standing wave Figure 1.1. The standing wave causes sound levels to be different in the room and can prove difficult to control. This causes an issue when attempting to measure the reverberation of a room where good quality acoustics is needed.

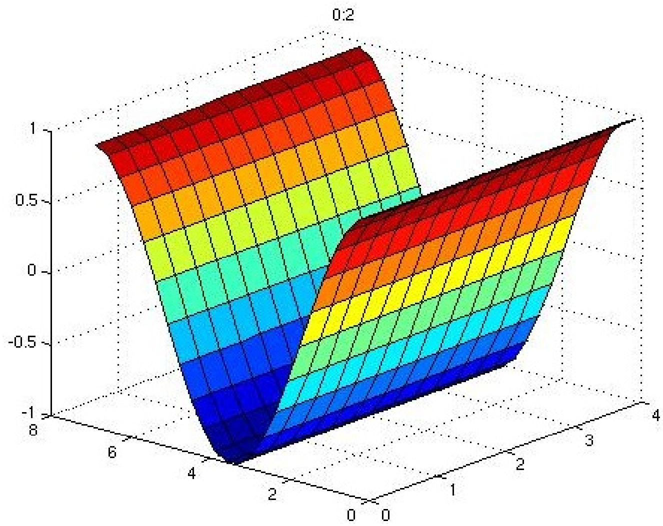

Figure 1.1 Standing Wave: Intensity is larger at the boundaries and zero in the middle

1.2 Sabine and Eyring's Reverberation Time Equations

Reverberation is heralded as having a "major role in every aspect of room acoustics"([2], p.115) and its attribute is always a distinct and necessary component when measuring a room. Once a sound field has reached a steady state (i.e. the entire field has equal sound distribution) the sound source can be removed and the following decay of the sound field is referred to as the reverberation. If $t=0$ at the moment the source is removed then once the resulting decay has diminished by a factor of *60dB* (one million) the amount of time passed is determined to be the reverberation time [1]. A depending factor on achieving proper reverberation comes from the assumption that a room is absolutely diffuse and that all energy is decaying at the same rate independent of room location.

1.2.1 Sabine's Reverberation Equation

With this assumption in place then the reverberation becomes arbitrarily dependent on the dimensions and the amount of absorption in the room. The decay in power in the room as a function of time becomes:

$$P(t) = V\frac{\mathrm{d}w}{\mathrm{d}t} + \frac{cA}{4}w \qquad (3.7)$$

Where V and A are the volume and 'equivalent absorption area' of the room, c is the speed of sound in air (343 m/s). The differential equation is independent of time when in the steady state and (3.7) can be expressed as the energy density:

$$w = \frac{4P}{cA} \tag{3.8}$$

The energy density in (3.7) becomes homogeneous and the damping constant δ:

$$w(t) = w_0 e^{-2\delta t} \;\Rightarrow\; \delta = \frac{cA}{8V} \tag{3.9}$$

Which can be related to the reverberation time by:

$$T = \frac{6.91}{\langle \delta \rangle} = 0.161\frac{V}{A} \quad \text{(Sabine's Reverberation Time Equation)} \tag{3.10}$$

This is the general form of Sabine's equation, general because their remains portions that require further clarification and will be discussed in a moment (i.e. equivalent absorption area). The simplicity of Sabine's equation leaves some skepticism regarding its accuracy to predict reverberation time for all rooms and this simplicity was challenged by Eyring's studies regarding Sabine's assumption of absolute diffusivity [4]. Though it cannot be argued that the robustness of this equation does not provide at least a fast prediction for many rooms. It is still referenced in the international standards ISO-354 [21] as the reverberation time equation as all attempts to reform (3.10) have not had such an impact as this initial expression.

In this study the reverberation time will be measured in a reverberation chamber and therefore equation (3.10) will need to be rearranged to find the average absorption coefficient of the chamber:

$$A = 0.161\frac{V}{T} \tag{3.11}$$

In this case *A* is referred to as the equivalent absorption area and evaluation of this variable will be important for modeling. Many references give instruction on how best to find this absorption area. Mange [12] explains the ISO-354 [21] standard concisely and ignores the inclusion of the power attenuation coefficient. By taking the difference of two reverberation time measurements in a reverberation chamber the equivalent absorption area is determined:

$$A = 0.161V\left(\frac{1}{T_{60F}} - \frac{1}{T_{60E}}\right) \tag{3.12}$$

Where T_{60F} and T_{60E} are the reverberation time full and empty of absorption respectively. This is then plugged in to find the absorption coefficient:

$$\alpha_s = \frac{A}{S} \tag{3.13}$$

In the case where the absorption of a room's surfaces is already known and the reverberation time is being calculated then (3.13) is then described as:

$$\alpha_s = \frac{1}{S}\sum_i S_i\alpha_i \;\Rightarrow\; \frac{1}{S}\left(S_1\alpha_1 + S_2\alpha_2 + \cdots + S_i\alpha_i\right) \tag{3.14}$$

And can then be used to change (3.10) to:

$$T = \frac{0.161V}{S\bar{\alpha}} \tag{3.15}$$

A benefit of the Sabine equation is that even as the absorption coefficient approaches unity the reverberation time will always be non-zero (Figure 1.2). This holds useful for practical application since the reverberation time cannot be totally removed.

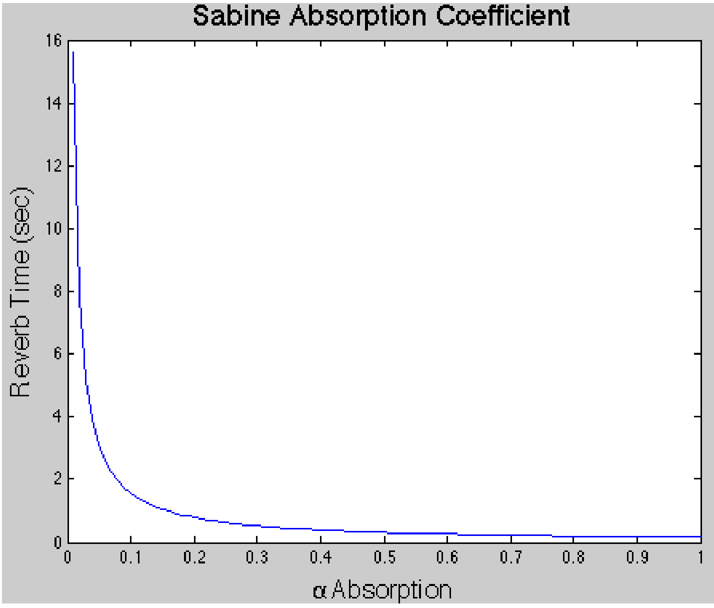

Figure 1.2 Sabine Absorption Coefficient versus RT (V=223m^3; S=226m^2)

The values of volume and surface area were chosen in accordance to the ISO standards and constitute a fairly cubic room. There does remain situations where the absorption coefficient (α) is calculated as being over unity (α>1) and this result is accepted usually because of the failure to create a totally diffuse room [13] as well as edge diffraction around objects [16]. The Norris-Eyring reverberation equation (or Eyring equation) attempts to reduce this error.

1.2.2 Eyring's Reverberation Equation

The basis of Carl Eyring's work was to introduce a reverberation time equation that was accurate in quiet rooms (i.e. 'dead' rooms) [4]. Since Sabine's work was based in highly reverberant rooms (i.e. 'live' rooms) his equation was not helpful in smaller rooms where reverberation needed to be accurately predicted. The smaller rooms, in this case, refer to radio stations where the broadcast rooms are rather small and therefore are susceptible to room modes. Eyring's focus on reverberation time came strongly from the method of image sources (Figure 1.3). The idea proposed was that when the primary source was activated each reflection became a secondary source so instead of sound reflecting off of walls the sound waves became new sources which in turn produced other sources and so on and so on.

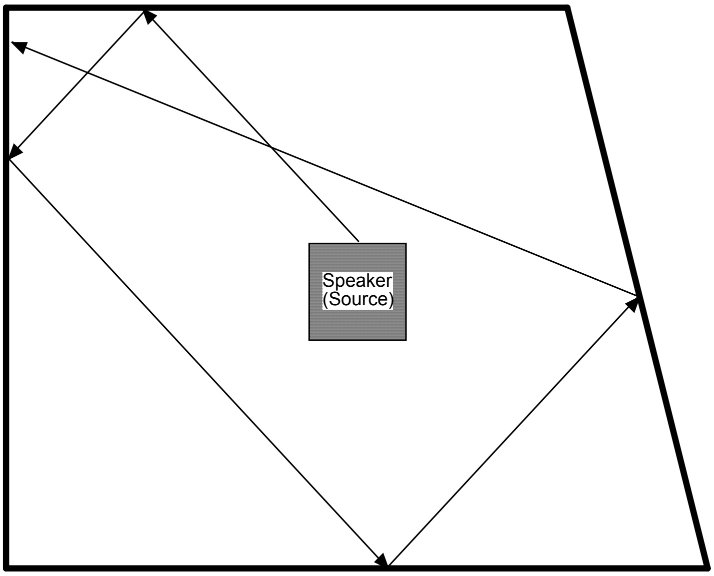

Figure 1.3 Image Source Method of 5 Reflections

This new perspective applies to reverberation as well in that when the primary source is turned off all the other sources were turned off. As time progressed all of the secondary sources would individually decay until *-60dB* was reached.

