Does the type of Diffuser matter?

Author: William Fehlhaber
Co-supervisor: Prof. I. Drumm
Supervisor: Prof. T. Cox

@00271181
School Computing, Science, and Engineering
College of Science and Technology
University of Salford, Salford, UK

Submitted in partial fulfilment of the Requirements of the Degree of Master of Science by Research, 2015

Abstract

A study was conducted to see how different diffuser designs affected the acoustic characteristics of a small room. This research tests a number of different geometries including a flat panel, convex poly-cylinder set, concave poly-cylinder set, triangular set, broad curve geometry and a quadratic residue sequence. This research employs a Finite Difference Time Domain model as well as scale model measurements in order to quantify the effects of these diffusers at a given receiver position. Simulations include a free field environment, in order to observe diffraction behaviour in the time domain, and a studio configuration in order to observe a more complicated scenario with a specific receiver position. The results of this research offer a few key findings. Firstly, there is a design compromise between how effectively a diffuser can scatter sound temporally and how well that same diffuser can offer similar behaviour over all angles of incidence. These are design limitations and compromises that warrant consideration when designing a diffuser geometry for a specific application. Secondly, a diffuser is most effective when the wave interacts along the appropriate design axis. The design axis is the direction in which the geometry is distorted. Thirdly, the type of diffuser can make a difference but, the appropriate diffusing geometry must be chosen in context of its proposed task. Otherwise, the diffuser geometry will not likely yield a difference beyond 3 dB in a given 3rd octave band. The end conclusion is that differences between diffusers for a given configuration are measurable but do not consistently yield variation in a 1/3rd octave band spectrum above a given threshold of 3 dB SPL and do not point to consistently possible audible changes (in the context of the room used).

Contents

List of Figures

Acknowledgements

I would like to thank Trevor Cox and Ian Drumm for their assistance over the course of this project. Their knowledge and guidance has helped me gain a better understanding of acoustics and its applications.

Introduction

The manipulation of reflections in order to change perceptual acoustic characteristics, is a central topic in room acoustics. Diffusers are commonly employed in order to control reflections, reduce colouration and minimize the intensity of echoes. In concert hall acoustics, they may be used for envelopment purposes, while in a studio, they may be used to reduce image shift for accurate monitoring and reproduction. While what diffusers "do" is well defined by a collection and consensus of experimental data and practical application, there are still many topics in active discussion. What diffuser designs are right for a specific task? Do some diffusers sound better than others?

The main goal of this research is to explore the effect of diffusers in the context of small rooms using the Finite Difference Time Domain method and a scale model. The numerical method allows for the observation of wave propagation in a given environment. Data can be collected for further manipulation from either the whole field or at specific points.

The use of simulation of acoustic environments in order to accurately predict performance is of key importance to civil planners, architects, acoustic consultancies and design firms. Simulation can help to solve problems in existing spaces by allowing users to recreate an environment and find solutions to a problem in a cost effective manner. This is especially important in critical listening environments such as studios and concert halls where the cost of trial and error is too high.

The ultimate question is: Does the type of diffuser matter? This report hopes to answer the question by simulating certain diffuser geometries in a given studio configuration. Questions that will arise include:

1. What determines if a specific diffuser is more effective than another?
2. Are there any design compromises or limitations that must be considered?
3. Does orientation matter?

This report is divided into separate sections that will guide the reader through the relevant fundamental concepts of acoustics in order to understand how these are applied and simulated. Chapter 1 outlines fundamental concepts of acoustics such as wave propagation and includes a derivation of the wave equation. Chapter 2 continues on to discuss different numerical modelling methods and why Finite Difference Time Domain was chosen for this research. The chapter also shows how the derivation from the previous chapter is changed to finite difference form. Chapter 3 outlines basic principles of room acoustics and the various sources of room colouration. The chapter then extends to a discussion of studio design and what was chosen for this project. Chapter 4 outlines the principles of diffuser design and which geometries were tested in this research. Chapter 5 gives a description of the experiments conducted and Chapter 6 illustrates the data and includes analyses of the resulting data. Chapter 7 is the conclusion and gives a summation of the results and some implications. This report does not include a dedicated literature review as the relevant subjects occupy a broad number of concepts. Therefore, each section will have a self contained literature review in order to decrease confusion and encapsulate the appropriate ideas.

Chapter 1

Basic Acoustics

There are a variety of texts that outline the relevant topics for this project however, the relevant physics to create the appropriate simulation is narrow in scope and non-debatable. Therefore, the review of the necessary literature for this section is brief.

Heinrich Kuttruff's academic text "Room Acoustics" [Kuttruff, 2009] offers thorough introductions to the immediately useful concepts of wave propagation. The first chapter discusses the wave equation and the physics behind wave propagation.

The Stanford Exploration Project [Sepstanford.edu, 2000] hosts a web page that outlines the derivation of the acoustic wave equation. This is the derivation used in this section as it is the most thoroughly explained derivation. Suzanne Fielding offers a full lecture listed as "The basic equations of fluid dynamics" [Fielding, 2007] which demonstrates the meaning of continuity of mass in fluid dynamics which is essential when deriving the wave equation.

1.1 Wave Equation

When a sound wave propagates through a medium, the particles of the medium, such as air, undergo vibrations about their mean positions in space. This travelling wave changes the localised density of molecules that make up that medium. The areas where molecules are more compressed are known as compressions and the areas where molecules are less dense are known as rarefactions. Once the wave has passed, the displaced particles move back to their original positions. Consequently, the variations of both pressure and velocity occur as functions of both time and space, the expression of which is known as the wave equation.[Burg et al.] [Kuttruff, 2009] [Everest and Pohlmann, 2009]

Newton's law of momentum conservation dictates that a small volume within a gas with mass, m, will undergo acceleration, a, if there is an applied force, F.

$$F = ma \tag{1.1}$$

The force arises from pressure differences, P, at opposite sides of the small volume as the wave propagates through the medium. The acceleration is the change in velocity, $\vec{u}$, over a period of time which means we can express the Newtonian Law as:

$$\frac{\partial P}{\partial x} = -\rho \frac{\partial u_x}{\partial t} \tag{1.2}$$

The second physical process is the conservation of mass which is expressed as Cox and D'Antonio [2009] Fielding [2007]:

$$\frac{\partial P}{\partial t} = -K \frac{\partial u_x}{\partial x} \tag{1.3}$$

-or-

$$\frac{\partial u_x}{\partial x} = \frac{1}{-K} \frac{\partial P}{\partial t} \tag{1.4}$$

This equation means that the change in pressure, P, is in proportion to a property of the medium called incompressibility K. $\vec{u}$ is the particle velocity and the subscript denotes the dimension.c is the speed of sound in the medium and, ρ, is the density of the medium.

$$K = \rho c^2 \tag{1.5}$$

The following set of equations will derive the wave equation from equations 1.2 and 1.3. The first step is to apply the spatial derivative, $\frac{\partial}{\partial x}$, to the conservation of momentum, equations 1.2. This yields:

$$\frac{\partial^2 P}{\partial x^2} = -\rho \frac{\partial^2 u_x}{\partial t \partial x} \tag{1.6}$$

The second step is to apply the temporal derivative, $\frac{\partial}{\partial t}$, to the conservation of mass, equations 1.3. This yields:

$$\frac{\partial^2 P}{\partial t^2} = -K \frac{\partial^2 u_x}{\partial t \partial x} \tag{1.7}$$

Substituting equation 1.6 into 1.7 yields:

$$\frac{\partial^2 P}{\partial t^2} = K \frac{1}{\rho} \frac{\partial}{\partial x} \frac{\partial P}{\partial x} \tag{1.8}$$

Which is the wave equation:

$$\frac{\partial^2 P}{\partial t^2} = c^2 \frac{\partial^2 P}{\partial x^2} \tag{1.9}$$

In order for this form of the wave equation to be true, then a few assumptions must be made. These include but are not limited to:

1. The fluid is static and Newtonian.

2. The fluid is irrotational.
3. There are no viscous forces.
4. The disturbance from the wave propagation is small.
5. The medium is homogeneous.

These are reasonable assumptions to make for the purposes of this project and these equations will form the foundations of the Finite Difference Time Domain simulations.

Chapter 2

Finite Difference Time Domain

Finite Difference Time Domain (FDTD) is a numerical technique that was proposed by Kane Yee in 1966 [Yee, 1966]. It offers a procedure for discretising the differential form of the wave equation as given in the previous chapter. This chapter begins with the formulation of the wave equation for two dimensions and explains the general method of how this equation will be applied for simulation. The chapter then proceeds to transform the wave equation into finite difference form. The chapter then continues to explain the advantages and disadvantages of FDTD as compared to other numerical techniques. There are key ideas to understanding Finite Difference Time Domain for use in acoustics.

Firstly, it is best to begin with an understanding of how FDTD is formulated. Compact FDTD methods tend to be distinguished by their method of spatial discretisation. Spatial discretisation is important because it allows the finite difference form of the equation to be solved. The method of meshing is also important because it can help describe the boundaries of a volume more accurately while offering more points to represent a wave front. A simplification of the effect of doing so is that the method of spatial discretisation determines the relative phase velocity of the medium for wave propagation along the axis of those degrees of freedom [Kowalczyk and Van Walstijn, 2010]. Relative phase velocity is an important consideration because it determines how fast a wave will travel at a given frequency in that medium. To be clear, this is an error, and the change in relative phase velocity is greatest along the axis of those degrees of freedom. There are methods and algorithms proposed that can help nullify the effects of this at added computational cost and time. The resulting dispersion error of this change in phase velocity can be redistributed as more degrees of freedom are added. [Kowalczyk, 2008].

The standard leapfrog (as proposed by Kane Yee [Yee, 1966]), an octahedral, a cubic close-packed and an interpolated method are only a few methods amongst many that have been investigated by Konrad Kowalczyk [Kowalczyk, 2008]. The standard leapfrog method is the fastest to compute and simplest to formulate and implement but is the least accurate for describing complex geometry. Due to its simplicity and widely documented formulation, it is the method chosen for this simulation.

However, it is not enough to consider solely which formulation would be used. While it is the most important starting point, it is also important to consider the method of computation. John B. Schneider's academic text [Schneider, 2013] is focused towards electro-magnetic wave simulation however, Chapter 12 is dedicated to acoustics and simulating acoustic wave propagation. This text offers insight to making a simulation scalable as well as improving code in order to make it distributable for parallel computation. There is nothing to debate in this text as it is not focused on the exploration of certain utilizations of FDTD. The main value lies in the procedures and methods offered for creating a simulation that runs efficiently. Schneider's paper details the technical aspects for writing a FDTD simulation including how to quantify error, the max usable frequency of a simulation and how to troubleshoot common stability issues [Schneider, 2013].

As this paper investigates the acoustic behaviour of small rooms, it is important to account for different boundary conditions. Reflections from boundaries of an acoustic space play a pivotal role in room acoustics, however different materials and wall constructions yield different reflection behaviours. Real boundaries yield frequency-dependant conditions and therefore the formulation for that given material should include a frequency-dependent, complex wall impedance [Kowalczyk, 2008].

A common practice for simulating the effects of real materials is through the use of FIR filter networks [Botteldooren, 1995] [Huopaniemi et al., 1997]. A secondary method is through the use of convolution. Both of these methods can increase computation time dramatically. Convolution is a computationally demanding method to implement. There is also the issue that there is a difficulty of validation as full bandwidth data of a boundary's impedance or a material's absorptive properties are rarely available as well as time consuming to produce [Jeong, 2010]. The other problem with the practical implementation of a convolution algorithm is that not all convolution algorithms are capable of being distributed on a GPU for computing. However, this is only an issue if you plan to port your program to other systems that may not have a GPU.

These considerations lead to another set of questions: How can one decide which materials to simulate (and provide a valid mathematical formulation) for a given experiment? Will the use of modelled boundaries offer any greater insight into the behaviours of diffusers, the resulting reflections or their implementation in a given small room? The next paragraph aims to guide why modelled boundaries were not used.

Firstly, the computational requirements to do this, were beyond the capability of the available computer and the simulation of surfaces seemed secondary to the desire to have an accurate

3D model (which was beyond the capability of the available computer). Lastly, the modelling of boundaries is unlikely to effect the utility of the general information from the simulations. One can still gain directivity information as well temporal and frequency information for any given point on the grid. However, one cannot just assume rigid boundaries. Therefore, a Perfectly Matched Layer (PML) is implemented for anechoic conditions and surface admittance is a purely real value that is adjusted to simulate non-rigid boundaries.

In summary, while none of these research papers discuss simulating diffusers or the results of diffusers, these papers do outline the considerations and decisions required in order to plan a FDTD simulation. Firstly, all of the following FDTD simulations used in this experiment are two dimensional, meaning only one plane of propagation is observed. The chief reason is that the computational capability of the available computer was limited. It did not have enough RAM to run a three dimensional simulation to the required resolution. Therefore, the diffusers were designed to reflect along a single plane and only required one plane of analysis. Secondly, the original two degree of freedom algorithm, as proposed by Kane Yee, was chosen as it is most widely available for retesting. Thirdly, all simulations were run at a resolution at 400 nodes per metre in order to simulate to a high frequency and create negligible dispersion error and minimize geometry discretisation errors. Lastly, no specific surfaces were modelled for the boundaries. However, anechoic conditions are simulated using a Perfectly Matched Layer (PML) and surface admittance is adjusted to simulate non-rigid boundaries. Both of these conditions may be non-physical but, they do not interfere with the ability to analyse diffuser behaviour.

2.1 Expansion to Two Dimensions

In Finite Difference Time Domain, a field is discretised into a finite number of coordinate points to form a grid with a finite step size between each point. The most fundamental form of FDTD, uses a grid for the pressure field P , which is offset both spatially and temporally from a field for particle velocity $\vec{u}$. When space and time are discretised into this field, future field values can be solved for in terms of known past field values. Figure 2.1 illustrates the basic concept [Cox, 2004] [Schneider, 2013].

In the figure, i is an index for the x direction and j is an index for the y direction. In order for this method to work, the step sizes Δx and Δy must be equal. u_x and u_y are the velocities for the x and y axes.

The previous equation 1.9 only describes one dimension of propagation. Even though acoustic phenomena is experienced in three dimensional space, this section will only expand the wave equation to two dimensions because that is what was used for this project.