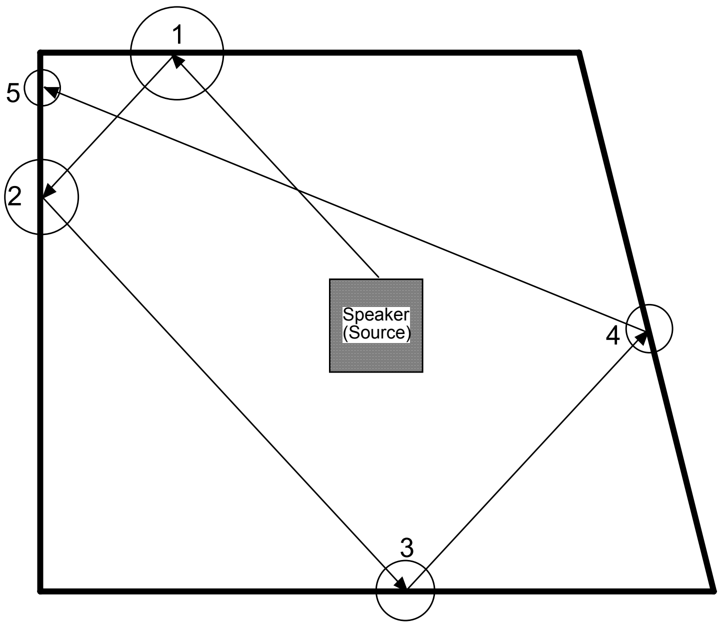

Figure 1.4 Image Source Method with Decaying Secondary Sources

Each circle in (Figure 1.4) represents the source of a sound wave and if a measurement is taken at a point where many circles overlap then the decay time will be extended until the last wave has decayed. This can then explain how the energy in the room decreases with time once the primary source is removed and can be plotted as an echogram (Figure 1.5).

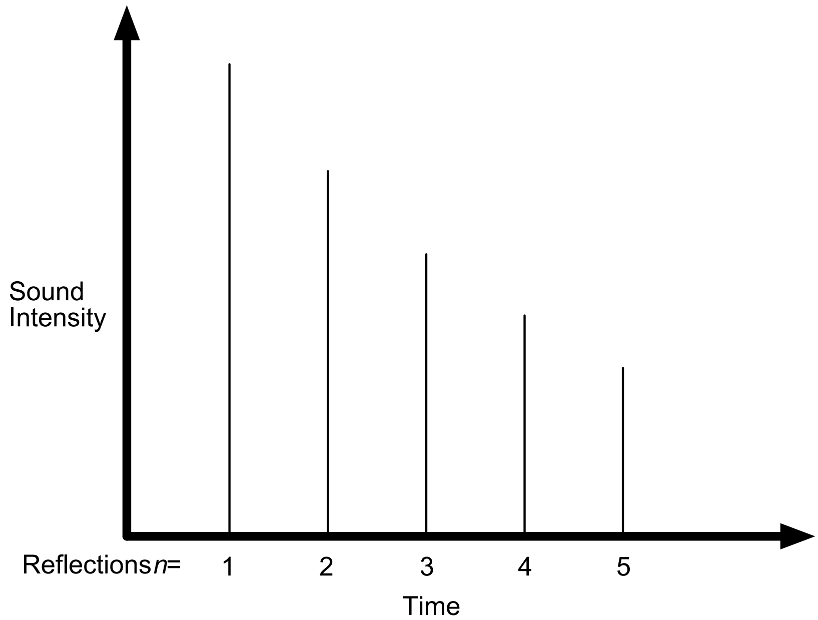

Figure 1.5 Echogram with Corresponding Reflection Numbers from Figure 1.4

The image source method and use of secondary sources proves that the decay of the total sound energy is not the same as the decay of only the primary source. Therefore reverberation is the decay of all reflections in the room (minus the first reflections) [2]. A practical method of viewing this sound decay is referred to as a Schroeder curve, after M.R. Schroeder's study of sound decay in concert halls [15].

Now that layout of Eyring has been discussed there needs to be a mathematical expression for how the energy decays when there are n number of reflections in a room. Using a differential equation to represent the density of reflections at a point at a time t in a given room:

$$\frac{\mathrm{d}N_r}{\mathrm{dt}} = 4\pi \frac{c^3 t^2}{V} \tag{3.16}$$

This simply states that as time increases the density of the reflections will too, this is independent of initial energy E_0. This expression is noted by Kuttruff [2] to be applicable in a room of arbitrary dimensions since surface area is not a factor (as opposed to only rectangular rooms). Now the average intensity of each reflection can be expressed when it is assumed that after each reflection the intensity affected by the attenuation coefficient *m* and a certain time *t* the average energy at a point:

$$E(t) = E_0 \exp\left\{\left[-mc + n\ln(1-\alpha)\right]t\right\} \quad \text{for } t \geq 0 \tag{3.17}$$

Now there is an expression for decreasing energy as a function of time, and reflection *n* will lose intensity by $(1 - \alpha)$ as time increases. When using Eyring's expression for the average number of reflections:

$$n = \frac{ct}{p} \tag{3.18}$$

Where *p* is the mean free path (MFP) and is determined by Sabine to be, $p=0.62(V)^{1/3}$. For a square room, $p=3.7V/S$, but generally the MFP is defined by the kinetic theory of gases [4] as, $p=4V/S$. So now (3.18) can be written to include the dimensions of the room and the MFP and becomes the total average number of reflections per second:

$$\bar{n} = \frac{cS}{4V} \tag{3.19}$$

This can now be put back into equation (3.17) and a solved for *t* to reveal another general reverberation time equation:

$$T = \frac{0.161V}{-S\ln(1-\alpha)} \quad \text{(Eyring's Reverberation Time Equation)} \tag{3.20}$$

Eyring equation incorporates Sabine's equation as well for live room absorption when $\ln(1-\alpha)$ is expanded out then $\ln(1-\alpha) \approx -\alpha$ which when this case replaces the denominator of (3.20) it becomes Sabine's equation (3.15). When these two situations are evaluated in equation (3.17):

$$E(t) = E_0 \exp\left[ct \frac{S \ln(1-\alpha)}{4V} \right] \quad \text{(For High Absorption, } \alpha \geq 0.3\text{)} \qquad (3.21)$$

and:

$$E(t) = E_0 \exp\left[ct \frac{-S\alpha}{4V} \right] \quad \text{(For Low Absorption, } \alpha \leq 0.3\text{)} \qquad (3.22)$$

Therefore it is shown that Sabine's equation is a special case of Eyring and that 'dead' and 'live' rooms can be represented by Eyring's reverberation time equation (Figure 1.6).

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Figure 1.6 Comparison of Absorption Coefficients

This leads to the conclusion that Eyring's equation does offer a more complete representation of reverberation as it is able to predict the same values for 'live' rooms as Sabine and produces a closer to zero reverberation time as absorption approaches unity. This approximation is proven by subsequent experiments undertaken by Eyring [4]. Since the publication of Eyring's equation (~1930) there has been more research done in the refinement of reverberation time equations.

1.3 Other Reverberation Time Equations and Comparisons

Direct comparisons with the Sabine and Eyring models have been done many times. These comparisons sometimes utilize complex numerical models [14] and other times the methods are experimentally derived expressions [2, 15, 18] that do prove to be effective. There have been no findings to suggest that either Sabine or Eyring are incorrect instead just a little to simplified. This result is not enough to make any significant changes in measuring the reverberation of a room although there have been several interesting approaches that do expand the study of room acoustics.

Only three reverberation equations will be discussed, of the many proposed expressions, based on the highest amount of notoriety. The studies of Millington, Fitzroy, and Puchades all incorporate portions of the Sabine and Eyring equations [13]. MFP and room dimensions remain the dependant factors and the given equations are Millington(3.23), Fitzroy (3.24), and Puchades(3.25):

$$T_{Mil} = \frac{0.161V}{S\alpha_{Mil}} = \frac{0.161V}{\sum_i S_i \ln\left(\frac{1}{1-\alpha_i}\right)} \qquad \text{(Millington)} \quad (3.23)$$

$$T_{Fitz} = 0.161\frac{V}{S^2}\left[\frac{-S_x}{\ln(1-\alpha_x)} + \frac{-S_y}{\ln(1-\alpha_y)} + \frac{-S_z}{\ln(1-\alpha_z)}\right] \qquad \text{(Fitzroy)} \quad (3.24)$$

$$T_{Puch} = \frac{0.161V}{S[a_x]^{S_x/S} \cdot [a_y]^{S_y/S} \cdot [a_z]^{S_z/S}} \qquad a_n = \ln(1-\alpha_n) \qquad \text{(Puchades)} \quad (3.25)$$

The similarities in the equations are all noticed with the incorporation of the MFP ($0.161V$) but the absorption expressions are all slightly different. Note that the subscripts of *x, y, z,* are all to denote the surface planes and when a room with non-flat surfaces is being used then the subscripts simply define the directional plane and the absorption is averaged.

1.3.1 Millington's Reverberation Equation

Millington's work is a direct attempt at making sure that absorption coefficients do not exceed unity (something that is common with Sabine and Eyring). The approach to combat this issue is to adjust the absorption coefficient value by taking the sum of the natural logarithmic expression for each surface. This is not necessarily doing anything except decreasing the absorption to be below 1. Figure 1.7 shows the conversion graph, duplicated from Ducourneau [13], and how the absorption coefficient is only adjusted by the denominator portion of (3.23).

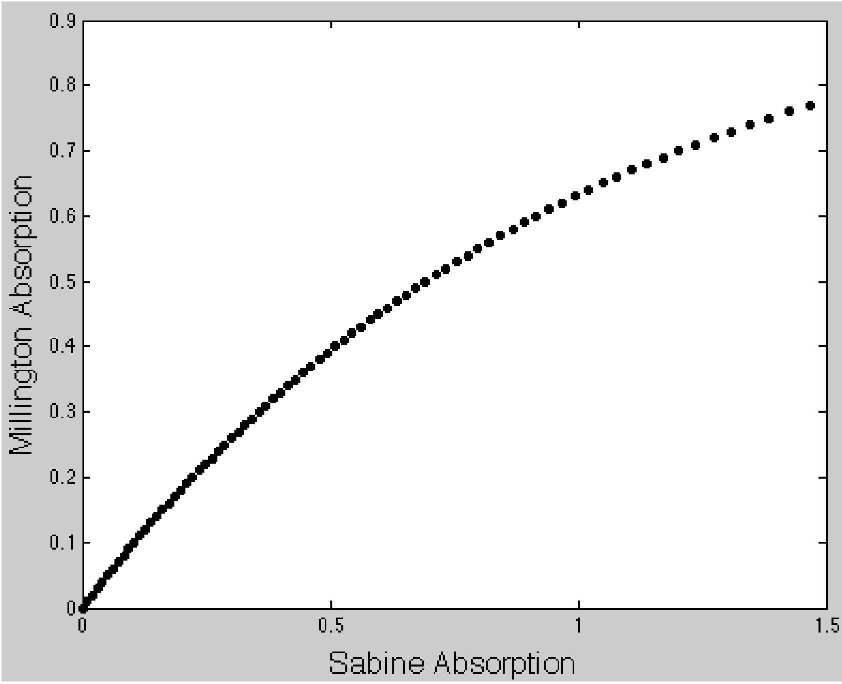

Figure 1.7 Dance and Hall's Adjustment of Sabine and Millington's absorption [13]

This allows the conversion of any Sabine value to avoid exceeding unity but it has problems when there is a high amount of absorption the RT becomes very close to 0 and therefore the adjustment plot must be used to use Millington's equation. This does allow for the absorption coefficient to be adjusted below unity, but the inclusion of a conversion of values from Sabine's coefficient shows that Millington's expression does not introduce any significant benefits.

1.3.2 Fitzroy's Reverberation Equation

The Fitzroy model of reverberation time used a the same absorption coefficient as the Eyring model, but took it a step further and applied this absorption to individual surfaces. Therefore the expression (3.24) is assuming that the parallel walls in a room have similar absorption coefficients. When this assumption is made each boundary then has the Eyring RT equation applied to it and are summed together, the results were found to be "…in surprising agreement with test measurements." [17]. In the results given regarding Fitzroy's work a strong point is made for the distribution of absorption in a room and it is stated that in a room with 3000 ft^2 of absorption spread throughout the room there is a shorter reverberation time than in a similar room with 7000 ft^2 absorption placed on only one boundary. Therefore the amount of absorption described by the Fitzroy equation appears to represent the effective absorption of the room. Where areas the Sabine and Eyring equations give a total room average of the absorption coefficient. Fitzroy does not establish a new equation altogether, but does seem to improve the current equations of Sabine and Eyring. Substitution of Sabine's absorption coefficient in place of Eyring's in the Fitzroy expression has no real objections, although there were no results reviewed for discussion in this case. A further note regarding Fitzroy is given in [13] where Neubauer created a modified Fitzroy formula that reviews situations where absorption is non-uniform on parallel walls but results were not presented nor reviewed.

1.3.3 Arau-Puchades Reverberation Equation

Puchades reverberation equation has a similarity with Fitzroy as the two equations both take into account the absorption applied to a particular surface. In the research done, Puchades admits that his research is rather just an improved Sabine (or Eyring) equation [18]. Thus (3.25) is related with much of the other equations that have been derived.

The approach taken by Puchades was to look at the decay rate of the energy in a room and this leads to the unique element in his expression (the exponent x/S; y/S; z/S). Taking the expression of a basic decay rate:

$$D = \frac{10\log\left(\frac{E_0}{E}\right)}{t} \tag{3.26}$$

Where D is dB per second E_0 is the initial energy and E is the remaining energy. If the average number of reflections of a given room is incorporate N then (3.26) becomes:

$$\bar{a} = \frac{D}{10}\frac{1}{N}\frac{1}{\log e} \tag{3.27}$$

Now if the parallel walls in their respective coordinate planes represent a room then (3.27) becomes:

$$\overline{a} = \left(\overline{a}_x\right)^{x/S}\left(\overline{a}_y\right)^{y/S}\left(\overline{a}_z\right)^{z/S} \tag{3.28}$$

Where this new absorption coefficient can be used in place of Sabine or Eyring's coefficient, but in the same respective equations. The placement of each new absorption value is seen in (3.25).

1.4 Diffuse Sound Fields and Reflections

So far there has been a large amount of discussion and derivation on reverberation with the assumption that diffusivity has been total. Although the practical examples of diffuse fields will not be discussed until Chapter 2 the theory behind diffusion is approached with the idea that it is possible to achieve a total diffuse field (which it is not possible only approximated). Diffusivity can be explained using any kind of wave propagation (i.e. sound, types of light). A simple explanation might best be explained with sunlight for there is a noticeable diffusion of sunlight when a thin layer of fog or haze is in the air (yet not cloudy), under this weather condition the sunlight appears to be scattered equally bright in all directions. This occurrence causes an even distribution of light energy in all directions and when this example is applied to room acoustics the same effect is desired.

1.4.1 Diffuse Reflections

Several authors give definitions to what a diffuse field is and it's difference from diffuse reflections. Dalenback [7] characterizes a diffuse reflection as behaving in contrast to a specular reflection and states the differences of the two terms of diffusion (not before admitting the lack of consistency in definitions of diffusion). It is stated that diffuse reflections add to diffusion and therefore the term diffuse reflection is related to the overall diffusion. Another term that can be used for diffuse reflections is scattering, but this is more of a synonym than a new term. Assuming a surface larger than the wavelength, a sound wave incident upon a specular surface will be reflected at the exact angle of incidence. A wave incident upon a diffuse surface will scatter the sound wave upon reflection (Figure 1.8).

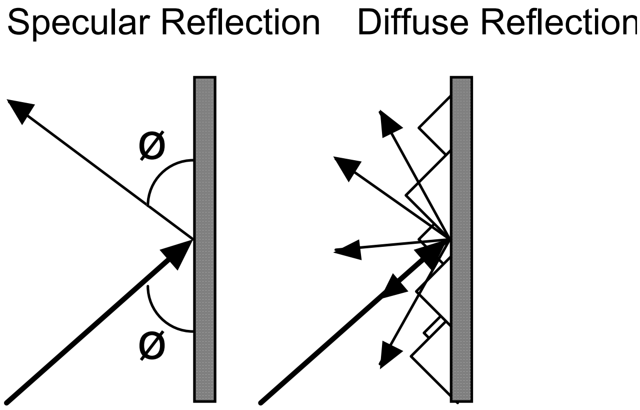

Figure 1.8 Examples of Reflections

These types of reflections increase the diffusivity of the room by spreading the distribution of sound waves in non-specular directions. The effect of diffuse reflections is a factor particularly in rooms where surfaces have rigid, uneven features that are comparable in size to the wavelength.

1.4.2 Diffuse Sound Field

Creating a diffuse sound field means that all locations in the room have an equal reverberant sound field and is independent of source location [6]. Expressing the SPL of an arbitrary point in a diffuse field:

$$L_p(r) = L_W + 10\log\left[\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)}{A}\right] \qquad (3.29)$$

Where L_p is the steady-state SPL, A corresponds to either Sabine or Eyring's equivalent absorption area (3.13), r is the distance from the source and Q and L_W are the directivity factor and source SPL respectively. Since (3.29) is a function of distance r from the source, a diffuse field will flatten out once the receiver is far enough from the source to avoid the direct sound field (Figure 1.9). The flattening out of the curve is evidence that at a large distance only the reverberant sound field is present.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 1.9 Sound Propagation SPL Lp(r) (Frequency Independent)

The flattening out of the curve is also evidence of a diffuse field because there no longer is a correlation between the distance and the sound power level, if the SPL continued to decrease then the sound field would continue to grow weaker as the distance increased ruling out that the field was diffuse.

The theoretical portions of room acoustics is important but when these theories are put into practice many unknown factors can interrupt proper prediction. Many of these models and equations have been tested in real world rooms primarily in the past century by a many acousticians.

Chapter 2 Practical Reverberation and Diffusion and the Problem with Absorption Coefficients

The fundamentals of acoustics were reviewed in Chapter 1 to introduce what terms are most important in room acoustics. Along with reviewing the fundamental parts of acoustics there was a discussion on the leading theories in reverberation time prediction. These reverberation time equations have all been backed up by experiment but they behave differently in describing different kinds of rooms. For example the Eyring and Sabine equations are found to be much alike in a room that contains a mid to high amount of absorption in the room, and yet the two theories diverge when the absorption coefficient of a room is very small. This leads to look at the everyday use of these expressions and to find an appropriate understanding of how accurate they are. Another topic to be reviewed in a real world situation is diffuse room theory. An absolute diffuse room cannot be achieved practically and therefore it is important to see how the performance of an approximate diffuse field affects absorption coefficient measurements.

2.1 Comments on Discrepancies found in Sabine and Eyring

It was stated previously that the Sabine and Eyring reverberation time equations often calculated an absorption coefficient that exceeded 100%. This value of absorption could lead to the assumption that total absorption should produce zero reverberation time and this assumption is incorrect.

2.1.1 Comments by Hodgson

Hodgson [11] attempted different configurations of experiments that aimed to specify how well the predictions of Sabine and Eyring are in a room with mid to high amounts of absorption. There is an exclusion of low absorption situations because it is widely known that these equations diverge in such cases. In Hodgson's absorption coefficient experiment the immediate problem with an accurate prediction expression is seen Figure 2.1. The Sabine values are drastically high as the frequency increases yet the Eyring value appears much closer to the actual absorption values. The C423 coefficients were achieved using a reverberation chamber that met the ASTM C423 standard.

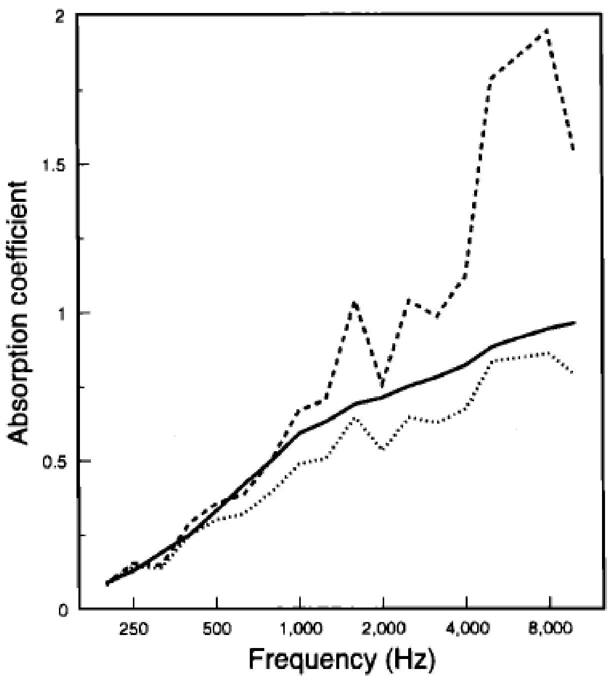

Figure 2.1 Hodgson [11] Absorption (ASTM C423 α — ; Sabine α --- ; Eyring α …)

The Eyring coefficients appear to represent the C423 values more consistently because Eyring is more valid for a wider range of absorbent materials. The two equations are derived under the assumption of a diffuse sound field and this could lead to the slight inaccuracies of Eyring, yet this assumption of diffusion should not be blamed entirely for the Sabine values. Instead it is proposed that the Sabine theory is only an approximation of the Eyring equation and does not provide valid absorption data when there is non-low absorption present. This study concluded that the Eyring reverberation time equation produced better predictions. Note: Hodgson does take time to evaluate the diffuseness of the room and finds that the exclusion of the $(1-\alpha)$ in the second part of equation (3.29) creates a large (~8-20dB) overestimation of the SPL in the reverberant field (when the receiver location is far from the source).