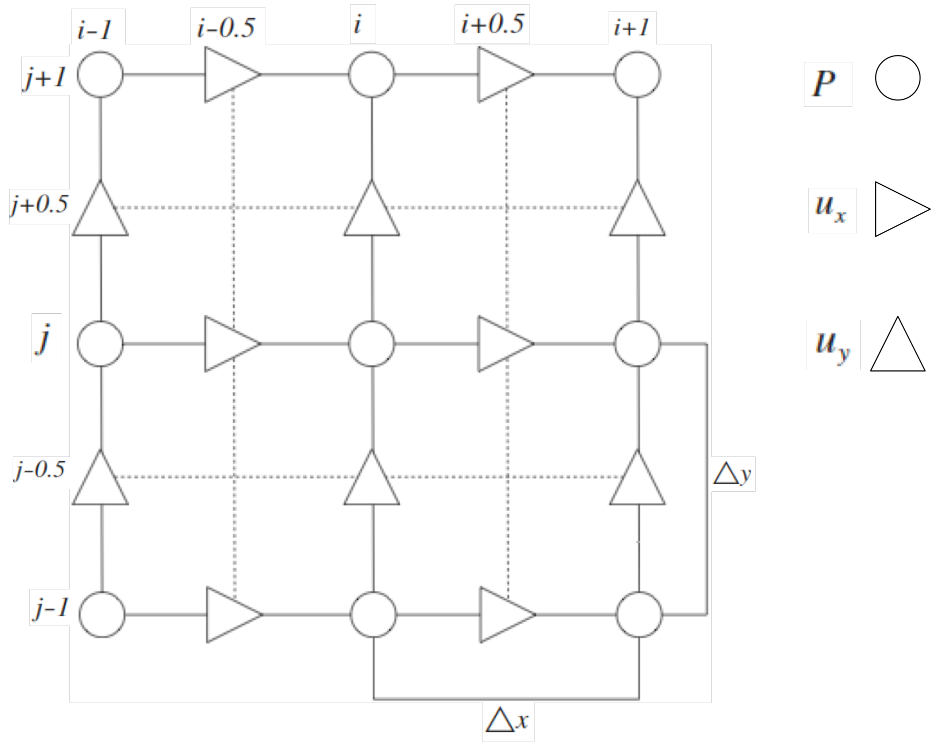

Figure 2.1: FDTD Diagram (from Cox [2004] and [Schneider, 2013])

Newtons Law in Equation 1.2 can be described for two dimensions as:

$$-\frac{\partial P}{\partial x} = \rho \frac{\partial u_x}{\partial t} \tag{2.1}$$

$$-\frac{\partial P}{\partial y} = \rho \frac{\partial u_y}{\partial t} \tag{2.2}$$

The conservation of mass in Equation 1.3 can be described for two dimensions as:

$$\frac{\partial P}{\partial t} = -K \left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} \right) \tag{2.3}$$

Therefore, the two dimensional wave equation is:

$$\frac{\partial^2 P}{\partial t^2} = c^2 \left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} \right) \tag{2.4}$$

2.2 Wave Equation in Finite Difference Form

As stated earlier, the sound pressure P and particle velocity $\vec{u}$ make up the grid in Figure 2.1. Both P and $\vec{u}$ are functions of time and position and therefore the equations used to represent this must include:

$$P_{i,j}^{n+\frac{1}{2}} = P\left(i\Delta x, j\Delta y, \left(n + \frac{1}{2}\right)\Delta t\right) \tag{2.5}$$

$$u^n_{x_{i,j}} = u_x\left(\left(i+\frac{1}{2}\right)\Delta x, j\Delta y, n\Delta t\right) \tag{2.6}$$

$$u^n_{y_{i,j}} = u_y\left(i\Delta x, \left(j+\frac{1}{2}\right)\Delta y, n\Delta t\right) \tag{2.7}$$

The variables Δx and Δy represent the spatial step size for the x and y while i and j represent the appropriate indexes. Δt is the temporal time step and n is the respective index. The update equations come in the form of [Cox, 2004] [Sepstanford.edu, 2000]:

$$P^{n+\frac{1}{2}}_{i,j} = P^{n-\frac{1}{2}}_{i,j} - K\Delta t\left(\frac{u_{x_{i+\frac{1}{2},j}} - u_{x_{i-\frac{1}{2},j}}}{\Delta x} + \frac{u_{x_{i+\frac{1}{2},j}} - u_{x_{i-\frac{1}{2},j}}}{\Delta y}\right) \tag{2.8}$$

$$u^{n+1}_{x_{i+\frac{1}{2},j}} = u^n_{x_{i+\frac{1}{2},j}} - \frac{\Delta t}{\rho}\left(\frac{P^{n+\frac{1}{2}}_{i+1,j} - P^{n+\frac{1}{2}}_{i,j}}{\Delta x}\right) \tag{2.9}$$

$$u^{n+1}_{y_{i,j+\frac{1}{2}}} = u^n_{y_{i,j+\frac{1}{2}}} - \frac{\Delta t}{\rho}\left(\frac{P^{n+\frac{1}{2}}_{i,j+1} - P^{n+\frac{1}{2}}_{i,j}}{\Delta y})\right) \tag{2.10}$$

The temporal step size, Δt:

$$\Delta t = \frac{\frac{s}{c}}{\sqrt{(\frac{1}{\Delta x})^2 + (\frac{1}{\Delta y})^2}} \tag{2.11}$$

s is the Courant Number and is given in the following equation. It is a necessary number for solving Finite Difference equations as it defines the relationship between temporal step size and spatial step size [Schneider, 2013]. If a wave is propagating across a discretised field, its amplitude needs to be computed at discrete time steps of equal duration and this duration must be less than the time for the wave to travel to adjacent grid points. For this two dimensional case, s must satisfy:

$$s \leq \frac{c\Delta t}{\Delta x} + \frac{c\Delta t}{\Delta y} \tag{2.12}$$

This expands out as more degrees of freedom are computed.

In a discrete simulation, the smallest possible wavelength must have at least 2 samples per period. However, the number of samples necessary to describe a single wavelength with reduced error is actually closer to 10 nodes per wavelength [Schneider, 2013] and there is a direct connection with the spectral resolution of the analysed signal. Therefore, the maximum frequency f_c is given as:

$$f_c = \frac{1}{10\Delta t} \tag{2.13}$$

2.3 Non Rigid Boundaries

A default FDTD model has rigid terminations which means that any acoustic simulation would have an infinite reverberation time. This is not useful for simulating believable rooms and therefore, the boundaries of a room should be able to reflect sound and simulate the loss of energy whether that is by transmission or absorption.

This can be accomplished by implementing the following set of variables at the terminations of the grid. B is the normalized surface admittance and is a real value. [Cox and D'Antonio, 2009] [Kuttruff, 2009]
Z is the surface impedance.

$$Z = \frac{\rho c}{B} \tag{2.14}$$

R is the reflection coefficient. The reflection coefficient is usually a complex value because there are changes in the amplitude and phase of the components of the wave. However, the values used in this experiment are real values for the sake of simplicity. [Everest and Pohlmann, 2009] [Kowalczyk, 2008]

$$R = \frac{(Z - (c\rho))}{(Z + (c\rho))} \tag{2.15}$$

α is the absorption coefficient.

$$\alpha = 1 - (\mid R \mid)^2 \tag{2.16}$$

These equations change for sound at oblique incidence. However, using this simplified approach does not affect the utility of the information about the behaviour of diffusers, which is the purpose of this project. Furthermore, there is no reason why the diffusers themselves cannot be considered absolutely rigid during the simulations.

2.4 Anechoic Terminations

For free field simulations there are a number of methods that can be used to implement anechoic conditions. Firstly, the variable α from the previous section can be changed to a value close to 1. This will give near anechoic conditions. However, a more common method is to implement a Perfectly Matched Layer (PML).

A PML is a method of implementing absorption gradually into a section of the grid in order to match the impedance of the medium with an absorbing boundary. x_{PML} is the width of the PML in nodes and equals 10 nodes. This value should be sufficient. x_i is the index for the PML.

Absorption for each node is introduced such that:

$$\alpha_i = \alpha \frac{x_i}{x_{PML}}^{2} \tag{2.17}$$

The maximum absorption for 1/10 of the PML is:

$$\alpha = \frac{1}{K\delta t} \ln(10) \tag{2.18}$$

The update equations in 2D for the PML area are:

$$P_{i,j}^{n+\frac{1}{2}} = P_{i,j}^{n-\frac{1}{2}} e^{-K\alpha\delta t} - \frac{1-e^{-K\alpha\delta t}}{K\alpha} K \left(\frac{u_{x_{i+\frac{1}{2},j}} - u_{x_{i-\frac{1}{2},j}}}{\Delta x} + \frac{u_{x_{i+\frac{1}{2},j}} - u_{x_{i-\frac{1}{2},j}}}{\Delta y} \right) \tag{2.19}$$

$$u_{x_{i+\frac{1}{2},j}}^{n+1} = u_{x_{i+\frac{1}{2},j}}^{n} e^{-K\alpha\delta t} - \frac{1-e^{-K\alpha\delta t}}{K\alpha} \left(\frac{P_{i+1,j}^{n+\frac{1}{2}} - P_{i,j}^{n+\frac{1}{2}}}{\rho \Delta x} \right) \tag{2.20}$$

$$u_{y_{i+\frac{1}{2},j}}^{n+1} = u_{y_{i+\frac{1}{2},j}}^{n} e^{-K\alpha\delta t} - \frac{1-e^{-K\alpha\delta t}}{K\alpha} \left(\frac{P_{i+1,j}^{n+\frac{1}{2}} - P_{i,j}^{n+\frac{1}{2}}}{\rho \Delta y} \right) \tag{2.21}$$

There are only 3 update equations. There should be at least 2 per boundary (one for pressure and one for the particle velocity along the relevant axis). However, this is really an issue of indexing and is up to the individual program but, the update equations are similar.

2.5 Pros and Cons of Finite Difference Time Domain

In acoustics, the Finite Difference Time Domain method is primarily used to model wave propagation in acoustic environments. As a mesh structure, interference and diffraction are inherently modelled [Kowalczyk, 2008]. As a time domain technique, FDTD can be used to analyse a single frequency or a broad bandwidth with a single simulation. For example, if a pulse is used as a source function, then the response of the system over a wide bandwidth can be obtained through the use of a single simulation [Schneider, 2013]. This is useful when attempting to acquire the impulse response of a room for auralisation purposes while accounting for the dispersion characteristics of rooms or objects with complex geometries or material properties. Another powerful feature of FDTD is that it can be used to simulate time variant systems such as structures that change in shape, as well as changing source or receiver positions. Lastly, solving for higher-order reflections does not increase the memory load for a given simulation time and resolution. Regardless, there are a variety of drawbacks with FDTD.

In the real world, sound wave propagation in air is constant for all frequencies in all directions of propagation and a particle of air does not have a limited number of degrees of freedom.

When the field is discretised, the phase velocity of the wave differs from the phase velocity of the modelled medium [Kowalczyk and Van Walstijn, 2010]. This causes high frequencies to travel at different speeds than lower frequencies. This is known as dispersion error and is not only frequency dependant but also directionally dependant. The original staggered grid method mentioned above is the original method proposed by Yee and is the method used in this simulation. However, it yields only first order accuracy and exhibits its strongest dispersion error along the x and y directions [Kowalczyk, 2008].

There are two ways to overcome this:

1. The user can change the method to use a higher order partial differential to redistribute the dispersion error or another FDTD scheme. However, deriving the update equations for a higher order partial differential is not an easy task and will create more multiply add operations which will make the simulation slower [Kowalczyk, 2008] [Botteldooren, 1995] [Schneider, 2013].

2. If another method is not chosen, the user must "over-discretise" or "over-sample" the field. The issue with this choice though is that it will increase computation time and memory consumption dramatically [Kowalczyk, 2008].

When describing complex geometries the grid must have a sufficiently small spatial step size in order to accurately describe the smallest geometric feature of an object. The larger the grid or the higher the resolution, the longer the simulation takes to run and the more memory that is required for the calculation. However, the relationship between the computational resources required and the resolution is linear. That is to say:

- For one dimension of propagation when the resolution is doubled for a given problem, the memory required and computation time are also doubled (2x).
- For two dimensions of propagation when the resolution is doubled for a given problem, the memory required and computation time are increased by 4x .
- For three dimensions of propagation when the resolution is doubled for a given problem, the memory required and computation time are increased by 8x .

2.6 Other Mathematical Models

There are other common simulation methods used in acoustics. These include Geometric Models and Boundary Element Models. One common geometric model, Ray Tracing is discussed here. All of the simulations make similar assumptions about the characteristics of the environment. For instance, the medium is assumed to be homogeneous and non-turbulent. However, this section aims to explain the limitations of these specific methods and reinforce the reasons why Finite Difference Time Domain was chosen.

In Ray Tracing models, the principles of geometric optics are applied to approximate the path of propagation of an acoustics wave. There are some key challenges that face such a simulation. Firstly, sound has a significantly longer wavelength than light and so small objects have little effect on an acoustic wave but diffraction effects, when they do occur, are significant [Kufner, 2008]. Secondly, modelling the relative phase of waves at a specific receiver position is important and is effected by the characteristics of the boundary. The main benefit of Ray Tracing is that it can be used to model all surface geometries and scattering effects. However, the computational requirements increase with the demand to compute higher order reflections. These disadvantages mean that Ray Tracing is usually only valid for approximating the behaviour of an environment at higher frequencies.

The Boundary Element Method (BEM) is another technique of solving the wave equation. The BEM provides a solution by combing boundary integral equations and the Finite Element Method in order to discretise the surface and describe its acoustic characteristics. The BEM can be used to efficiently discretise a complex surface geometry for modeling. Like FDTD, the BEM can be used to model the entire range of human hearing provided that the mesh size of discretisation is significantly smaller than the wavelength of the highest frequency required.

However, there is a key disadvantage: BEM gives rise to fully populated matrices and computation time grows as the square of the problem size [A. Hargreaves, 2015] . Therefore, when a surface is complicated and must be described by a large number of elements or the wavelength tested requires more elements on a single surface, the computational requirements increase [Siltanen et al., 2010]. Computation time is increased if solutions are needed over a large bandwidth or a large bandwidth a high frequency resolution. Lastly, BEM is not suitable for this research as it simply does not allow for the analysis of wave propagation in the time domain.

Chapter 3

Basic Room Acoustics

This research is chiefly concerned with the implementation of diffusers in small rooms. This chapter will open with a statement of the relevant literature pertaining to a variety of topics in room acoustics and will then continue to introduce acoustic phenomena in small rooms and the different perceptual effects that may be created. The last section of the chapter will describe different small room designs and how these designs differ.

It may be best to begin with the basic concept that room acoustics is chiefly concerned with the propagation of waves in a confined volume of air. There are several objective parameters that are used to describe the performance of a room. The most fundamentally measurement is the impulse response of the room. From that measurement one can extract the reverberation time, RT60, as well as the reverberation time of different frequency bands and the frequency response of a room at a given receiver position [Rossing, 2007]. This research is concerned with the response at the listening position in a studio environment.

Other subjective and objective parameters that can be extracted from the impulse response include Clarity, Sound Strength, Spaciousness [Rossing, 2007]. However, these parameters (as well as others) are not as useful in this context because they require an integration time of 80 milliseconds. Sound will travel a path distance of roughly 27 metres which means that most reflections will likely arrive back to the listening position in a small room in that time. Due to this, the basic analyses mentioned in the previous paragraph will form the extent of the data compared.