2.1.2 Comments by Mange

Mange [12] attempts to solve the absorption coefficient problem by introducing a shorter mean free path value. It is assumed that hanging plane diffusers creates the diffuse field in the room and causes shorter paths between surfaces. The idea behind this work was to introduce the value of MFP in Sabine's equivalent absorption area equation and by doing so should give the absorption coefficient of a room with a smaller MFP. The manipulation is done on equation (3.15):

$$A = \left(\frac{60V}{1.086c}\right)\left(\left(\frac{1}{T_{60S}}\right) - \left(\frac{1}{T_{60B}}\right)\right)$$

Where *MFP=(4V/S)* and is represented instead as:

$$A = \left(\frac{60S(MFP)}{4.344c}\right)\left(\left(\frac{1}{T_{60S}}\right) - \left(\frac{1}{T_{60B}}\right)\right) \qquad (4.1)$$

This approach does not work as it unexpectedly increases the absorption coefficient even more. This gives confirmation that the overestimation of the Sabine absorption coefficient is not due to the mean free path being shortened when hanging diffusers are present.

2.1.3 Comments by Sum

More comments regarding the problem with Sabine's reverberation equation is by Sum [22] who only focuses on Sabine. Sum approaches the same problem as Hodgson with absorption coefficients that are greater than 100%. The studies undertaken are done from a statistical approach rather than experimental processes. The discussion given by Sum refers to the definition of the problem of absorption coefficients exceeding unity and refers to this issue as a false understanding of what constitutes 100% absorption. If coefficient values are able to, and do, exceed unity then that must not be the maximum value and this leads to the conclusion that the Sabine absorption coefficient is a misleading name. The term 'Sabine absorption factor' is suggested as a better way of describing α_{Sab} as a factor that changes from room to room. The different physical traits of every room would cause the Sabine factor to represent an attenuating coefficient within the Sabine equation, yet it would not be representing a sound absorption coefficient capable of total or zero attenuation.

2.1.4 Comments by Cops

The final study to review was conducted by Cops [23] and his attempt to pinpoint the factors that affect the repeatability of absorption measurements. Even when the ISO-354 standard is followed very closely the results calculated are difficult and it is stated that the use of highly accurate measurement systems (computers) are not considered the source of error, instead the error must be introduced by any of the following: room design/dimensions, sources, receivers, and absorptive materials.

The setup of the reverberation chamber is based on achieving a diffuse sound field, and is done by increasing the number of diffusers (0, 7, and 12 diffusers) and an attempt at increasing the diffusivity by placing absorption in the corners with no hanging diffusers. The latter method is attempting to increase diffusivity by removing the axial and tangential modes that are associated with low frequencies, and also are the octave bands that are the hardest to control. A major portion of the study is placed on the affect of having objects in the corners of the room with no diffusers being hung in the room at all. The affect that these corner objects has is effective in the low frequencies and it is recommended that the use of corner objects to increase diffusivity be pursued in an attempt to achieve a diffuse sound field without the need of hanging diffusers (which adds area, and is a time consuming task).

2.1.5 Review of the Inconsistencies with Sabine

It is apparent from the different research papers discussed that there remains a lingering problem of achieving consistency in the Sabine absorption measurements. From these studies several key points have been found, each of which do not provide a solution, but introduce insights to the problem.

Hodgson makes the statement that the Eyring equation is a more reliable way to achieve accurate reverberation times and absorption coefficients and also states the importance of including the $(1-\alpha)$ in the absorption equation.

Mange explores the problem by attempting to adjust the MFP when there are hanging diffusers present. The results unexpectedly increase the amount of absorption beyond unity and is convincing proof that the MFP of the room is not the culprit of coefficients that are greater than 1.

Sum studies the absorption coefficient problem by using statistical analysis and suggests that the problem of absorption coefficients being greater than unity needs to be retooled. Instead of producing an absorption coefficient, the Sabine equation should give an absorption factor that affects the reverberation time, and also creates an explanation as to why Sabine does not produce a zero reverberation time when there is 100% (or more) absorption coefficient.

Finally, Cops introduces the idea of removing hanging diffusers and replacing them with absorption in the corners of the room to produce a more consistent amount of absorption across the frequency band. This is shown to be affective at evening out the absorption coefficients, but does not do anything to reduce the coefficient to below 1 (many of Cops tests give coefficients close to 2!).

Much of this research gives new ideas for creating diffusivity as well as dealing with large absorption coefficients. The most practical information from these results is the confirmation of Eyring's equation being the most accurate equation in practical situations.

2.2 Practical Diffuse Sound Field Theory

Previously the topic of diffusion was based on the definition and theory of an absolute diffuse sound field without any insight into the practice of achieving a diffuse sound field (or lack thereof). The theories that were covered in the first chapter introduced diffuse reflections and a diffuse sound field, these same topics will be considered when discussing real world applications of diffuse sound fields.

2.2.1 Practical Diffuse Fields

The initial reason that a diffuse sound field is not achievable in practical situations is due to interference patterns that occur at the boundaries of a room [5]. This tends to be more noticeable at lower frequencies (<1000Hz) since the wavelengths are longer and therefore the change in pressure is more disruptive and can be clearly heard. The higher frequencies (>1000Hz) would not be as subjective unless a receiver was placed very close to the boundary.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 2.2 Variation in Pressure Level Near Wall [5] (cps=Hz)

As the receiver is moved away from the wall there is a change in decibels; this behavior exhibited in Figure 2.2 can be attributed for the difficulties in creating a diffuse sound field but is only a small factor. The larger inabilities to create a proper diffuse field lies in the construction of the room particularly if a room does not have rigid boundaries and contains too much absorption. This leads to the understanding that a diffuse room can be achieved by a room that is constructed of heavy materials and is relatively empty (i.e. reverberation chamber). A reverberation chamber is typically built of heavy masonry, is not parallelepiped, and contains nothing except the materials being tested. It is common for reverberation chambers to contain hanging plain diffusers to help distribute the sound energy.

Measurements have been done [6] to find out what kind of room is diffuse. Measurements performed to define how diffuse a room is include measuring the SPL at increasing distances from the source (as done in Figure 1.9). Hodgson was able to take measurements in seven different rooms that differed in dimensions and average absorption and concluded that the Eyring model fails when there is a lack of diffusivity claiming that it overestimates SPL near the source and overestimates at far distances. Zeng's [8] measurements prior to Hodgson conclude a similar finding and states that the SPL appears to be underestimated at further distances when using Eyring but cannot confirm how evenly distributed the sound field is.

2.2.2 Practical Diffuse Reflections

Diffuse reflections are capable of adding to the diffusivity of the room and certain diffusers are designed and placed on walls to help scatter sound waves incident upon them.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 2.3 Four reflection combinations. S-Source D-Diffusor. (a) Specular-Specular, (b) Specular-Diffuse, (c) Diffuse-Specular, (d) Diffuse-Diffuse [7]

When walls are not treated for diffuse reflections there is still a good chance that the boundaries still produce a large amount of diffuse reflections [9] and might not require treatment. But for portions of walls that receive a large number of initial reflections it might be decided otherwise. The different combinations of reflections can be consolidated to four basics (Figure 2.3). These combinations can all occur in the same room as long as there is at least two specular, and two diffuse walls present. When ray tracing is being utilized to understand the acoustics of a room the specular-specular combination is the easiest to model. A way of distinguishing if diffuse reflections are occurring is to view an echogram of the impulse response. A simple example of an echogram was shown in Figure 1.5 with all of the reflections being specular reflections of the associated image source figure. But viewing an echogram of a real room where diffuse reflections are present shows that each diffuse reflection has a decay of its own.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 2.4 Diffuse Reflections in Echogram [7]

Creating diffuse reflections is important in portions of a room that collects a number of direct impulses. These fundamentals to room acoustics will be tested in an experimental process to try and quantify the issues of diffusion and absorption.

Chapter 3 Experiment Design & Setup

Measurements for this experiment were made in a scale model reverberation chamber of 1/10th scale. The specifications of this model are based upon the standards stated in ISO-354 and are followed as close as possible although inconsistencies do arise in being able to scale down all objects placed into the chamber such as the loudspeaker source and the microphone receiver. To be sure that any independent noise sources (background noise) are reduced to as low of levels as possible the chamber is placed into a semi-anechoic room. The placement of the scale chamber into the semi-anechoic room enables very reliable measurements to be achieved.

3.1 Scale Reverberation Chamber

The reverberation chamber is scaled down to 1:10th the size of an actual reverberation chamber in accordance to ISO standards. The entire chamber is made from plastic with a thickness of *1.5cm* with one pair of parallel walls (front and back) and the ceiling and floor being parallel as well. The sidewalls are not parallel and differ by an approximate 10º angle. The length of the sidewalls is generally averaged when attempting to determine the modal frequencies. The volume of the room is 223m^3 FS (FS corresponds to Full-Scale) with a surface area of 226m^2 FS. The walls of the chamber only have one pair of non-parallel walls (the side walls) and this is not considered to significantly affect the experiment, as splayed walls are claimed to not affect the overall diffusion much [16]. The dimensions of the chamber are viewed in Figure 3.1. The chamber is constructed out of transparent acrylic and all walls have a thickness of approximately 1” (2.54cm). The roof of the chamber clamped down by four latches (two per side wall).