However, there is some objective data known about how human hearing works that may indicate if there are possible perceptual effects when comparing simulated rooms. Chapter 7 of Kuttruff's text [Kuttruff, 2009] opens with the idea that the acoustic designer has to find ways to meet the expectations of the average or listener for whatever space it is. In section 7.2 he discusses the conditions which lead to the perceptibility of reflections. He presents data that dictates: The threshold of perception for a reflection with a 50 ms delay changes depending on the type of signal as well as the angle of incidence. He raises the point that humans are less sensitive to reflection interference when listening to music rather than speech. Further within the same chapter, Kuttruff defines that perceptibility of a reflection is a function of both delay time and level [Kuttruff, 2009]. These points are discussed in greater detail within the chapter.

Besides perceptual effects, there is the main topic which is the design of the room itself. There are some practical considerations when dealing with small rooms for production purposes. It is not unusual for a modern professional studio to be expected to produce content for a number of formats including mono, stereo, and surround as well as Dolby Atmos in the near future. At this time Dolby Atmos is more common for use in dubbing theatres and block buster film post production. This research tests the results of a 5 point surround system. There are a few accepted general designs that are discussed later in this chapter. However, the main concern is that these methods were intended for stereophonic reproduction [Walker, 1995] [Walker, 2007]. This predicament is a central topic that this research does not address and could be greatly aided by.

> The stereophonic reproduction has generated few fairly stabilised and accepted principles of design such as a reflection free zone in front of the room, the Live End-Dead End principle, left-right symmetry of the monitoring room, symmetrical placement of the Left and Right loudspeakers. The stereophonic design principles do not directly extend to multichannel reproduction, and the current lack of clear design approach is generating a lot of debate. [Varla et al.]

3.1 Acoustic Phenomena in Small Rooms

Room acoustics is concerned with sound propagation in enclosures where the medium is bounded on all sides [Kuttruff, 2009]. The sound that is heard in most environments is a combination of the direct sound from the source or sources and the indirect reflections from surfaces and other objects[Cox and D'Antonio, 2009]. The reflected sound can be either specularly reflected or scattered as a diffuse reflection. Both absorbers and diffusers tend to be used in tandem in order to control sound propagation in the environment. One of the central topics in room acoustics is how to manipulate these reflections in a way to affect how the sound is perceived at a listening position. In a small room, boundaries are so close to the listening position that many reflections will arrive within the first few milliseconds[Everest and Pohlmann, 2009]. These sections aim to define some of the key aspects that affect studio and listening room design.

3.1.1 Room Modes

Room modes are a number of resonances that exist in a constrained volume when the medium (air) is excited by a source (speaker). Room modes are the result of standing waves that occur when half the wavelength (and multiples of that wavelength) of a signal is equal to a dimension of propagation within the room. There are well established methods for calculating the modal frequencies of cuboid rooms. However, the important point is that all rooms are finite bodies and all finite bodies resonate. The larger the room, the longer the wavelength for the fundamental frequencies. In small rooms such as studios and listening rooms, fundamental resonant frequencies are likely to lie within the range of human hearing.

Modal phenomena yields some perceptual effects. The magnitude of modal frequencies is likely to be increased and as this is the resonant frequency of the volume of air, the decay time for these frequencies is increased. This gives the perception of a room having a tonal characteristic [Kuttruff, 2009] [Cox and D'Antonio, 2009]. It is possible to create a diffuser that is large enough to affect room modes, but this is not practical and so room modes are not relevant to the typical bandwidth of diffusers.

3.1.2 Colouration and Echo

Colouration is defined as changes in timbre. Timbre is the perceptible attribute of a signal which enables an observer to judge that two non-identical sounds, having the same loudness and pitch, are dissimilar. Timbre depends primarily upon the waveform, but also upon the sound pressure and the temporal aspects of the signal [Rubak, 2013].

A source of colouration is caused by the interference between the direct and reflected sounds. If a reflected sound combines with the direct sound under 50 ms, the human ear acts as a short time integrator. This integration behaviour restricts the ability to resolve successive acoustic events that happen within that time frame and therefore, humans perceive the tonal characteristics of the signal. The threshold of colouration (Figure 3.1) is shown as a function of delay time and amplitude [Kuttruff, 2009].

The threshold is lowest (most disturbing) when the delay is between 1 ms and 25 ms but rises (less of a problem) when the delay time is above 25 ms. Between 25 ms and 50 ms the perception of colouration turns into a perception of rough successive events. This is commonly referred to as flutter echo. If a reflection is delayed beyond 50 ms it will be heard separately and will be perceived as a distinct echo [Kuttruff, 2009]. In the context of small rooms, a sound wave can travel about a 17 metre path length over the course of 50 ms. In most small room environments, reflections will occur within the first few milliseconds as the path length is a fraction of 17 metres.

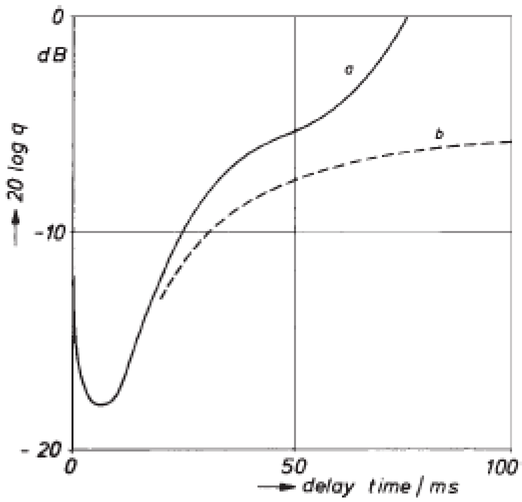

Figure 3.1: The threshold of disturbance for separate signals as a function of delay time and amplitude. From [Kuttruff, 2009]

3.2 Studio and Listening Room Design

There is a standard set by the International Telecommunications Union for how to design a listening room environment for experimental work. Rec.ITU-R BS.1116-1 [ITU, 1997] proposes that "the use of standardized methods is important for the exchange, compatibility and correct evaluation of the test data". The standard then goes on to outlines a number of features that of the room construction that must be validated by measurement. The standard lists a number of considerations governing reverberation time tolerances, the operational room response curve and room dimensions. According to Rec.ITU-R BS.1116-1, the following room dimension ratios should be observed to ensure a reasonably uniform distribution of the room modes:

$$1.1\frac{w}{h} \leq \frac{l}{w} \leq 4.5\frac{w}{h} - 4 \qquad (3.1)$$

where l is the length, w is the width, and h is the height of the room.

R. Walker had illustrated that, for a given room volume, it is possible to plot the modal variation or distribution for different room ratios [Acoustics.salford.ac.uk, a]. The analysis showed that there were only a few room ratios that could be applied to a range of room volumes. However, there is more than the one outlined by the ITU standard.

Furthermore, there are some other limitations. Both analyses are only applicable to rectangular rooms with rigid boundaries as absorption is neglected and all modes are treated the same. It is also found that ratios are generally found to be an incomplete analysis because ratios themselves are not robust enough to describe architectural variations such as slanted walls and partitions as not every room is perfectly rectangular [Acoustics.salford.ac.uk, a] [Varla et al.] [Walker, 1995].

Figure 3.2: Armin Van Buuren's private studio (From [Senior, 2009])

Listening room environments and studios that actually meet this exact specification are not common. If a business were to require a space for sound reproduction purposes, such as a studio, then that business must be located in an area with enough potential traffic in order to generate the revenue to operate. Typically, this means an urbanized environment. In a city, the ability to acquire the real estate to develop an already existing space is expensive enough. The likelihood of finding a space of these exact proportions as well as acquiring the rights to develop, severely hamper the ability to create rooms to this standard. Therefore, most businesses tend to retrofit the rooms they have available. To illustrate this point, both Figure 3.2 and Figure 3.3 display the main monitoring and mixing environments used by professionals. Neither of these rooms fit the ITU standard completely.

Due to the many constraints hobbyists and businesses have to work with, the ITU standard is used more as a set of guidelines and Rec.ITU-R BS.1116-1 includes a notice that states "This Recommendation forms the base reference for the other Recommendations, which may contain additional special conditions or relaxations of the requirements included in this Annex" [ITU, 1997]. Therefore, there are some broader goals designers try to achieve when creating a monitoring environment for studios.

Most studio designs try to achieve the following broader aspects [Errede, 2015]:

- The room should be acoustically isolated. This is not simulated and is assumed.
- For accurate imaging, a listening room should be symmetrical about the vertical plane along the principal listening axis. This is probably why rectangular rooms form the

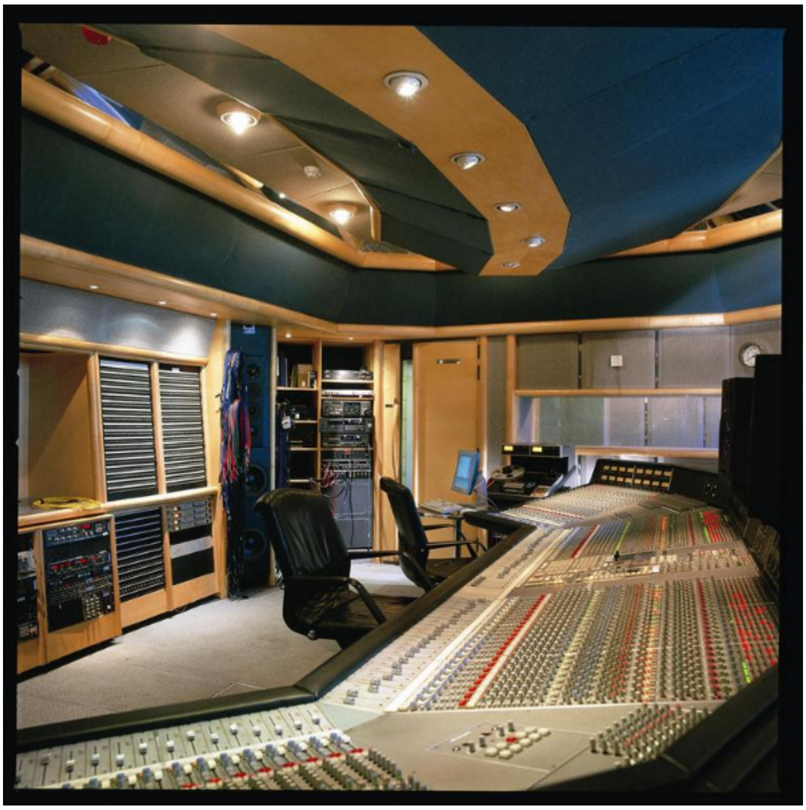

Figure 3.3: Air Studio's Studio 2 at Lyndhurst Hall (From [Air, 2015])

basis of many standards.

- The reverberation time (RT_{60}) should be under 0.5 seconds.
- The frequency response of the room should be relatively even. This means that room modes should be controlled with resonant absorbers and speaker and listening positions should be positioned accordingly. This also means that colouration effects due to reflection interference should be reduced either through the use of diffusers or broadband absorption.

To be clear; a room that meets these goals can be achieved if one follows the guidelines set out by the ITU standard. However, there is a lack of flexibility in the ITU standard that hampers its application to most situations. To address this problem, there are a number of different studio room configurations that have been formulated over previous decades, however, only two will be described.

3.2.1 Live End Dead End

The Live End Dead End (LEDE) is an older method of addressing room acoustics for small studio applications. The section containing the monitoring equipment is dampened or treated with a large amount of absorptive material. The section of the room behind the listening position is treated with diffusers in order to avoid any intense echo that may color the sound or cause image shift.[Cox and D'Antonio, 2009]

This design is flexible as it can be used to treat rooms of irregular geometries as well as smaller rooms. However, it is usually only used for mono and stereo monitoring. This is partly due to the fact that during its inception, most audio was consumed in the form of stereo recordings. However, surround sound systems of 5.1 are becoming increasingly popular due to developments in the video game industry and a developing independent film industry with lower budgets. Therefore, despite this design not being the most effective, it is still common for project use.

However, this design suffers from acoustics that vary widely throughout the space. This design also requires that the room is perfectly symmetrical about the listening axis and offers a small listening position. This design also requires a minimum room size to control the effects of interfering reflections and requires significant absorption even at lower frequencies.

3.2.2 Reflection Free Zone and Controlled Image Design

A Reflection Free Zone (RFZ) is a method of addressing room acoustics created in the 1980's. The design creates a spatial and temporal reflection free zone surrounding the listening position. The zone is spatial, because it only exists within a certain area of the room; and it is temporal, because the interfering reflections are only controlled over a certain window of time [Cox and D'Antonio, 2009] [Walker, 2007]. Essentially, the boundaries of the room are angled in order to reflected sound away from the listening position to create a longer mean free path for the wave to travel[Fazenda and Angus, 2002]. However, this prediction typically only holds true at higher frequencies. The terminating or rear wall surface is comprised of absorbers and diffusers.

The Controlled Image Design (CID) is a similar method created in the 1990s by Bob Walker [Walker, 1995]. It also uses angled boundaries to lengthen the path of propagation like the RFZ but does not employ the use any absorbers. This means that CID's require large amounts of space and have not been used outside of the BBC or major production facilities.

Neither of these designs are flexible or cheap to implement. They have certain size requirements in order to achieve the required delay time. However, they are effective and are more common for 5.1 monitoring with professionals in post production environments.

3.2.3 Test Studio Design

The small room environment simulated in this experiment is a Live End Dead End Model. This was done because the design of a RFZ or CID usually employs the use of geometric simulations. These tools were simply not available. Furthermore, the scale model that was available was cuboid in shape and fitting an RFZ or CID within it would have greatly limited the available testable bandwidth as well as increasing costs of testing.

The FDTD algorithm used in these simulations was only second order accurate. If a fourth order approximation was used (which adds more degrees of freedom for calculation) a more complex geometry such as angled walls, would have been a feasible option. However, with only a second order accurate discretisation, the error of describing the geometry, over the entire boundary, would have been to high despite oversampling.

Chapter 4

Basic Principles of Diffusers

An acoustic diffuser is an acoustic treatment that is used to spread sound evenly through a space. This chapter will establish the basic principles of diffusers and diffuser operation. The chapter will then proceed to offer a detailed explanation for each diffuser design used in the following experiments. There are some key ideas and literature that may help guide an understanding of acoustic diffusers and why these designs were chosen.

There are a wide range of acoustic diffusers available in the market that come in a variety of geometries, sizes and materials for consumer and professional applications. The implementation of these diffuser types can yield praise or criticisms. While there are comments on the aesthetic appeal of certain designs, some critics say certain designs sound better than others or that there are correct ways of applying said designs. This is well summarised by Trevor Cox [Cox, 2004]:

> "Informal conversations with practitioners have indicated that diffusers, either the presence or lack of them, are sometimes cited as reasons for the acoustics of a space failing to meet expectation. It is hard to know how much weight to put on these opinions, because they are usually not borne out by psychological measurement using test juries and following scientific methods, but are simply individual opinions, albeit from recognised experts."

Further confusion arises due to manufacturers who market their products with extraordinary claims that simply cannot be true and are not backed by measurement results.

Firstly, it is best to understand what an acoustic diffuser is meant to do. Diffusers assist in the process for a room to become a diffuse field by breaking up specular reflections. A small room can never be a diffuse field because there are generally poor diffusion characteristics at low frequencies and room mode excitation will cause the reverberation times at different frequencies to vary throughout the space. Left untreated, a flat surface could potentially deliver a reflected wave that is identical to the source wave. This may yield the comb filtering effects discussed in the previous section. By breaking up these specular reflections, the source can be easier to localise and colouration effects due to interference can be diminished. This may cause certain subjective descriptions of the space such as “spaciousness” and the removal of echoes. However, relating “global” descriptive coefficients to diffusers is difficult [Cox and D’Antonio, 2009].

A relevant paper is “The Analysis of Several Diffusers in a Reverberation Chamber by FDTD Method” by Baoli, Wu, Benqing and Shiming. The paper aimed to quantify if different diffusers are more effective in creating a diffuse field by looking at field uniformity in a simulated reverberation chamber. However, there is limited context given in the paper. The paper dictates little about the conditions of the environment including reverberation time. The conclusion stated that “it is found that the diffusers have good characteristics to enhance the reflected field and we can obtain better homogeneous field by reasonable arrangement of diffusers”[Baoli et al., 2002]. Unfortunately, what is reasonable was never clearly discussed. Also, these simulations were used to understand reverberation chambers and not small rooms with absorption and diffusion.

Coefficients are useful as they can be used to clearly evaluate and rank diffusers in an easily measurable and reproducible way [Cox and D’Antonio, 2009]. Two common coefficients used in diffuser design are the scattering coefficient and diffusion coefficient. Changing coefficients may simplify the optimisation of their design for a specific scenario as well as facilitate their input into geometrical models.

The scattering coefficient is intended to provide a simplified understanding of how much energy is removed from the specular direction. The specular component is the proportion of energy which is reflected in the same way as would happen for a plane surface [Cox and D’Antonio, 2009]. The scattered components give the energy reflected in a non-specular manner. This coefficient is also frequency dependent. The diffusion coefficient is a single figure that states the amount of diffuse reflections that can be expected for a given frequency band at a single source position [Cox and D’Antonio, 2009]. While a diffuser yielding temporal spreading may yield a stronger diffusion coefficient, there is not a direct correlation between the spatial and temporal responses that can be gathered by the diffusion coefficient alone. Therefore, it is not compatible in geometric modeling methods. [Redondo et al., 2007] [Cox et al., 2015]

> ...We must note however that the frequency variability of the time-space spreading relationship implies that any projected relationship between ISO and AES results is likely to be complex (see for instance [50]), and that the main reason for differences in results using the two standards is that the diffusion coefficient (see equation (15)) has a tendency to underestimate the spatial spreading. [Redondo et al., 2007]

Please note the citation ’[50]’ in this excerpt refers to the paper by Cox and DAntonio titled

"Contrasting surface diffusion and scattering coefficients" which was given at the 17th ICA, Italy in 2001. This paper is cited in this paper as [Cox and DAntonio, 2001].

The idea of temporal redistribution is an important facet that is discussed in greater detail, with examples, later in this chapter. To be put simply, it is the property that allows for the diminishing of comb filtering due to interference. However, there are unresolved questions. Do these coefficients translate directly to a change in some physical or measurable objective characteristics? Does this objective characteristic create a consistently observable or noticeable subjective change? The experiment involved in this research may shed some light as to how complex these relationship may be while not offering a final resolution.

> ... preliminary results concerning the time domain features of the sound reflected by three different surfaces have indicated that FDTD can be useful for the evaluation of sound diffusers in terms of time-spreading. Further research must be carried out in this area, to build a knowledge (objective and subjective) of the ability of sound diffusers to spread sound in time in addition to their well-known spatial spreading, towards a global time-frequency parameter to quantify scattering. [Redondo et al., 2007]

4.1 Diffuser Operation

As the name would imply, diffusers are acoustic devices that aid in the process of diffusion. Broadly speaking, a diffuser has a given geometry that breaks an incident wave front and reflects the components of that wave front in many directions. It is well understood, and easy to visualise, that when a wave is incident upon a smooth flat surface, there is only one reflected wave. If the incident wave strikes a corrugated surface, more reflected waves are produced. However, not all corrugated surfaces are diffusers.

In order to understand diffuser design, it is useful to define what the ideal acoustic diffuser is. The ideal acoustic diffuser will reflect an incident wave in all directions equally for all frequencies at any angle of incidence.

The core principles of diffuser operation relate to the fundamental considerations of wavelength and object diffraction.

- At low frequencies when the wavelength of the sound is much larger than the dimension of the surface irregularity, or object, then the wave diffracts around the object.
- When the wavelength of the sound is similar to the dimensions of the surface irregularity, then the resultant wavefront is a product of the intricate wave interference. The simplest model is that every point on the surface acts as a point source and

radiates sound back into the field. The resultant pressure distribution depends on the relative phase and magnitude of all waves received.

- At high frequencies, the scattering can be calculated by considering the surface to be a series of smaller plane surfaces. At this scale, Snell's Law can be accurately applied. If the angle of incidence equals the angle of reflection, specular reflection will result.

The fundamental principles of diffraction tell us the very simple fact, that diffusers are band limited devices. There will be a lower limiting frequency which usually controls the depth of corrugations and this is often a starting point for diffuser design. Before exploring different diffuser designs, it is best to know how a basic geometry interacts with a wave in order understand what characteristics designers are trying to avoid.

Figure 4.1 illustrates a cylindrical wave reflected from a planar rigid surface. Upon reflection, the wave simply changes direction and results as specular reflection. The reflected wave is essentially unaltered meaning that none of the wavefront was reflected in another direction as all components of that wavefront are still in phase. In a room such as a studio, this reflection could be perceived as colouration which would make accurate sound reproduction difficult as it would interfere with the direct sound from whatever monitoring method was used.

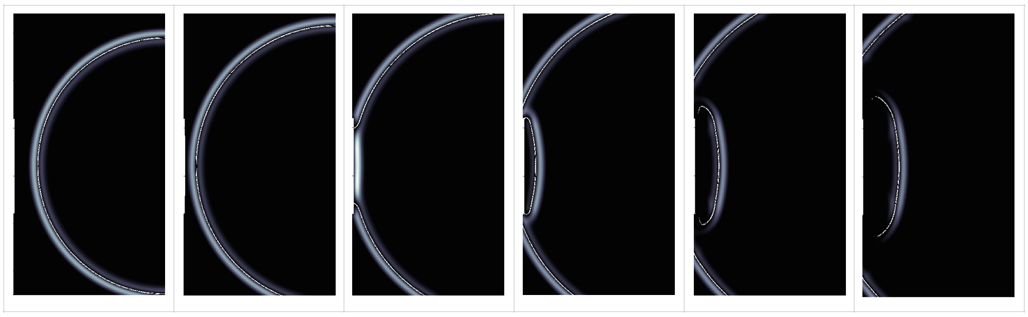

Figure 4.1: Flat Panel Reflection

The next step is to create another simple surface that can be used as a diffuser. If one combines two flat panels, a triangle is achieved. Triangles can come in all manners of angle combinations however, the following set of images (Figure 4.2) illustrates a wave incident upon an obtuse triangle.

If one continues to add vertices, then a curved surface can be achieved. Figure 4.3 illustrates the effects of a cylindrical wavefront approaching and interacting with a convex curved surface.

In the case of both the triangular and curved simple surfaces, the reflections that result, may be distributed spatially or directed towards another area in the field. However, there are some other flaws with each design. In the case of the triangle, if the wavefront was incident perpendicular to either face, then that face of the triangle would behave like a flat panel.

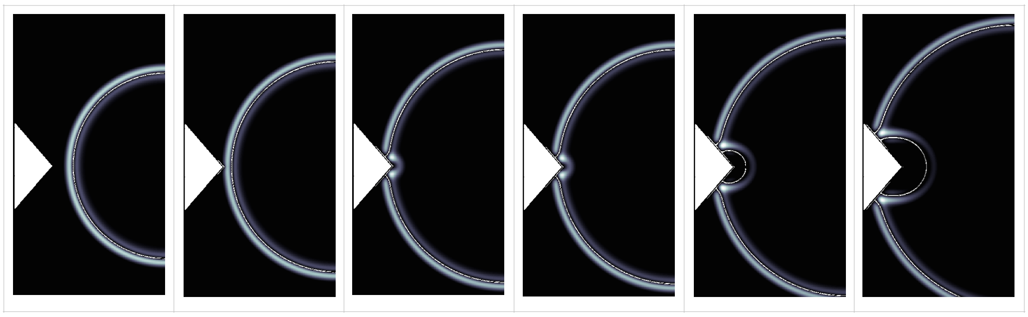

Figure 4.2: Triangular Diffuser Reflection

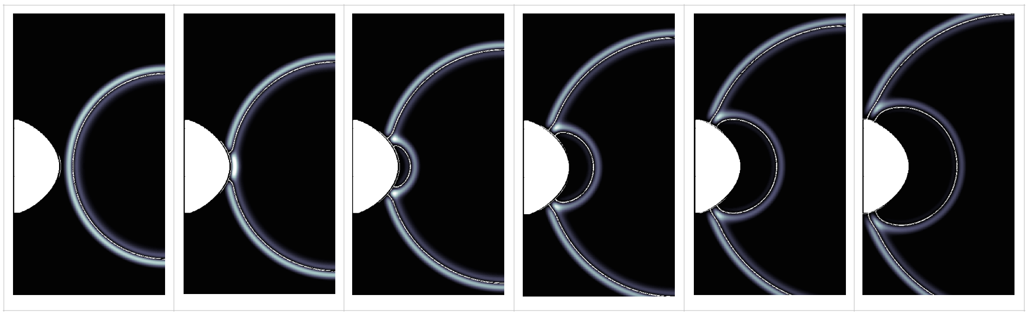

Figure 4.3: Convex Diffuser Reflection

However, when the angle of incidence is 0°on axis, the reflection along that same axis is severely attenuated. Upon adding more vertices to create a curved surface, the reflected wavefront is more bowed and the sound is more spatially distributed. In the case of the curved surface, it is generally safe to assume that this behaviour would persist across a wide range of angles of incidence. However, both simple geometries have the same fundamental problem as the flat panel. The pressure of the reflected wavefronts are negligibly different from the incident wavefront. If the reflected wavefronts were to arrive at a listening position, the reflection could be perceived as colouration with a comb filtering effect. To prove this point, the following set of figures (Figures 4.4 - 4.6) show the temporal response and a narrow-band frequency response of each basic animation.

Please note, that these simulations do not indicate the strength of a reflection towards a given area of the field and do not equate to a polar response pattern. These figures are simply intended to show the basic behaviour of certain simple surfaces in relation to diffuser design. However, the above figures do display how comb filtering is a possible perceived auditory effect. Essentially, the reflected wave is a delayed copy of the direct sound. This delay means that the frequency components of the reflection are not always in phase with the direct sound. The time delay between the direct sound and the reflection determine the frequency spacing of the minima and maxima as shown when comparing the convex and flat surfaces frequency responses. The relative amplitudes of the direct to reflected wave determine the levels of the minima and maxima. As the reflection from the triangle has a significantly smaller amplitude

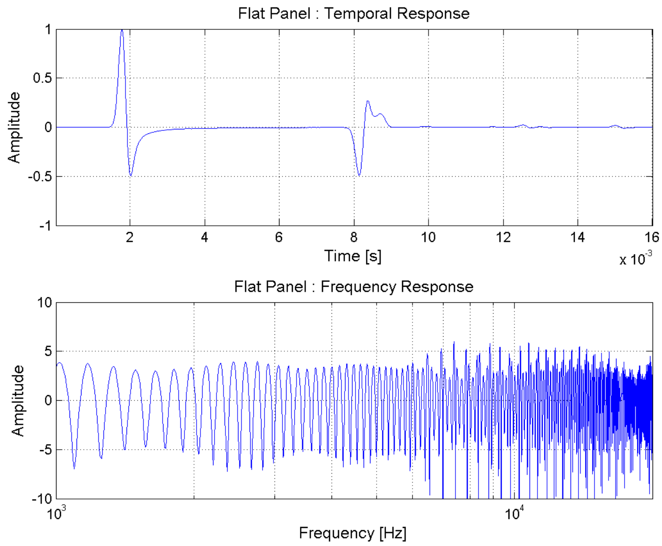

Figure 4.4: This figure shows the temporal response and narrow band frequency response of the Flat Panel.

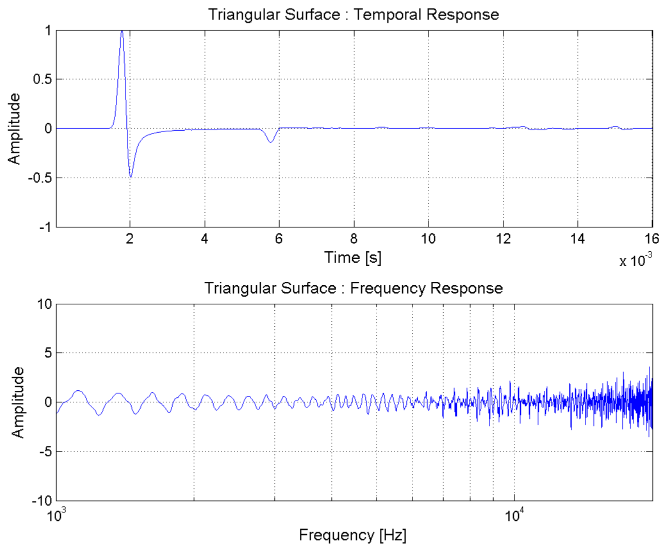

Figure 4.5: This figure shows the temporal response and narrow band frequency response of the Triangular Diffuser.

then the direct sound, the comb filtering effects are not as exaggerated. Comb filtering is an undesirable effect especially in small critical listening environments such as studios because the spectral content of the source cannot be perceived accurately.

These preceding figures indicate that it may be possible to cause diffusion more effectively by breaking the wavefront in time and therefore causing sets of compression and rarefaction to occur in a distributed manner over a period of time. This concept can be illustrated with a classic Schroeder diffuser. Again a set of images (Figure: 4.7) are presented which are followed by the accompanying temporal and frequency responses (Figure: 4.8).

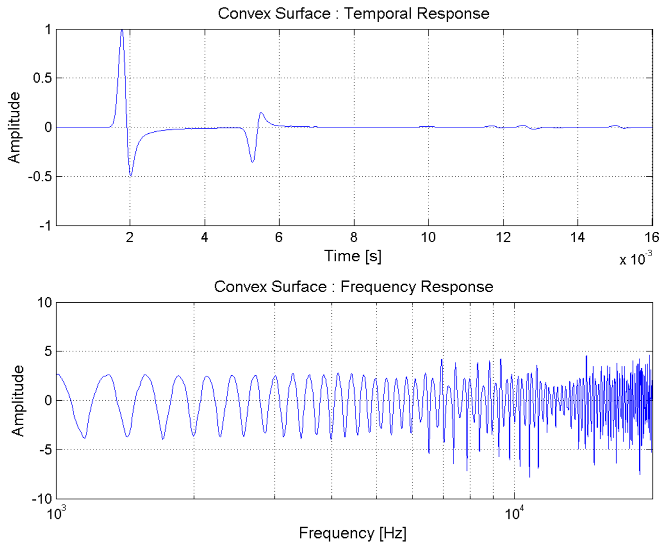

Figure 4.6: This figure shows the temporal response and narrow band frequency response of the Convex Diffuser.