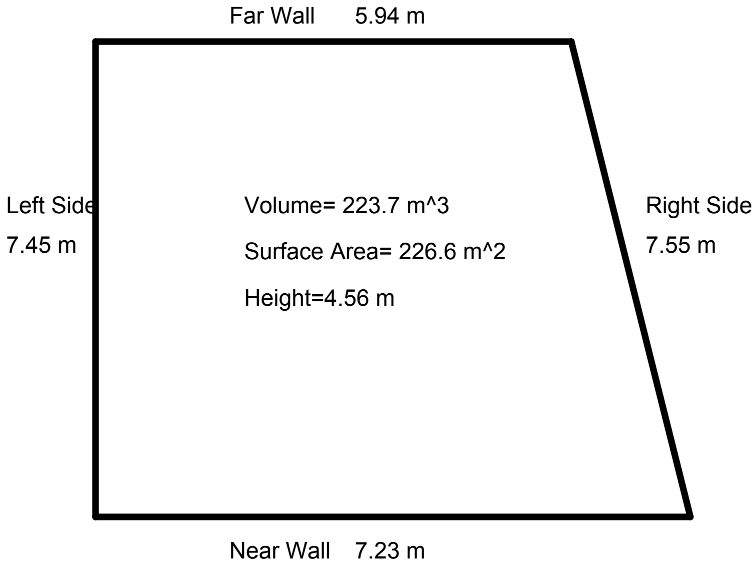

Figure 3.1 Reverberation Chamber Dimensions Full-Scale

3.2 Source and Receiver Locations

The microphone used is a Bruel & Kajer 4165 microphone with the wires from the microphone passed through pre-drilled holes in the chamber. The holes in the chamber are a snug fit with the wires and help to reduce the amount of sound pressure from escaping. Large gaps left between the wires and the chamber might attribute to errors in absorption coefficient measurements. The wires are present in every room configuration and are considered to be a characteristic of configurations with no absorption. Moving the microphone around the chamber was done with the use of a small microphone holder that enabled the microphone to be aimed away from nearby surfaces. In situations 3 and 5 the microphone was left hanging by its wire only, the stand was not present. There are five locations for the microphone and two positions for the sound source as shown in Figure 3.2. This layout is used to test all portions of the room and acquire sound intensity measurements. Using a small scale made it difficult to follow the ISO guideline that states that at least four microphone positions and three source positions should be attempted. Considering the microphone and source are not to scale it was not possible to attempt these number of positions without being too close to a boundary and/or not being a significant distance away from a previous location.

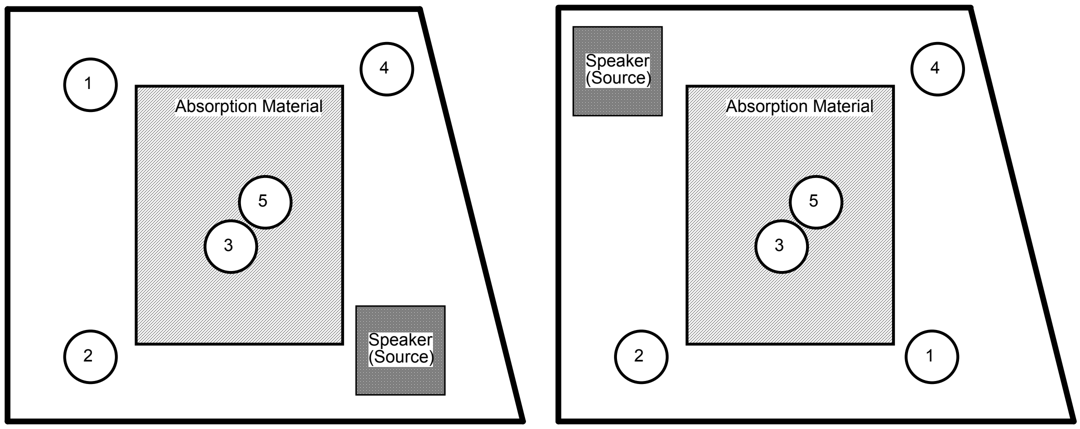

Figure 3.2 Chamber Floor plan: Source 1 (left), Source 2 (right)

The use of two different source locations is to avoid stimulating the same room modes but in the presence of a diffuse sound field the source location should be independent. The microphone locations:

Distance from Source

- **Location 1: Far Opposite Corner (~7m FS)**
- **Location 2: Near Opposite Corner (~6m FS)**
- **Location 3: Middle Ceiling (High) (~5m FS)**
- **Location 4: Far Adjacent Corner (~6m FS)**
- **Location 5: Middle Floor (Low) (~4m FS)**

The source is a small tweeter speaker with a frequency range of 63HzFS to approximately 45kHzFS. The location of the speaker is in two locations that are shown in Figure 3.2.The tested frequency range is the octave bands from 125HzFS to 8kHz and the results from the experiment focus primarily on the 500Hz and 1kHz octave bands. The axial room modes are found by averaging the lengths of the unequal dimensions and using equation (3.5) and (3.6). The modes and frequencies are found in Table 3.1. With these axial modal frequencies occurring below any measured octave band the test measurements are able to avoid any problems that may have been introduced.

	Length	Frequency
Width	6.58 meter FS	26.0 HzFS
Length	7.5 meter FS	22.8 HzFS
Height	4.56 meter FS	37.6 HzFS

Table 3.1 Room Modes of Reverberation Chamber

3.3 Absorbers and Diffusers

The absorbers used were on scale with the rest of the chamber. They consisted of soft black foam encased in wooden mounts as ISO-354 instructs. The absorption should be 5% to 6% (approx. 10 - 12 m^2) of the total surface area of the chamber and in this experiment there were 4 situations of the room without absorption and 8 total situations that include combinations of four, six and nine absorbers (full situation data is included in Appendix A). As stated in ISO-354 if the volume of the chamber is greater or lesser than $200m^3$ then the amount of absorption should be adjusted by a factor of $(V/200m^3)^{2/3}$. In this situation the volume is greater than $200m^3$ and therefore the amount of absorption is increased by a factor of *1.077*. Each absorber has a surface area of 1.40 m^2 FS giving each combination of absorption a surface area of $5.6m^2$ *FS*, $8.4m^2$ *FS* and $12.5m^2$ *FS* respectively. The absorption coefficients were then measured using Sabine and Eyring's equation as determined in Chapter 1. Having a chamber that is too crowded with materials can cause sound rays to become trapped in portions of the room (i.e. between an absorber frame and wall, or between plane diffusers and ceiling) and not allow those rays to hit the absorbers.

The diffusivity is created following ISO-354 standards that allows for plane diffusers hung from the ceiling to be used. The octave frequency bands will range over *2.5kHz – 20kHz* or *250Hz – 2kHzFS*. Plane diffusers were used that were made out of warped sheets of wood with a smooth laminate finish (to avoid any significant absorption). The plane absorbers are capable at increasing diffusivity when sound waves diffract around the edges (Figure 3.3). The diffusers were used in three situations in an attempt to find out how many diffusers were needed before the room was saturated. The situations included having no diffusers, 3 diffusers ($35m^2$ *FS*), and 5 diffusers ($53\ m^2$ *FS*) and represented 15% and 23% of the total surface of the room. The diffusers were spread out evenly and care was taken to hang the panels with twine at different heights to avoid creating a false ceiling.

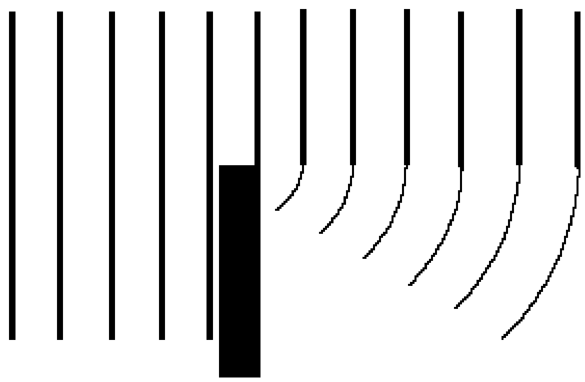

Figure 3.3 Diffraction of a Wave at a Boundary

A false ceiling could affect absorption measurements by trapping sound waves in certain parts of the chamber and give a false appearance of a smaller volume. Different sized wood panels were used to achieve the correct percentage of total surface area of the room; each plane diffuser ranged in area from *10 - 15*m^2 *FS.*

3.4 Computer Setup

At the center of the experiment was a personal computer running the software suite WinMLS. This software was used to make three different measurements: pressure per octave band, reverberation time per octave, and Schroeder curves of the 1kHz octave band. The software output signal was a sine swept wave ranging from 63Hz to 16kHz and the input was, as previously noted, with each microphone location measurement consisting of a mean of five different measurements to ensure repeatability and consistency. The data that was recorded was exported to a script in MatLab and a spreadsheet program (Excel) so that comparisons of the different situations could be done effectively and also to calculate absorption coefficients. These scripts are included in Appendix B. A schematic of the hardware layout is present in Figure 3.4.