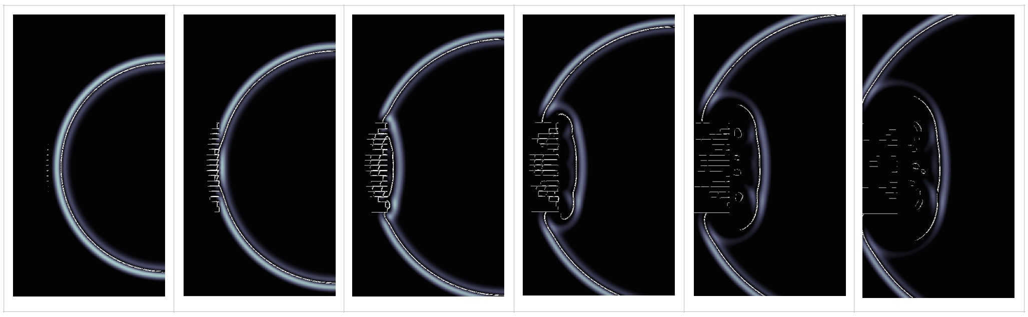

Figure 4.7: This series of images shows the interaction of a cylindrical wave with a Schroeder Diffuser.

The basic operation and design of a Schroeder diffuser will be discussed in the next section. However, this demonstration shows that a Schroeder diffuser creates a more intricate interference pattern upon reflection. The temporal response illustrates that at a specific receiver point, the reflection is really a number of delayed reflections with varying phase relationships. This results in a frequency response that is less representative of a comb filter especially at higher frequencies.

The results of these basic demonstrations illustrate that there is more to a diffuser design or choice than simply its spatial scattering behaviour. There is also temporal scattering behaviour that is necessary to consider. However, it may be a mistake to think of the Schroeder diffuser as "another surface" because a Schroeder diffuser is, essentially, an arrangement of flat panels. Therefore, a broad statement can be made that effective diffusers are arrangements of simple component surfaces. However, which ones are more effective, why

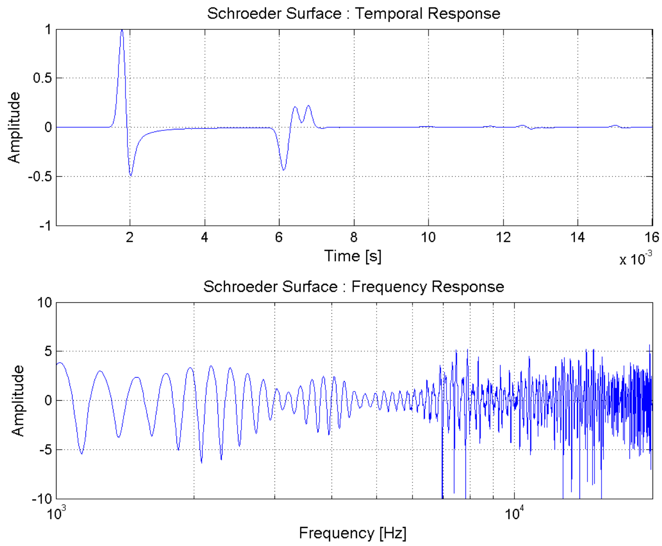

Figure 4.8: Schroeder Geometry Temporal and Frequency Response

and how are still unanswered. Furthermore, these opening demonstrations take place in a free field environment. They are not indicative of the much more complex behaviour of scattering exhibited by more complex diffuser surfaces or real rooms with added boundaries and surface orientations.

4.2 Diffuser Designs

This section will give a brief overview of the surfaces used for each simulation. A reason will be given for their selection as well as basic design criteria. These diffusers were not chosen to test particular existing products or designs. They were simply chosen to offer a broad comparisons between different geometries in order to gain insight to the behaviours of these objects. In total six surfaces are tested.

4.2.1 Flat Panel

A flat panel is included for every simulation. While not acting as a control, it forms some basis for comparison. This is done in part because, the spatial and scattering behaviours of flat panels are well understood and some reasonable assumptions can be made as to what should be expected. This panel is not angled in any way so the animations from Figure 4.3 represent the method of implementation used (flat against a boundary). The dimensions of the simulated panel are listed in the table.

Length	2.40 metre

4.2.2 Convex Diffuser

Some authors claim that convex cylindrical devices offer astounding diffusion characteristics. This is where Alton Everest and Ken C. Pohlmann's [Everest and Pohlmann, 2009] text disagrees with Cox and DAntonio [Cox and D'Antonio, 2009]. This idea is not completely the case as clearly demonstrated in the section above. However, the last section ended with the idea that effective diffusers are arrangements of simple component geometries. Following that thought, we can ask: What happens when convex cylinders are arranged to form more complex poly-cylindrical diffusers? Is the reflection a more intricate interference pattern or can we simply expect more of the same?

Length	2.40 metre
Diameter of Large Pipe	0.80 metre
Diameter of Medium Pipe	0.55 metre
Diameter of Small Pipe	0.25 metre

The design of this diffuser is based off of actual sizes of materials that could be found for the scale model. The full scale dimensions of the simulated diffuser are listed in the table. The poly-cylinders are arranged by decreasing diameter from a central larger poly-cylinder. Each poly-cylinder is exactly half of a cylinder. Figure 4.9 displays an image of the model.

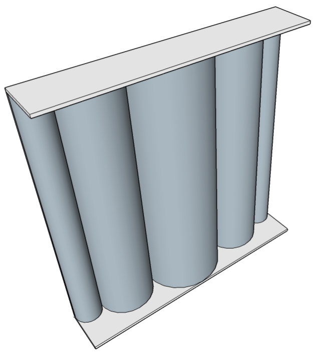

Figure 4.9: Convex Diffuser

4.2.3 Concave Diffuser

The Master Handbook of Acoustics claims that concave surfaces are to be avoided at all cost when controlling reflections in a room. It is logical to assume that at higher frequencies, the wave will be brought to a focus at some point away from the curve as dictated by fundamental ideas concerning conic sections. This same idea is used by astronomers when designing primary and secondary mirrors for telescopes. The "acoustic mirror" phenomena still has modern relevance when designing parabolic microphones.

Length	2.40 metre
Diameter of Large Pipe	0.80 metre
Diameter of Medium Pipe	0.55 metre
Diameter of Small Pipe	0.25 metre

In diffuser design, if the focus is too close to the listening position (which is a reasonable risk to assume in small rooms) then the reflection may be perceived to be louder then the direct sound. However, does that dictate that the concave shape should be avoided entirely? What if that focus is moved to within the curve or close to the device? If one was to follow this logic, which is based off of the assumption that we can equate the behaviour of sound to rays of light, then is not reasonable to expect dispersion beyond the focal point?

The design of the concave diffuser used in this project should, in theory, exploit that. The arrangement is essentially, the inverse of the convex diffuser. Therefore, the focus should be at the "face" of the device. The full scale dimensions of the simulated diffuser are listed in the table while Figure 4.10 displays an image of the model.

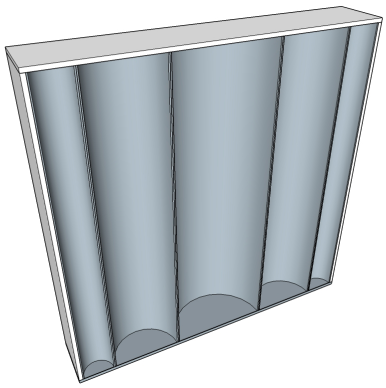

Figure 4.10: Concave Diffuser

4.2.4 Triangular Diffuser

Arrangements of triangles have been sought for use as diffusers as well. With so much possible variation, the geometry of a triangle or pyramidal shape can offer a wide variety of scattering behaviours. Depending on the angle of incidence to the face of a triangle (or set of triangles), a wave can be reflected to the an angle far off axis or specularly.

The Triangular Diffuser used for the simulations and scale model is an arrangement of four unique triangles. Of course, from diffuser to diffuser the triangles are in the same arrangement. The dimensions of the full scale simulated diffuser are listed in the table. Figure 4.11 displays an image of the model.

Length	2.850 metre
maximum Depth	0.475 metre

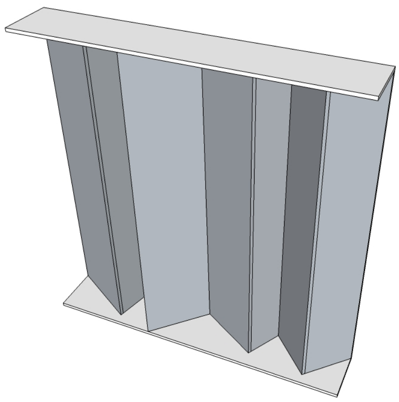

Figure 4.11: Triangular Diffuser

4.12 - 4.13 show the angles and measurements of the components of the triangular diffuser for reconstruction purposes.

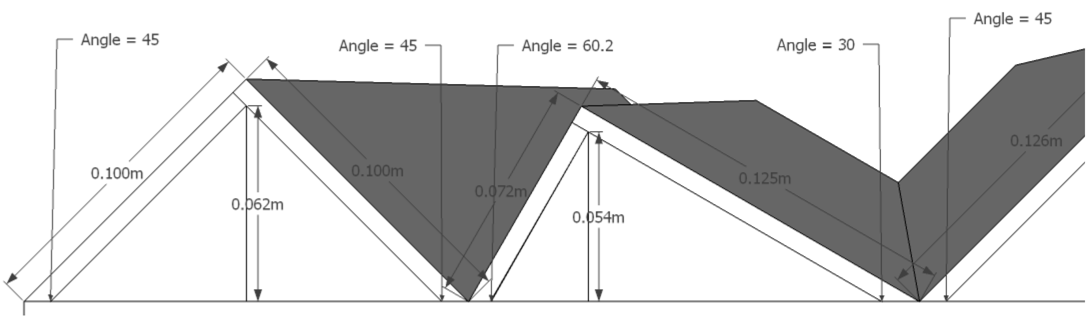

Figure 4.12: Triangular Diffuser Construction [Left Side]

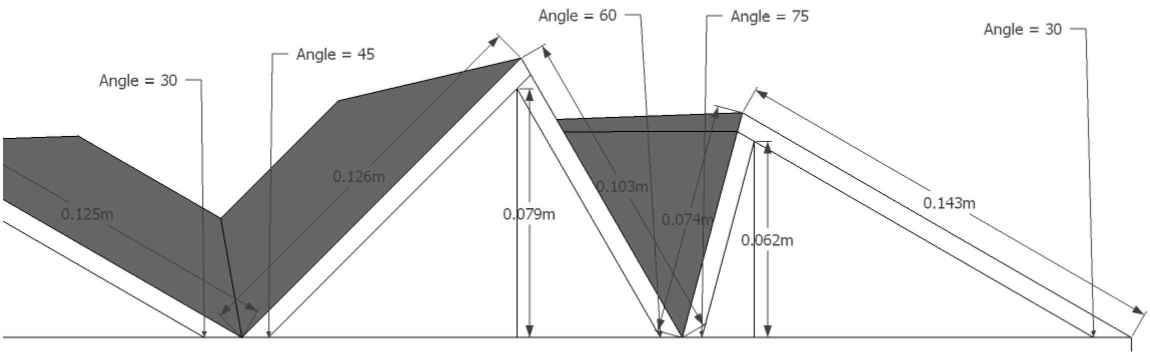

Figure 4.13: Triangular Diffuser Construction [Right Side]

4.2.5 FM Diffuser

The FM Diffuser is not representative of any established diffuser design. The purpose of this design is to find out how large curved surfaces interact with a wave in a small room. This kind of geometry is typical of optimized curves, bi-radial and bi-cubic designs. To be clear, this curve can be recreated by the following set of values:

$$f_a = 1.0Hz \tag{4.1}$$

$$f_b = 0.75Hz \tag{4.2}$$

$$a = 0.4 \tag{4.3}$$

$$b = 1.2 \tag{4.4}$$

a is equal to half of the diameter of the large central pipe of the curved diffuser times scaling. b is equal to half of the overall size of the other diffuser configurations. This is done for scaling purposes.

$$y_b = bsin((f_b 2pi)t); \tag{4.5}$$

$$y_a = asin((y_b f_a 2pi)t); \tag{4.6}$$

$$curve = (\mid min(y_a) + y_a \mid)/2 \tag{4.7}$$

While these designs tend to be used in large auditoriums and other large scale projects, certain studios have employed the use of such geometries. The main question to ask is: Are these designs as useful in smaller rooms or are they being utilised out of context?

The dimensions of the simulated diffuser are listed in the table. The following figure 4.14 displays a cross sectional image.

Length	2.85 metre
maximum Depth	0.40 metre

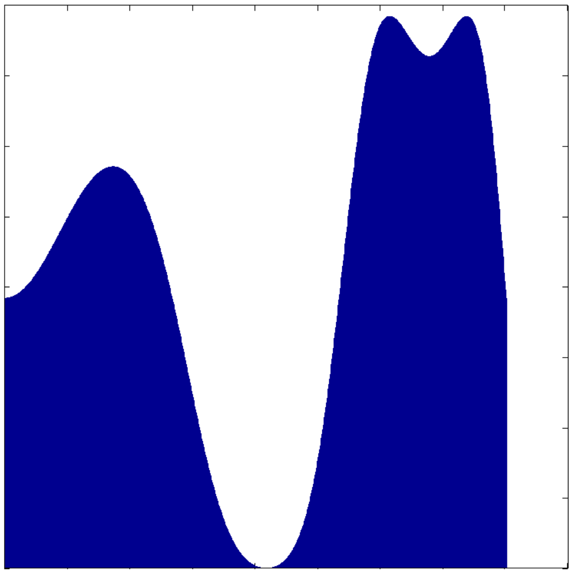

Figure 4.14: Curved Diffuser from Frequency Modulation

4.2.6 Schroeder Diffuser

A Schroeder Diffuser consists of a series of wells of the same width but different depths. The wells are separated by thin fins so that plane wave propagation will dominate within the wells. Ideally, these fins are infinitely thin and rigid and the depths of the wells are determined by a number sequence such as a quadratic residue sequence or primitive root sequence.

As the wavefront enters each well, it travels at the same speed but for different distances. The sound wave takes time to propagate in and out of wells, causing sections of the reflected wave to be delayed. The resulting interference pattern of the reflected wave is more complex because all of these waves have similar magnitude but different phases. Therefore, the polar distribution of the reflected pressure is determined by the choice of well depth and the original wavefront is redistributed temporally.

The Schroeder Diffuser used for testing is based off of $N = 43$. N must be prime for the design to operate correctly. The design wavelength $\lambda_0 = 0.4$ metres which corresponds with the depth of the other diffuser designs. This a frequency of about 858 Hz. The width of wells on Schroeder Diffusers tends to vary between manufacturers from 2 cm to 10 cm. However, the well width used here is 5 cm.