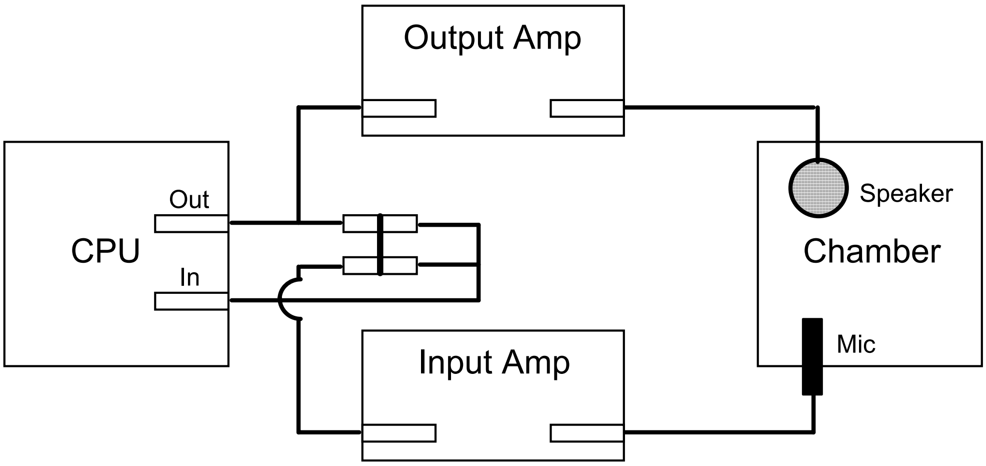

Figure 3.4 Computer Hardware Layout

Chapter 4 Results and Discussion

Finding a correlation between theoretical and measured absorption coefficients is important to creating accurate predictions for real rooms where a diffuse sound field is absent. The experiment that was discussed in the previous chapter is designed to create many different situations where the diffusivity and absorption of a room is changed by use of hanging plane diffusers and square foam absorbers. Ideal results will give a concise view of how the predictions (theory) and the real world (measured) absorption coefficients differ. The following results are displayed to present proof of this ideal result.

4.1 Creating a Diffuse Sound Field

Earlier it was discussed why a diffuse sound field is necessary to a room and how it enables absorption coefficients to be more accurately measured, it has also been stated how close to a real diffuse sound field is possible in practice. The approximation of a diffuse field can be increased by introducing diffusers into a room that enables sound waves to diffract around the edges and increase the distribution of energy in the room. Following the method in ISO-354, creating a diffuse sound field the equivalent absorption area should be measured in an empty room and then adding diffusers to the room until the equivalent absorption area reaches the ISO limit or the values flatten out. The octave bands of most importance will be 1kHz – 10kHz (100HzFS – 1kHzFS) and it should be noted that atmospheric effects have been ignored on all calculations. The density of the chamber is small and therefore it is safely assumed that the air density and temperature remain constant throughout the experiment. The number of plane diffusers attempted are 0, 3 and 5 but proved difficult to increase beyond this due to the amount of space available. The diffusers represent 15% and 23% of the total surface area in the room. With 5 diffusers hanging there was a physical limit reached, as there was no more space to include additional diffusers. The equivalent absorption area is plotted against the ISO value for given frequencies in Figure 4.1 and show that the absorbers used are accurate for the lower frequencies but do not approach the maximum limit *(A_{max})*. The absorption area was calculated using equation *8.1.2.1* from ISO-354.

$$A_{\max} = \frac{55.3V}{cT_{Empty}} \qquad (6.1)$$

Where T_{Empty} is the reverberation time of the empty chamber. The situations presented and equivalent absorption can be viewed in Table 4.1.

Freq.	ISO-354 (A_{max})	Situation 4 0 Diff.	Situation 5 3 Diff.	Situation 15 5 Diff.
125Hz	7.0	5.4	6.3	6.7
250Hz	7.0	4.3	4.5	4.4
500Hz	7.0	4.1	4.2	4.3
1000Hz	7.5	3.8	4.2	4.8
2000Hz	10.2	4.8	5.7	6.5
4000Hz	14.0	4.9	6.4	7.0

Table 4.1 Equivalent Absorption Areas for Empty Situations (m^2)

With 5 diffusers placed into the chamber and no more space available this is considered the closest approximate value of diffusivity to be reached in this chamber. This only shows the diffusivity according to the equivalent absorption area and does not prove anything associated with absorption coefficients as there are no absorbers present in these situations.

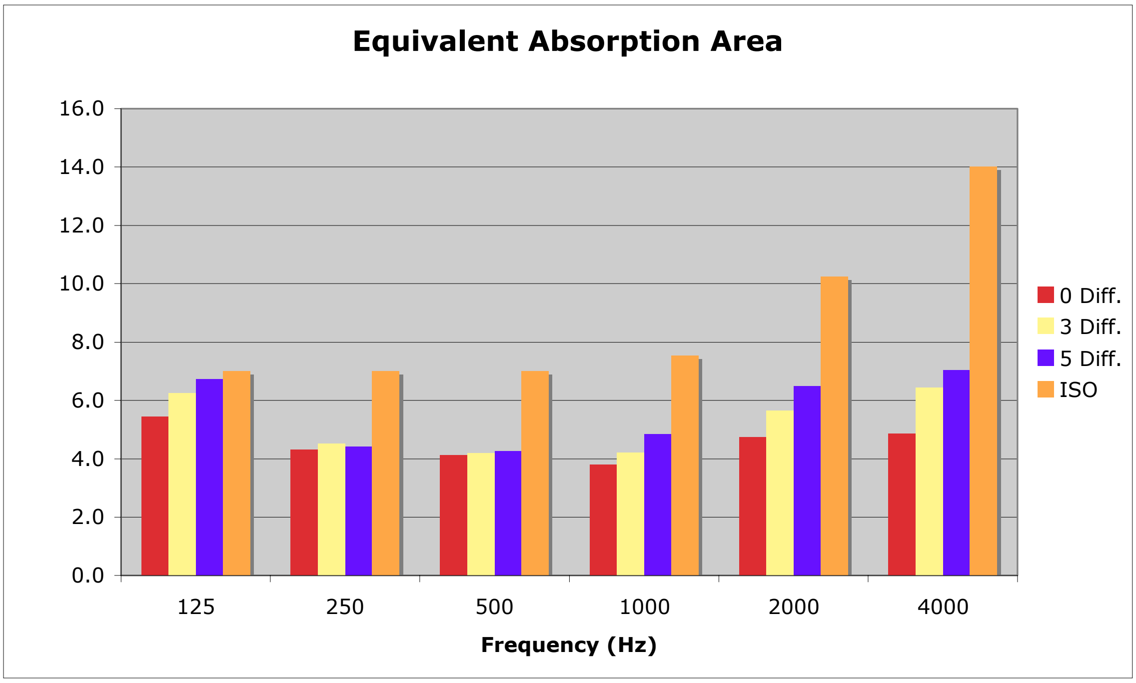

Figure 4.1 Equivalent Absorption Areas from Table 4.1

From this perspective a better approximation to a diffuse field is to be desired in all of the frequencies except the lowest. But looking at an initial comparison of absorption coefficients the amount of diffusion present with 3 or 5 diffusers makes little difference

(Figure 4.4). The hanging plane diffusers are not the only source of increased diffuseness in the room and there can be more diffusivity attributed to factors such as diffuse reflections following what was stated in [9] that a large number of untreated surfaces are diffusely reflective. This defines what the maximum diffusity of the room is and occurs when there are 3 or 5 diffusers present. This can be used to compare to non-diffuse situations (0 diffusers). Measurements of absorption will be compared in all three configurations of diffusers.

4.2 Absorption Coefficient Measurements

The absorption material that was used in the experiment was porous, thick foam similar in nature to a sponge. Using a coated wood frame that was created to scale according to ISO-354 the dimensions were approximately *1.2 x 1.2 x 0.5* meters and had a surface area of approximately $1.4m^2$FS, it is an approximate surface area because the wood frame represents a variable amount of absorption. Using the configurations of absorbers and diffusers a good approximation of what the absorption coefficient of one of these absorbers is. Sabine and Eyring are used to determine the absorption coefficients only, the use of the other reverberation time equations discussed earlier base their results on either Eyring or Sabine and are irrelevant.

4.2.1 Four Absorbers

The initial number of diffusers is *2.5%* of the total surface area of the room; this is below the prescribed amount of absorption (5 – 6%). Each plot is calculated using Sabine's absorption coefficient that uses the reverberation time of an empty situation and an absorber filled situation, the absorption coefficient averages are found in Appendix A for each figure. As the number of diffusers is increased the absorption coefficient increases as expected, but the case of 3 diffusers increases the absorption coefficient more than with 5 diffusers with a possible explanation being that there are too many diffusers present.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.2 Absorption Coefficients with 4 Absorbers (5.6m^2FS)

The absorption coefficients for the octave bands of 100Hz – 800Hz:

Frequency	0 Diff.	3 Diff.	5 Diff.
100Hz FS	1.10	1.19	1.32
200Hz FS	1.04	1.08	0.93
400Hz FS	0.94	1.11	1.08
800Hz FS	1.02	1.32	1.18

Table 4.2 Absorption Coefficients for 4 Absorbers

When there are a large number of diffusers hanging from the ceiling the amount of volume in the room might acoustically be reduced due to a false ceiling affect. If this is the case then the room is behaving as if there is smaller room present with few or no diffusers present yet having the same measured reverberation time. When there is a large RT in a small room it essentially decreases the measured absorption and this is apparent in Figure 4.2. This can be confirmed if the 3 and 5 diffuser situations are compared again, but this time reducing the volume in the 3 diffusers situation to match the effective volume of each room. Reducing the volume from *223m^2FS* to *205m^2FS* shows convincing evidence that the 5 diffusers is effectively reducing the room's volume by ~10%. When the room with 3 diffusers has a reduced volume the absorption coefficients match the 5 diffuser situation better (Figure 4.3).

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are needed to see this picture.

Figure 4.3 Diffuser effect on Volume

4.2.2 Six Absorbers

Increasing the number of absorbers to *4%* of the total surface area will begin to represent a proper measurement of the absorption behavior in the reverberation chamber. The plot of the 6 absorbers is seen in Figure 4.4 and shows the coefficients increasing. The appearance of the decreased absorption with 5 diffusers is not seen when the number of absorbers has been increased. Instead the number of diffusers appears to produce the same amount of diffusion and is relatively similar. With each of the combinations of absorption there appears to be a larger amount of absorption present at the 200Hz frequency. The wavelength at 200Hz is similar no matter what amount of diffusion is present.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.4 Absorption Coefficients with 6 Absorbers (8.4m^{2}FS)

The values for the absorption coefficients:

Frequency	0 Diff.	3 Diff.	5 Diff.
100Hz FS	0.87	1.07	1.12
200Hz FS	1.04	0.98	0.97
400Hz FS	0.80	1.00	1.05
800Hz FS	0.93	1.21	1.16

Table 4.3 Absorption Coefficients for 6 Absorbers

Kuttruff ([2] Figure 2.7) presents insight as to why there is a similar value of absorption at this frequency due to the wavelength and any trapped air behind the absorbers. It was stated that the depth of the absorbers is approximately *0.5* meters and the wavelength at 200Hz is *1.71* meters. According to Kuttruff flow resistance is created when there is a layer of air behind an absorber (different pressures on each side of the foam).

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.5 Flow Resistance effects on Absorption Coefficient (Kuttruff Figure 2.7)

The ratio between the depth and wavelength is *0.3* and with the assumption that the flow resistance in the chamber is just above or just below $r_s=\rho_0 c$ then the absorption coefficient approaches *1.0* (Figure 4.5). The explanation of flow resistance does not provide significant proof for similar values of absorption coefficient since there is no similar trends in absorption at frequencies corresponding to other maximums found in Figure 4.5 meaning that the flow resistance is not a factor in this case on the behavior of the absorption coefficients.

4.2.3 Nine Absorbers

The amount of absorption is increased to the ISO-354 prescribed amount at *5.3%* of the total surface area of the chamber. This amount produces a lower calculated absorption than the situations where less absorption was present. With the chamber becoming very crowded the situational data for 5 diffusers was omitted.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.6 Absorption Coefficients with 9 Diffusers (12.4m^{2}FS)

The dramatic difference between the numbers of diffusers in Figure 4.6 introduces the problem of diffuse field absorption coefficients and non-diffuse field absorption. But this appears to be more of a difference than what would be attributed to a lack of diffusion in the chamber, and a more realistic explanation might come from possible errors in calculation or measurement.

Frequency	0 Diff.	3 Diff.
100Hz FS	0.91	0.92
200Hz FS	0.67	0.80
400Hz FS	0.52	0.98
800Hz FS	0.56	1.12

Table 4.4 Absorption Coefficients for 9 Absorbers

Another possible explanation could be found in Fitzroy's work where a large room with only one boundary covered in 3000ft^2 of absorption had a shorter reverberation time than a similar room with the 230% more absorption [17]. The big difference between the rooms for Fitzroy was how the absorption was distributed throughout the room. When this ideology is applied towards this chamber measurement then the 3 diffusers enabled a more distributed amount of energy around the chamber and could lead to more sound energy being incident upon the absorbers. Without the diffuse field the sound energy was not incident on the absorbers as much, which increased the reverberation time and decreased the absorption coefficient (Figure 4.7).

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.7 Reverberation Time and Standard Deviation

The measured reverberation times of the nine absorbers situations do present a lower reverberation time for Situation 17 that had diffusers present. Using Eyring to calculate the absorption coefficient reduces all the values seen in Figure 4.6 but the differences remain fairly constant (-0.2) across all frequencies (Figure 4.8).

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.8 Eyring Absorption Coefficient

Up to this point it seems that the values that are produced use of the diffuse fields are valid and are creating a difference between the chamber situations with and without the hanging diffusers. The largest differences can be explored now that the situational differences have been observed.

4.3 Relationship between Diffuse and Non-Diffuse Situations

An Schroeder Curve of the reverberation time can be used to see which situations have diffuse reflections and how it affects absorption. Viewing the 1kHz octave band in several of the situations to try and find any deviations from a consistent decay slope. The example echogram shown in Figure 1.5 is very similar to how an Schroeder Curve is constructed. As reflections around a room decay the amount of energy decays down to *-60dB* (reverberation time) and the slope of all of the points creates the curve.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.9 Schroeder Curve at 1000Hz

The curves all do appear to have different reverberation times, but each situation does contain different configurations of diffusers and absorbers so these curves are not valid to compare directly. But since each curve is taken at 1000Hz the curves that have similar times can be compared. In Figure 4.9 it appears that many of the situations have RT's of between 2.0 – 3.5 seconds. It should be noted that the two longest curves are empty of any absorption and the situation 16 curve (which has shown a low absorption coefficient) is also outside of the range. This basic observation is consistent with the reverberation time per octave band measurements. The curves in the noted range have different values of absorption and diffusers as well and it is appropriate that situation 17 does have the shortest time considering it has the most efficient amount of diffusion (3 diffusers) and nine absorbers (the highest amount tested). The amount of absorption in situations 3, 10, and 13 are all equal but situation 3 does not have any diffusers present where 10 and 13 have 3 and 5 diffusers respectively but have very similar RT's.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.10 Schroeder Curves with Same Amount of Absorption

The difference in time is approximately 0.8 seconds (between situations 3 and 10) and would prove troublesome where achieving an accurate reverberation time at a particular frequency was necessary. There were two source locations used as to make sure that diffusivity was consistent in the chamber and this reasoning shows similar absorption coefficients regardless of where the source is located. By using a different source location for the empty situations results in Figure 4.11.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.11 Different Source Locations Effect on Absorption

The slight change in absorption at *800Hz* for situation 3 is the biggest deviation (about 0.2) and appears to be an effect of the lack of diffusers since the same frequency with Situation 10 is nearly exact. This can rule out the source location causing significant changes to the decay of sound in a room and understand that the less diffuse situation is still relatively independent of source location. The differences in absorption relate directly to the measured reverberation time (Figure 4.12).

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.12 Reverberation Time and Standard Deviation

Looking at Figure 4.10 and noticing the difference in time at *-60dB* for these situations might give a clue as to what a theoretical (diffuse) decay curve and a non-diffuse decay curve would look like. Using the difference in time (~0.8 sec.) and applying it as a "diffusivity constant" to the pressure values can adjust the non-diffuse sound field to match the diffuse field decay rate (slope) along the entire band (Figure 4.13). An issue does appear with this simple method since there cannot be a definite way of knowing what a decay curve in a diffuse field will look like in an arbitrary room.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Figure 4.13 Adjusted Non-Diffuse Decay by Directivity Constant

This method would also require at least one measurement (an most likely more if many octave bands are important) which would require that a diffuse field attempt to be created instead of using time to measure a non-diffuse field and attempting a prediction on how the absorption in the room would be effected.

4.4 Discussion about Results

The experimental results have been able to achieve the same discrepancies in absorption coefficients using a scale model as would be found in a full size reverberation chamber. Adding hanging diffusers to the ceiling of the room in a random distribution was effective at increasing the energy distribution in the room until a certain amount of surface area was reached. When too many plane diffusers were used the absorption coefficient decreased across all frequencies because the mean free path of the sound rays in the room were reduced and caused the rooms volume to appear smaller.

Using different configurations of absorption in the chamber allowed for an accurate value of the absorption coefficient. With the configurations of 4, 6, and 9 absorbers the value of absorption for Sabine is *0.80* and for Eyring *0.77* with error being *+/-0.08* and *+/-0.07* respectively. This amount of absorption used in the chamber was valid for the experiment according to ISO-354. The best results were achieved using absorption area of less than *5%* of the total surface area as it was consistent with absorption area greater than *5%* and therefore is considered valid. Situations 3 and 10 were directly compared by Schroeder decay curves Figure 4.10, absorption coefficient Figure 4.11 and reverberation time Figure 4.12 and the comparison showed discrepancies in all three categories that were created. Adjustments to the Schroeder decay and the absorption coefficient was attempted as a mathematical approach to solving any differences between prediction and measurement. The adjustments could be used to make proper predictions, but the data required to make the predictions required measurements and therefore are considered inefficient.

Understanding the cause of the absorption coefficients reduction in non-diffuse fields cannot be strictly confined to the reasoning that it is because of too many diffusers in the room. But the appearance of a smaller room volume does bring up a point that this might be why some rooms are more difficult to predict reverberation time. It is difficult to predict a room that contains a mix of high absorptive and low absorptive objects and the diffraction effects around low absorptive objects reduce the need for any additional diffuse treatment. The use of other reverberation time formulas may prove to be more affective than others but if the absorption coefficients of a room are unknown to begin with then prediction still relies heavily on the equations of Sabine.

This research into discrepancies of absorption coefficients in diffuse and non-diffuse sound fields has achieved the same problems that have been noted in the referenced research but no general solution has been achieved, although solutions to arbitrary rooms can be found on a case-by-case scenario.

Conclusion and Further Works

Research in diffuse sound fields has often found a problem when using absorption coefficients from a diffuse field, in a non-diffuse field. The experiment undertaken for this paper has produced the same inconsistency in absorption coefficients regardless of the presence of a diffuse field. Some of the fundamental theories of room acoustics were applied such as: reverberation time, absorption coefficients, and diffusivity towards a reverberation chamber of $1/10^{th}$ scale to easily change the configuration of the chambers absorption and diffuseness. Measurements taken in the chamber produced proper results and up scaling the values to full size gave valid results as well as the observation of modern room acoustics problems (i.e. Sabine Absorption Coefficient exceeding unity). Exploration of several reverberation time equations were done to understand why Sabine and Eyring's equations are still the most widely used equations where most of the other equations discussed were modifications to Sabine or Eyring rather than a totally new approach. The best situation results of the scale chamber experiment should be attempted at full scale to check the accuracy of a wider bandwidth of frequency. Since the chamber required that the frequencies be scaled down there could not be an exploration to higher than 10kHz due to concerns of atmospheric effects interfering.

The largest factor in this experiment was the ability to create a diffuse field. This particular factor creates interest in further research in understanding how important diffuse fields are and if there was a possible way to create a diffusivity factor into absorption and reverberation time equations. A diffusivity factor could help increase prediction accuracy in non-diffuse rooms instead of assuming perfect diffuseness in rooms and having to deal with measurements that do not agree with theory. Further works in research of absorption coefficients will likely improve with further computer simulation regarding image sources and ray tracing methods.