Most Schroeder Diffusers are only built with a $N = 7$ to $N = 13$ range. The reason is because Schroeder diffusers require precision during construction. Every component must be planar and every fitting must be square while maintaining structural integrity. For most situations, this does not present an issue as the diffusers are smaller as they are designed for a higher frequency (shallow depth) or are used in conjunction with duplicate diffusers. However, duplicate diffusers can yield periodicity effects which lead to uneven scattering of a sound wave. The design in this experiment is $N = 43$ because the diffuser needs to cover the same surface area of the wall as the other designs while still maintaining a reasonable well width. The periodicity effects should be avoided as this would complicate the comparison against the other surface designs.

The sequence s_n is determined by:

$$s_n = n^2 moduloN \tag{4.8}$$

For a $N = 43$ sequence this yields:
$s_n =$ (1, 4, 9, 16, 25, 36, 6, 21, 38, 14, 35, 15, 40, 24, 10, 41, 31, 23, 17, 13, 11, 11, 13, 17, 23, 31, 41, 10, 24, 40, 15, 35, 14, 38, 21, 6, 36, 25, 16, 9, 4, 1, 0)
To determine the well depths, d_n, s_n is inserted into:

$$d_n = \frac{s_n \lambda_0}{2N} \tag{4.9}$$

The following figure 4.15 displays a cross sectional image of the result of the sequence with fins inserted.

Therefore if the wells are 5 cm and the fins are 1 node. Then the dimensions should be as listed in following table.

Length	2.85 metre
maximum Depth	0.40 metre

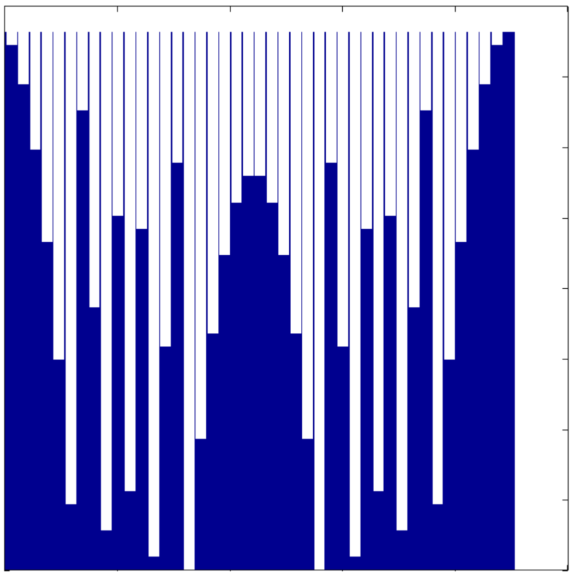

Figure 4.15: Schroeder Diffuser

Chapter 5

Experimentation Methods

5.1 Experiment 1: Simulated Free Field Test

This simulation is devised in order to understand the dispersion characteristics of diffusers in isolation.

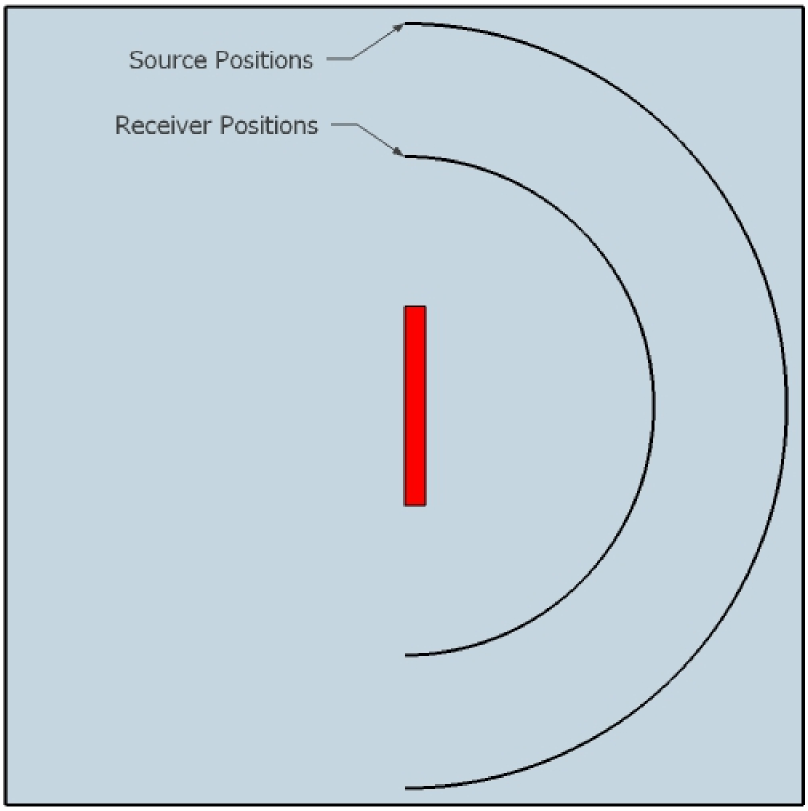

Figure 5.1: This image illustrates the Anechoic Simulation Setup. The red region outlines a basic area where a diffuser geometry would be tested.

Figure 5.1 illustrates the simulation set up. The diffuser is placed in a field with near anechoic terminations. The field is 6 m by 6 m. The diffuser (red) is placed in the center of the room.

The source is placed along an arc around the diffuser. This distance is $l + 2$ where l is the length of the diffuser in metres. The source positions tested are at 0° (on axis), +30°, +45°, +60° and +90°. There are 180 receiver positions arranged along an arc at a radius of $l + 1$. The Courant Number is 0.707. The resolution for this grid is 400 nodes per metre which yields a sampling rate of 274560 Hz. The highest resolvable frequency of this simulation is 27456 Hz. Again, the oversampling is done to minimize the effects of dispersion error and geometry discretisation error.

Each geometry is tested for one source position at a time, therefore, there are 5 tests per diffuser design. For the sake of simplicity, the surface of the diffuser is assumed to be rigid so the surface impedance is infinite. Each simulation will use a Gaussian Pulse to deliver a wide bandwidth signal from the source positions. This means that each simulation will collect 180 impulse responses. From these tests, we hope to understand:

- How does a specific diffuser geometry scatter sound spatially?
- How does a specific diffuser geometry scatter sound temporally?
- How does this scattering behave over a number angles of incidence?

5.2 Experiment 2: Simulated Room Test

This simulation is devised in order to understand the effect of the diffuser designs in an example small room. The chosen scenario is illustrated in Figure 5.2. It consists of a 5.1 monitoring system in a Live End Dead End Room with a width of 4.35 m and a length of 9 m. The absorbing regions are shown as green and the diffusers are red. The green areas correspond with an absorption coefficient, α, of 0.7. The sources (pink) are arranged around the listening position in a circle with a 1 m radius. Due to the fact that the room is symmetrical, only half of the source positions are necessary for each test.

Only one source position is used for each test, in other words, combined source position responses are not tested. Again, the simulation is run at a resolution of 400 nodes per metre. The simulated time is 0.4 seconds. Each simulation will provide a room impulse response at the listening position. From these tests, we hope to understand:

- Do the effects of these different diffuser designs yield a difference beyond a 3 dB threshold?
- Do certain geometries treat colouration more effectively or offer different behaviour?

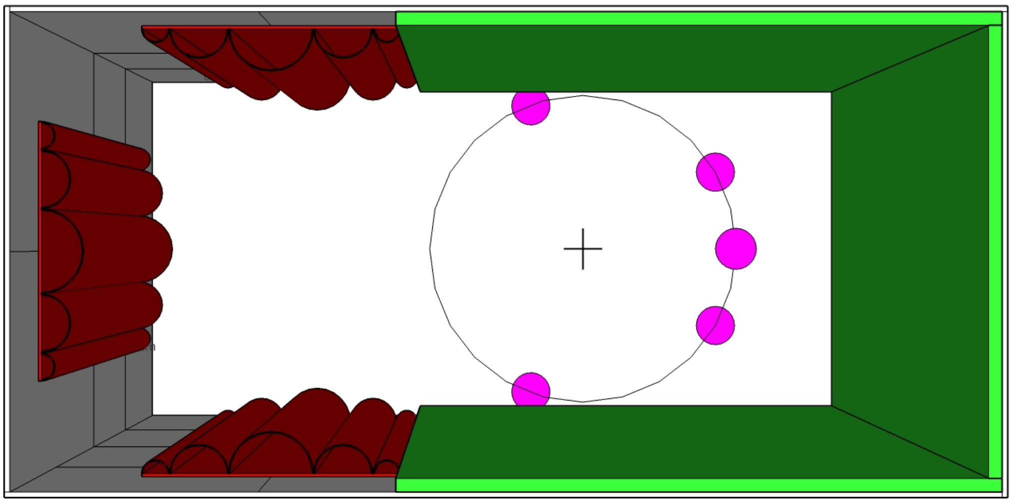

Figure 5.2: This figure is an illustration of the set-up method for Experiment 2. An example diffuser geometry is shown in red. The absorbing boundaries are shown in green. The tested sources are shown in pink. The various dimensions are marked accordingly.

A 3dB threshold is used because this is the threshold for a single specular reflection. The paper titled "The sensitivity of listeners to early sound field changes in auditoriums" attempted to answer what characteristics could be used to measure the perceptual characteristics of diffusers used in concert halls. Unfortunately, some measurements were not applicable to this study, such as Clarity Index because they require the use of an 80ms integration window. This is not really feasible in small rooms because, as stated earlier, most reflections will arrive within the first few milliseconds. The paper [Cox et al., 1993] was not able to find a threshold for diffuse reflections. This is possibly due to the fact that diffuse reflections are not like specular reflections in that there will be masking between octave bands due to the different delayed reflections with different relative phases.

5.3 Experiment 3: Scale Model Room Test

The previous experiments are only two dimensional even though humans observe and interact with the physical world in three dimensions. It is possible to create a 3D FDTD simulation. However, this was not done and the reasons are explained in the section labelled Further Work.

Scale models are a well established method of testing theoretical room designs. They are typically used when planning concert hall acoustics which means the scale is typically around 1:20. Not only is the geometry of the room smaller by scale but the wavelength is also reduced by scale. This means that the model requires the use of high frequency transducers, smaller microphones and materials that behave similarly at scale.

Considering this scenario is concerned with small rooms, the scale is 1:5. This means that the materials used do not change and the scale of the wavelength is manageable. The measurements do not require any specialized transducers for the source or receiver.

Qty.	Equipment Name	Notes
1	WinMLS PC	
1	Fluke Multimeter	
1	B+K Microphone and pre-amplifier	0.25" (6.35 mm) diameter
1	B+K Microphone Power Supply Unit	
1	Microphone Stand	
1	Tweeter Unit	Celestion T3939/P
4	Diffuser Model	
	Porous Absorbent Acoustic Foam	1 cm thick
1	Scale Model	

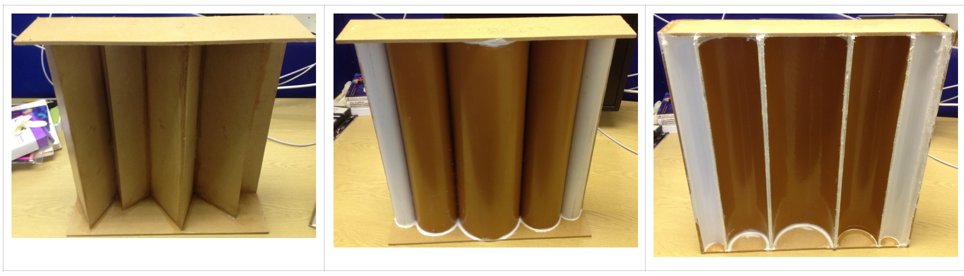

Figure 5.3: Scale Diffusers

Figure 5.3 displays the diffuser models built for scale model testing. Only three designs were built to a pre-planned specification. The components of the diffuser are held together with a strong adhesive appropriate for bonding the materials. An adhesive is more appropriate for this application as an adhesive is a fluid and can fill an irregular volume. The cavities behind the diffusing surface are filled with closed cell-extruded polystyrene foam so that there is less air within the cavity. Any other major gaps are closed with caulking. A seal is formed around all joining portions using silicone so that no air leaks can occur to create a Helmholtz Resonator. The faces are coated with varnish so that the MDF used for construction does not absorb sound at higher frequencies.

As this is a 3D test another diffuser and absorber are added to the environment. Both of these devices are added to the "ceiling" portion. Figure 5.4 shows the method used to secure the acoustic treatments for testing. Wires were used to tie the devices to the support posts. All positions were marked for placement between testing procedures. Figure 5.5 shows the inside of the room (facing the back) with all wall panels in place. An acoustic absorber material was also used to cover the entire floor in order to attenuate reflections from the

Figure 5.4: This is a view of the scale model with all treatments secured [Outside]

different tested orientations.

Figure 5.5: This is a view of the inside of the scale model with no treatment. This is done to convey an understanding of how the construction is pieced together.

The entire testing rig was calibrated. Assuming calibration is accomplished, the testing method for a given diffuser design is as follows:

- Run 5 sine sweeps (1kHz-20kHz) for a given source position. The impulse responses are averaged later. The reason why these impulse responses were averaged is because, in the real world, a transducer such as a speaker will not yield exactly duplicate results for every test.
- After all three source positions are tested; rotate the diffusers as shown in Figure 5.6. Moving clockwise from the top left, these orientations are designated as:

x-horizontal/y-horizontal, x-horizontal/y-vertical, x-vertical/y-horizontal, and x-vertical/y-vertical. X refers to the plane splitting the room, along the vertical listening axis, into left and right partitions. Y refers to the plane splitting the room, along the horizontal listening axis, into top and bottom partitions.

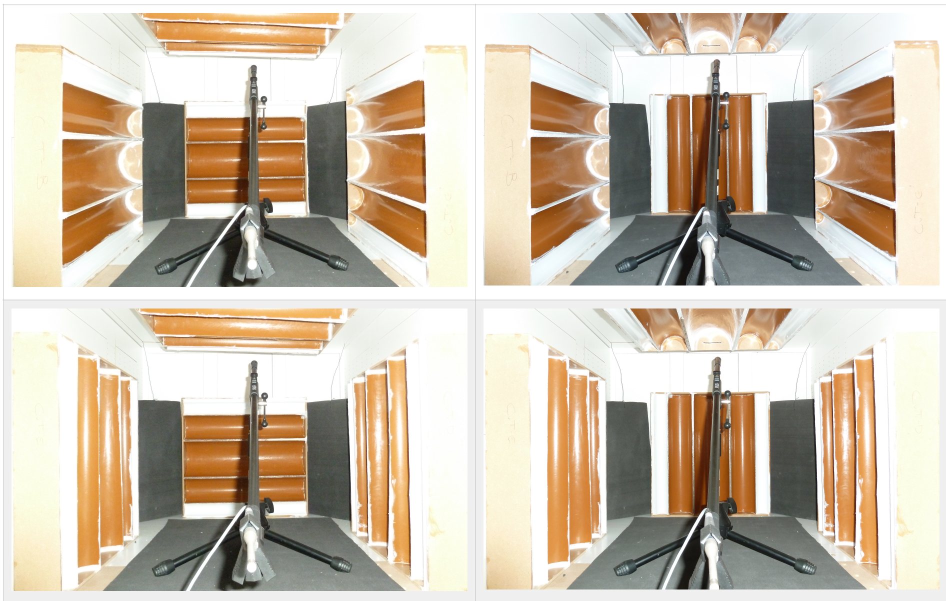

Figure 5.6: These are the tested orientations used in each test. Only the Concave Diffuser is shown here however, this same orientation method translates for the other diffuser models as well. Moving clockwise from the top left, these orientations are designated as: x-horizontal/y-horizontal, x-horizontal/y-vertical, x-vertical/y-horizontal, and x-vertical/y-vertical.

Our objectives for these tests are similar to Experiment 2. From these tests, we hope to understand:

- Are the effects of these different diffuser audible?
- Do certain geometries change colouration effect more effectively?

Chapter 6

Data Analysis

6.1 Experiment 1: Data and Analysis

Figure 6.1 shows the polar response of the flat panel at 3 different octave bands for 0°, +30°, +60° source placements. These plots indicate that the flat panel reflects sound evenly over a wide area. However, a polar plot's main disadvantage is that it only allows for spatial observation at one individual frequency or octave band. This method is not robust enough in order to examine the temporal aspects of the signal which have been established as an important aspect in examining colouration effects.

Figure 6.2 reveals the true nature of these reflections. The color map is essentially a group of impulse responses. It shows only the reflections over the 180 receiver positions for each of the 5 source angles tested. Essentially, you can think of the color map as a set of impulse responses but they are represented within their broader context and so they are used in this section for each geometry. The first test (Flat Panel 0°) shows the 180 responses of the reflection for the source at the 0° (on axis) position. The extreme off axis position is labelled as flat panel 90°. These colormaps are useful as they illustrate the relation between delay time, magnitude of reflection and angle all in the time domain.

As it has already been revealed the flat panel does not cause temporal disturbances in the reflected wave and the color map confirms this. The flat panel (not a diffuser) shows us exactly what should be expected given by the behaviour shown in Figure 4.1. When the source is placed at the on axis position (0° set), the reflection is strongest at the on axis receivers, and is weakest at the extremes of the arc. As the source position moves, the strongest reflection also moves away from the source angle as can be expected by Snell's Law and the delay of the reflections in relation to each other changes as well. Therefore, at the 180° receiver position, the incident wave is closely followed by the reflected wave. When the source position is moved to the extreme off-axis position (flat panel 90°), the flat panel offers extremely attenuated reflections. However, these reflections are not the result of sound reflecting off the face, these are the result of edge diffraction. These edge diffractions are the

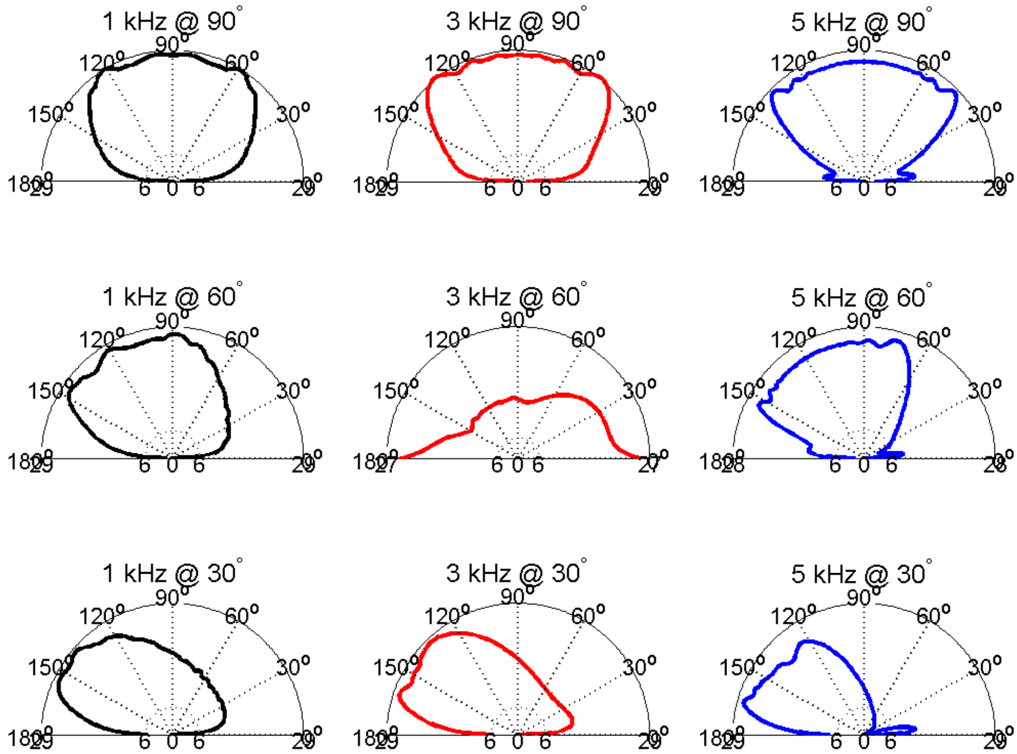

Figure 6.1: This is the polar response plot of the flat panel in an anechoic environment. The black lines in the first column show the response of the 1/3rd octave band centred at 1 kHz. The red lines in the second column show the response of the 1/3rd octave band centred at 3 kHz. The blue lines in the third column show the response of the 1/3rd octave band centred at 5 kHz. The first row shows the results of the tests for the source at 0° (on axis). The second row shows the results of the tests for the source at +30° off axis. The third row shows the results of the tests for the source at 60° off axis.

other two lines that can be seen creating an X like configuration in flat panel 0°. This X is located in front of the main reflection and is located at approximately sample 4500.

The Convex Diffuser design yields a more complex color map (Figure 6.3) and it may be best to begin with the on axis source position, off-axis receiver position first (top of the color map). For the extreme off-axis case's receiver at 180° there is only a single strong reflection. Following the receiver responses towards the 0° receiver position, there are five distinct reflections that branch out from this point. Following the plots from Convex Panel 90° to Convex Panel 0° two of these curve forward as they are closest to the source and these are the reflections off of the sections of the poly-cylinders that face those receivers. The other two that are more delayed and attenuated are the result of reflections from the poly-cylinders on the opposite side of the main poly-cylinder as dictated by the design. The reason for the attenuation in Convex Panel 90° and 60° is because only the lower frequencies can diffract around the main poly-cylinder. This effective filtering which is controlled by the rules of wave

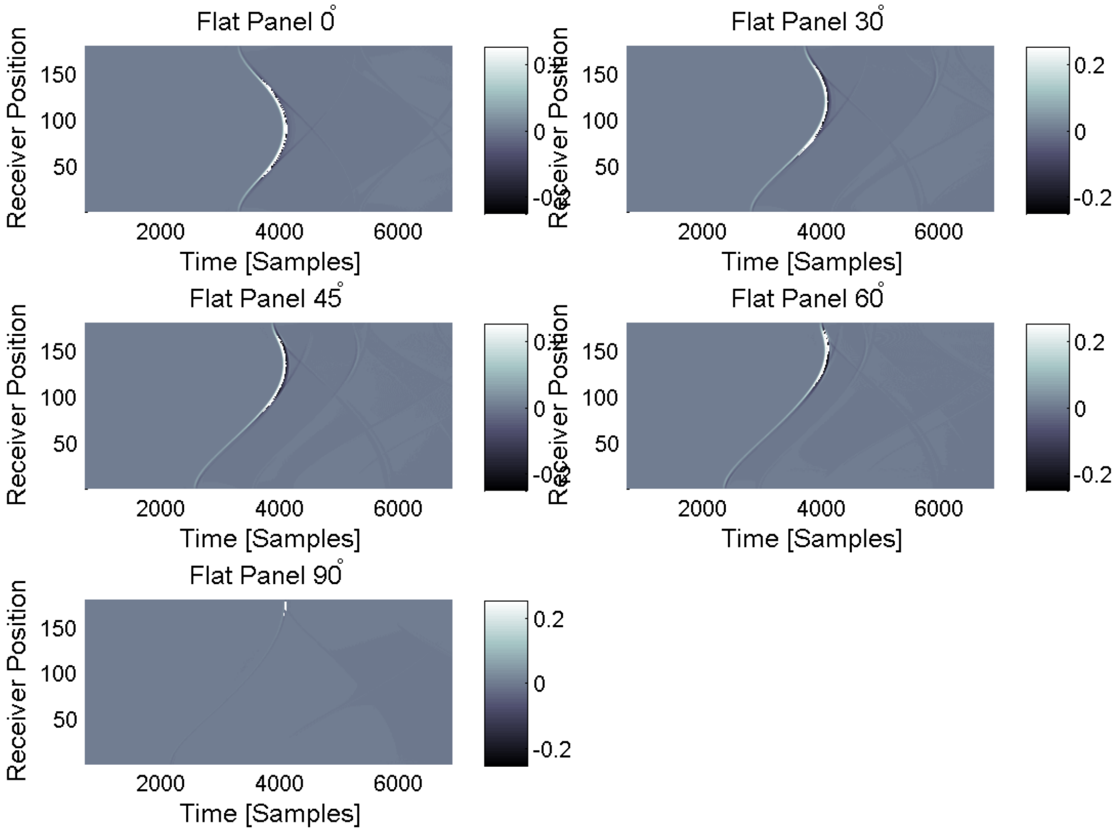

Figure 6.2: This group of colormaps display the results of the flat panel in an anechoic environment. Each colormap is a test for a given source position. In other words, Flat Panel 0° shows the results of the flat panel at 0° on axis. The z-axis (color axis) is in Pascals.

diffraction basically dictates that at the extreme receiver positions, there are two reflections that result in very little interference and resemble the incident wavefront and one of them (0° position) is severely attenuated. The other more median positions such as the on-axis receiver will yield a wavefront that is less attenuated then the 0° position and offers more interference than either extreme.

As the source position is moved towards the on-axis position (Convex Panel 90°), the reflections become more equally attenuated at the extreme positions and result in a single wave with some "oscillatory" behaviour that occurs over a period of 0.0011 seconds (basically the original wave). The oscillations are actually caused by a series of reflections that arrive at repetitive intervals. However the other receiver positions receive more interfering reflections over a period of time about 10 times that of the extreme receiver positions. Convex Panel 0° reveals that in the broader context, the extreme receiver positions yield a similar reflection to the source sound while the on-axis receivers are located such that there are more interfering reflections.

The concave diffuser displays different behaviour as shown in 6.4. At the extreme source

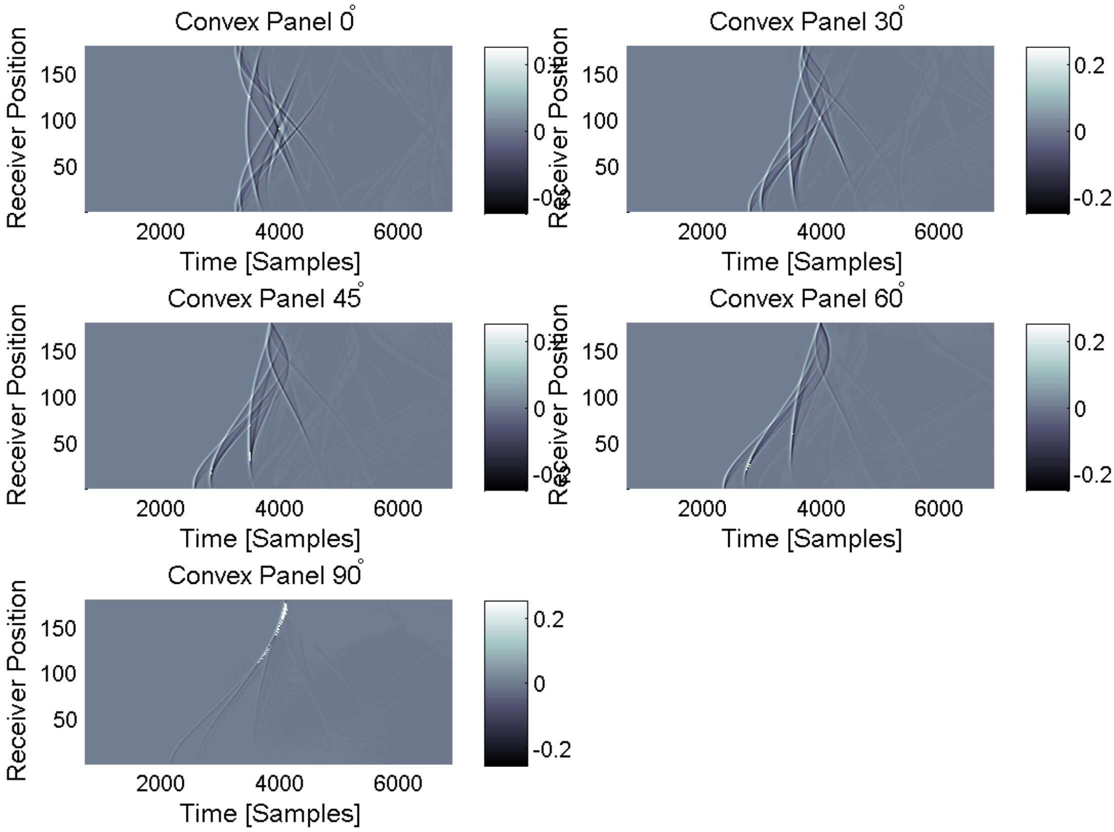

Figure 6.3: This group of colormaps display the results of the Convex Diffuser in an anechoic environment. Each colormap represents a test for a given source position. The z-axis (color axis) is in Pascals.

positioning (off-axis), the extreme receiver positions yield equal amplitude. However, there are other reflections that are the result of both edge diffraction and reflections within the poly-cylindrical curves. They are severely attenuated due to the filtering effects of wave diffraction discussed in the case of the convex diffuser. The lower frequencies (longer wavelength) can diffract around the separation between the poly-cylinders. The higher frequencies are reflected by the surfaces. Depending on the angle of incidence, the reflection can be delayed for the entire time take to travel around the poly-cylinder. However, this only occurs in that specific circumstance. Ultimately, where this design displays its different behaviour is at the on-axis source response (Concave Panel 0°). In this scenario, the reflected waves create a window in time (roughly around sample 4290) where the pressure is concentrated. This concentration of waves is due to the fact that some reflected components of the incident wave travel, approximately, the same distance.