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Appendix A

A.1 Situation Data

Situation	Absorption	Diffusers	Source Loc.	Notes
1	0	0	1	Empty
2	4	0	1	
3	6	0	1	
4	0	0	2	Empty
5	0	3	2	Empty
6	0	3	1	Empty
7	4	3	1	
8	**6**	**3**	**1**	**OMITTED**
9	4	3	2	
10	6	3	2	
11	6	5	1	
12	4	5	1	
13	6	5	2	
14	4	5	2	
15	0	5	2	Empty
16	9	0	2	
17	9	3	2	
18	**9**	**5**	**2**	**OMITTED**

Empty=No Absorption Present

A.2 Situation Absorption Coefficients

Figure 4.2 Absorption Coefficients with 4 Absorbers (5.6m^{2}FS) (Averages)

Empty Situation	Absorber Situation	Sabine (250Hz – 8kHz)	Eyring (250Hz – 8kHz)	Sabine (63Hz – 10kHz)	Eyring (63Hz – 10kHz)	Diffusers
1	2	0.82	0.79	0.78	0.76	0
5	9	0.94	0.90	0.89	0.86	3
15	14	0.90	0.86	1.08	1.03	5

Figure 4.4 Absorption Coefficient with 6 Absorbers (8.4m^2 FS) (Averages)

Empty Situation	Absorber Situation	Sabine (250Hz – 8kHz)	Eyring (250Hz – 8kHz)	Sabine (63Hz – 10kHz)	Eyring (63Hz – 10kHz)	Diffusers
1	3	0.73	0.70	0.73	0.69	0
5	10	0.85	0.82	0.86	0.82	3
15	13	0.86	0.82	0.90	0.86	5

Figure 4.6 Absorption Coefficients with 9 Diffusers (12.4m^{2}FS) (Averages)

Empty Situation	Absorber Situation	Sabine (250Hz – 8kHz)	Eyring (250Hz – 8kHz)	Sabine (63Hz – 10kHz)	Eyring (63Hz – 10kHz)	Diffusers
4	16	0.38	0.37	0.53	0.51	0
5	17	0.78	0.74	0.76	0.72	3

Appendix B

B.1 MATLAB Absorption Coefficient Calculation

```
clear all;

%%%%%%%%%%%%%%%%%
%Room Dimensions%
%%%%%%%%%%%%%%%%%
    %Speed of sound m/sec
    c=343;
    %Far/Near Length
    X_near=7.23;    %Near Wall Length
    X_far=5.94;     %Far Wall Length
    X_avg=(X_near+X_far)/2;
    %Side Wall Length
    Y_left=7.45;
    Y_right=sqrt((X_near-X_far)^2+Y_left^2);
    Y_avg=(Y_left+Y_right)/2;
    %Height
    Z=4.56;

%%%%%%%%%%%%%%
%Surface Area%
%%%%%%%%%%%%%%
    SA_top=(X_far*Y_left+(((X_near-X_far)*Y_left)/2));
    SA_right=Y_right*Z;
    SA_left=Y_left*Z;
    SA_near=X_near*Z;
    SA_far=X_far*Z;
    SA_total=2*SA_top+SA_right+SA_left+SA_near+SA_far;
    V=SA_top*Z;     %Volume of the room
    No_Points=9;    %Number of frequency Octaves

%%%%%%%%%%%%%%%%%%%%%
%Situation Variables
%%%%%%%%%%%%%%%%%%%%%
    sit1=10;    %Absorption Situation (For Single Digits do not add a 0)
    sit2=6;    %Empty Situation (For Single Digits do not add a 0)
    Absorbers=6;
    Abs_SA=1.4*Absorbers;      %Surface area of Absorption
%%%%%%%%%%%%%%%%%%%%%%
%Absorption Data Files
%%%%%%%%%%%%%%%%%%%%%%
    dataFile1=[...
    'sit',num2str(sit1,'%2d'),'RT_pos0.txt';...
    'sit',num2str(sit1,'%2d'),'RT_pos1.txt';...
    'sit',num2str(sit1,'%2d'),'RT_pos2.txt';...
    'sit',num2str(sit1,'%2d'),'RT_pos3.txt';...
    'sit',num2str(sit1,'%2d'),'RT_pos4.txt'];

%%%%%%%%%%%%%%%%%%%%%%
%Empty Room Data Files
%%%%%%%%%%%%%%%%%%%%%%
    dataFile2=[...
    'sit',num2str(sit2,'%2d'),'RT_pos0.txt';...
    'sit',num2str(sit2,'%2d'),'RT_pos1.txt';...
    'sit',num2str(sit2,'%2d'),'RT_pos2.txt';...
    'sit',num2str(sit2,'%2d'),'RT_pos3.txt';...
    'sit',num2str(sit2,'%2d'),'RT_pos4.txt'];

%%%%%%%%%%%%%%%%%%%%%%%%%%
%Input of Absorption Data%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%
    datafileSize=size(dataFile1);
    Data_count=datafileSize(1);
    for j=1:Data_count                  %File Input Loop
        test=fopen(dataFile1(j,:));     %Select DataFiles
        dataSet1=[];                    %Initiate DataSet Matrix
            for i=1:No_Points           %Data Collection Loop
                giver=fgetl(test);
                [f,Rtime]=strtok(giver);
                f = str2double(f);
                Rtime = str2double(Rtime);
                dataSet1=[dataSet1; f Rtime];
                time_avg(i,j)=dataSet1(i,2);
            end
    end
    for m=1:No_Points                   %Points Averaging Loop
        Aa(m,1)=mean(10.*time_avg(m,:));
    end

%%%%%%%%%%%%%%%%%%%%%
%Input of Empty Data%
%%%%%%%%%%%%%%%%%%%%%
    for j=1:Data_count                  %File Input Loop
        test=fopen(dataFile2(j,:));     %Select DataFiles
        dataSet1=[];                    %Initiate DataSet Matrix
            for i=1:No_Points           %Data Collection Loop
                giver=fgetl(test);
                [f,Rtime]=strtok(giver);
                f = str2double(f);
                Rtime = str2double(Rtime);
                dataSet1=[dataSet1; f Rtime];
                time_avg(i,j)=dataSet1(i,2);
            end
    end
for m=1:No_Points                   %Points Averaging Loop
    Ae(m,1)=mean(10.*time_avg(m,:));
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculate Alpha Bar and Equivalent Sound Absorption%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Sabine Absorption%
    Equiv=[sit2 sit1;55.3.*V./(c.*Ae) 55.3.*V./(c.*Aa)];
    Abs_Sabine=(0.161*V).*(1./Aa-1./Ae)/Abs_SA;

%Eyring Absorption%
    We=exp(-0.161*V./(SA_total.*Ae));
    Wa=exp(-0.161*V./(SA_total.*Aa));
    Abs_Eyring=SA_total/Abs_SA.*(We-Wa);
    Abs_Average=(Abs_Sabine+Abs_Eyring)./2;

%Averaging of Absorption over Full Octave Bands
    Abs_avgF1=mean(Abs_Sabine(:,1));
    Abs_avgF2=mean(Abs_Eyring(:,1));

%Averaging of Absorption over Partial Octave Band
%Average Absorption Coefficients
    holder1=0; holder2=holder1;             %Initialize Counters
    n2=5;
    n3=8;                 %Part Octave Limits
    for n=n2:n3
        Abs_avg1=holder1+Abs_Sabine(n,1);   %Sabine Loop
```

```
        Abs_avg2=holder2+Abs_Eyring(n,1);   %Eyring Loop
        holder1=Abs_avg1;                   %Sabine Counter
        holder2=Abs_avg2;                   %Eyring Counter
    end
    Abs_avg1=Abs_avg1/(No_Points-(n2-1));   %Sabine Average
    Abs_avg2=Abs_avg2/(No_Points-(n2-1));   %Eyring Average

%Absorption Coefficient Plots
RTequation=[Abs_Sabine];% Abs_Eyring];% Abs_Average];
AbsorbPlot=size(RTequation);
AbsorbColor=['y' 'b' 'g'];
figure(2)
for u=1:AbsorbPlot(2)
    plot(dataSet1(:,1)./10,RTequation(:,u),AbsorbColor(u))
    hold on
end

title({['Absorption Coefficient: Situation (Empty : Absorb)
',num2str(sit2),' : '...
    ,num2str(sit1)];['Part Octaves -- (Sab) Avg.= ',num2str(Abs_avg1),' :
(Eyr) Avg.= '...
    ,num2str(Abs_avg2)];['Full Octaves -- (Sab) Avg.=
',num2str(Abs_avgF1),' : (Eyr) Avg.= '...
    ,num2str(Abs_avgF2)]},'fontsize',12)

xlabel('Frequency (Hz)','fontsize',12)
ylabel('Absorption \alpha','fontsize',16)
xlim([25 1000])
ylim([0 1.5])
```

B.2 MATLAB Reverberation Time Import from WinMLS

```
function sit01_ReverbTimeImport()

clear all

No_Points=9;        %Length of File Max:32746

%Data Files to Open
%%%%%%%%%%%%%%%%%%
dataFile=[...
'sit1RT_pos0.txt';'sit1RT_pos1.txt';'sit1RT_pos2.txt';'sit1RT_pos3.txt';'
sit1RT_pos4.txt'];

Acolor=['r' 'm' 'b' 'k' '--g' 'y' 'm' 'k' 'g' 'k'];
datafileSize=size(dataFile);
Data_count=datafileSize(1);
time_avg=zeros(No_Points,Data_count);
time_mat=[];

for j=1:Data_count
    test=fopen(dataFile(j,:));
    dataSet1=[];
        for i=1:No_Points
            giver=fgetl(test);
            [f,Rtime]=strtok(giver);
            f = str2double(f);
            Rtime = str2double(Rtime);
            dataSet1=[dataSet1; f Rtime];
            time_avg(i,j)=dataSet1(i,2);
        end

%     figure(2)
%     semilogx(dataSet1(:,1),dataSet1(:,2),Acolor(j))
%     hold on
%     grid on
end

%Calculate Mean Frequency Values for Each Data Plot
for m=1:No_Points
    time_mat(m,1)=mean(10.*time_avg(m,:));
end
%Standard Deviation Calculations
Std=sqrt((2.42+3.59./Data_count)./(dataSet1(:,1).*time_mat(:,1)));

%Mean Reverb Time Plot
figure(2)
semilogx(dataSet1(:,1),time_mat(:,1),'r','linewidth',3)
hold on
grid on

%Standard Deviation Plots
figure(1)
semilogx(dataSet1(:,1),Std,'r','linewidth',3)
hold on
grid on

end
```