The convex and concave diffusers are inverse designs and when compared to one another they demonstrate an important idea. Convex Panel 0° reveals that the first reflection received at the extreme receiver positions and the first reflection received on axis are of similar amplitude. In contrast, Concave Panel 0° reveals that the first reflection received at the

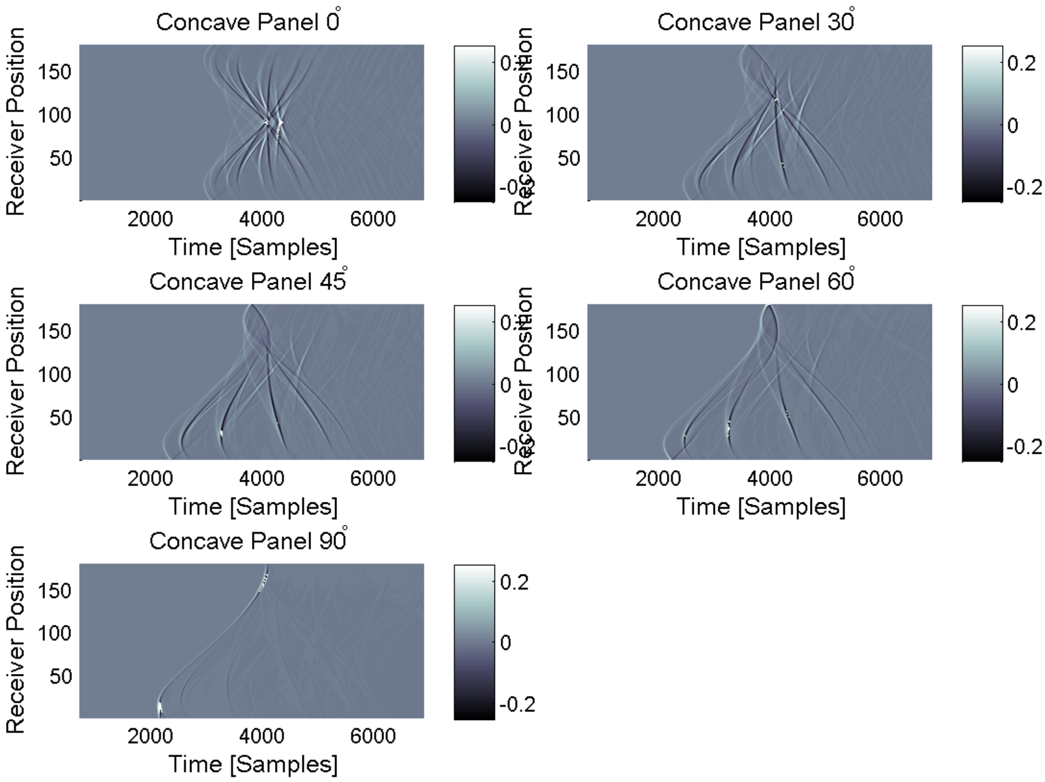

Figure 6.4: This group of colormaps display the results of the Concave Diffuser in an anechoic environment. Each colormap represents a test for a given source position. The z-axis (color axis) is in Pascals.

extreme receiver positions is severely attenuated compared to the the first reflection received on axis. Again, this is due to wave diffraction and it is wavelength dependant. This same phenomena can be revealed through the use of polar plots the colormap just has other benefits. This behaviour points towards a design trade-off between the ability for a surface to diffuse a wave from a number of angles of incidence versus the ability for a surface to offer temporal distribution over a larger area.

The Triangular Diffuser is the first design that exhibits asymmetry and it is unsurprising that the distribution of reflections is asymmetrical as shown by 6.5. This design is difficult to judge for effectiveness over a number of source positions as strong reflections are not evenly spread across the receiver positions for this design.

Each reflected wave that is clearly shown, comes from a face of the triangle. Throughout all of these plots, there are specific locations where pressure is concentrated just like with the concave diffuser. These can be more easily seen as white and black areas. These concentrations are caused by points in time when reflected waves meet at a specific receiver position at the same time. For example:

1. At Triangular Panel 0° there are concentrated pressures at approximately [position 50,

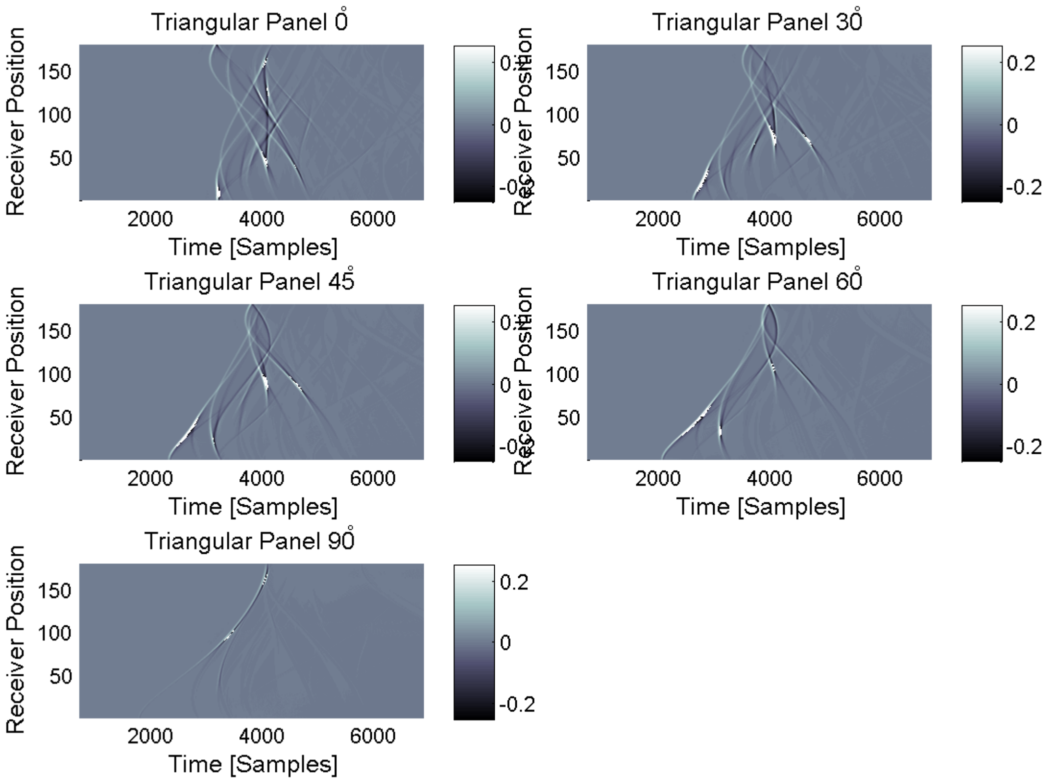

Figure 6.5: This group of colormaps display the results of the Triangular Diffuser in an anechoic environment. Each colormap represents a test for a given source position. The z-axis (color axis) is in Pascals.

sample 4000] and [position 10, sample 3500].

2. At Triangular Panel 30° there are concentrated pressures at approximately [position 75, sample 4000] and [position 75, sample 5000].

These are only a few amongst others in each graph. Unlike the concave diffuser, these concentrations do not exist at one point in time or position. Furthermore, they are not spaced evenly through time or amongst receiver positions. These concentrations change in position and time as the angle of incidence changes. However, there are a number of edge diffraction effects from the apex of the triangles as well. These can be seen as the attenuated areas of a reflected wave. These areas are usually the reflections with earliest arrival. “Usually” is the operative word because this design does not consistently have all apexes of the triangles yielding the first reflection as source positions change.

Like the triangular diffuser, the FM diffuser exhibits asymmetry and again, it is difficult to judge’s where stronger reflections will occur. The concentrations change in position and time as the angle of the source changes. As a much simpler shape (like the Flat Panel) there are less resulting reflections. Less double reflections occur due to the fact that there are only two main protrusions from the geometry. 6.6 reminds us that one of the protrusions is smaller

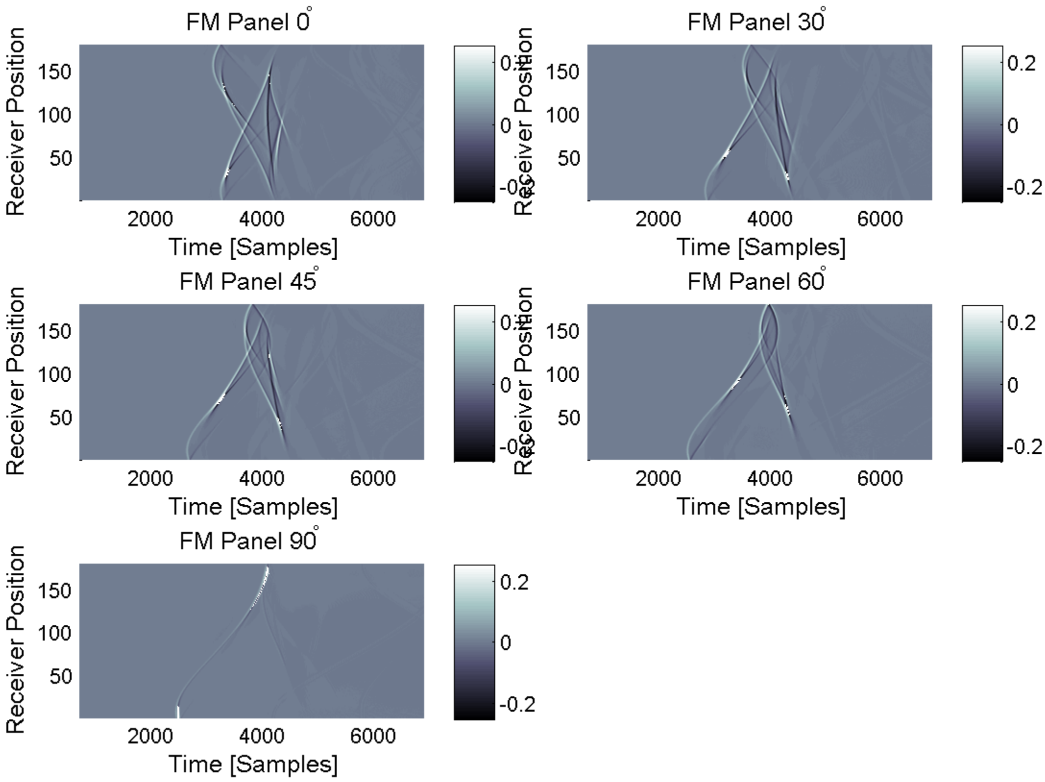

Figure 6.6: This group of colormaps display the results of the FM Diffuser in an anechoic environment. Each colormap represents a test for a given source position. The z-axis (color axis) is in Pascals.

than the other. There are few edge diffractions to speak of as there are only two edges. Furthermore, any disturbances from edge diffractions are likely to be attenuated and not receivable to the other receiver angles because the wavelength and size of the edge diffractions are smaller compared to the size of the two protruding sections.

The Schroeder diffuser yields a color map with a number of smaller "ripples" that are the result of the delayed reflections of wave propagation down the wells. This is similar to the concave diffuser however, the Schroeder diffuser yields a much larger number of delayed reflections due to the larger number of corrugations. Another similar characteristic of the Schroeder diffuser is the attenuation effects at the extreme receiver positions. The behaviour demonstrated seems to reinforce the idea of the design trade-off discussed earlier between the ability for a diffuser to scatter sound temporally and offer that behaviour across all angles of incidence.

This section will now be concluded to reinforce and remind what the results of this specific simulation shows. As can be expected, different diffuser geometries will interact with an incident sound wave and exhibit different reflection behaviour. The more complex a surface is (more corrugations, variation in surface geometry) the more reflections that can be expected.

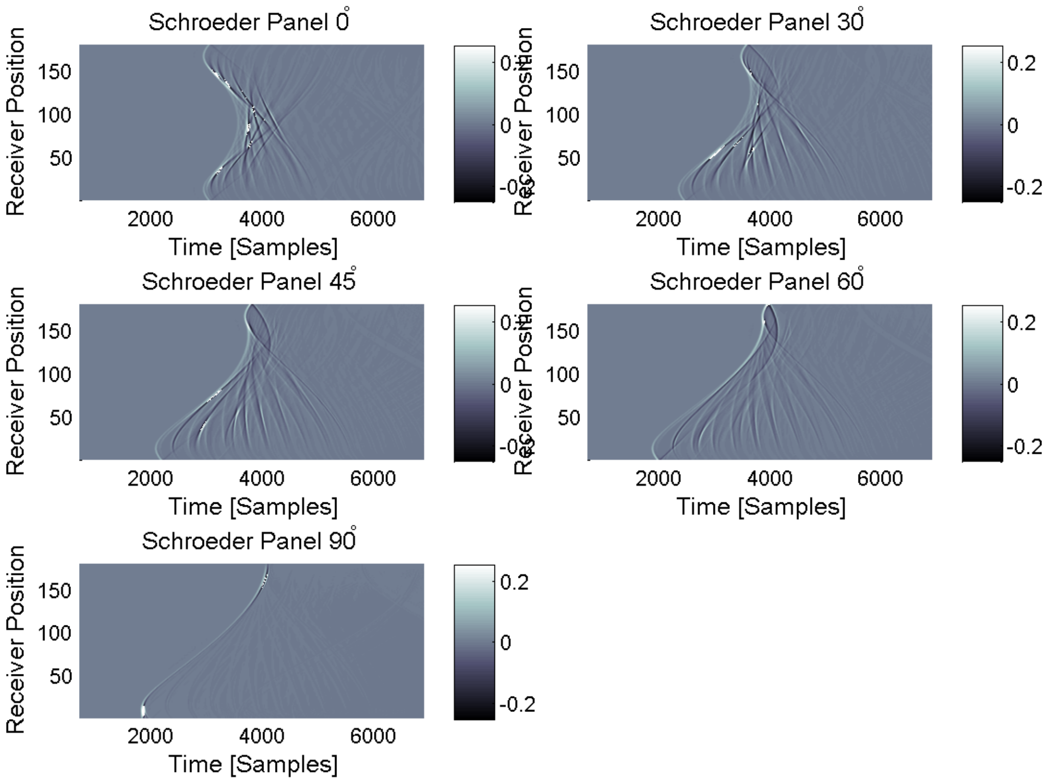

Figure 6.7: This group of colormaps display the results of the Schroeder Diffuser in an anechoic environment. Each colormap represents a test for a given source position. The z-axis (color axis) is in Pascals.

However, the more important behaviour observed is that any diffuser geometry will not hold its ability to scatter sound temporally or spatially over all angles of incidence. These diffuser designs are based off of a criteria to be wall mounted and so they are subject to a cuboid constraint. Therefore, when the wave interacts along the design axis (the axis of distortion of the surface) then they yield whatever behaviour was intended and work most efficiently. However, when the wave does not interact along the design axis, the ability to scatter sound spatially or temporally becomes less effective. This happens gradually over the angles of incidence and when the source is at the extreme off axis position, the diffusers behaves as a flat panel would with that same angle of incidence. The reason is because the variations or distortions in surface geometry will impede the propagation of a wave.

6.2 Experiment 2: Data and Analysis

Experiment 2 examined the effects of the different diffuser geometries in a simulated 2D small room. Figures 6.8 - 6.9 illustrate the broad band Schroeder curves of the impulse response of each test. The reason to look at the Schroeder Curve and reverberation time, is because we must know if the reverberation time changes to a value outside of what is recommended by convention. The amount of absorption in this configuration means that this room's reverberation time does not change dramatically from source position to source position for a given diffuser geometry.

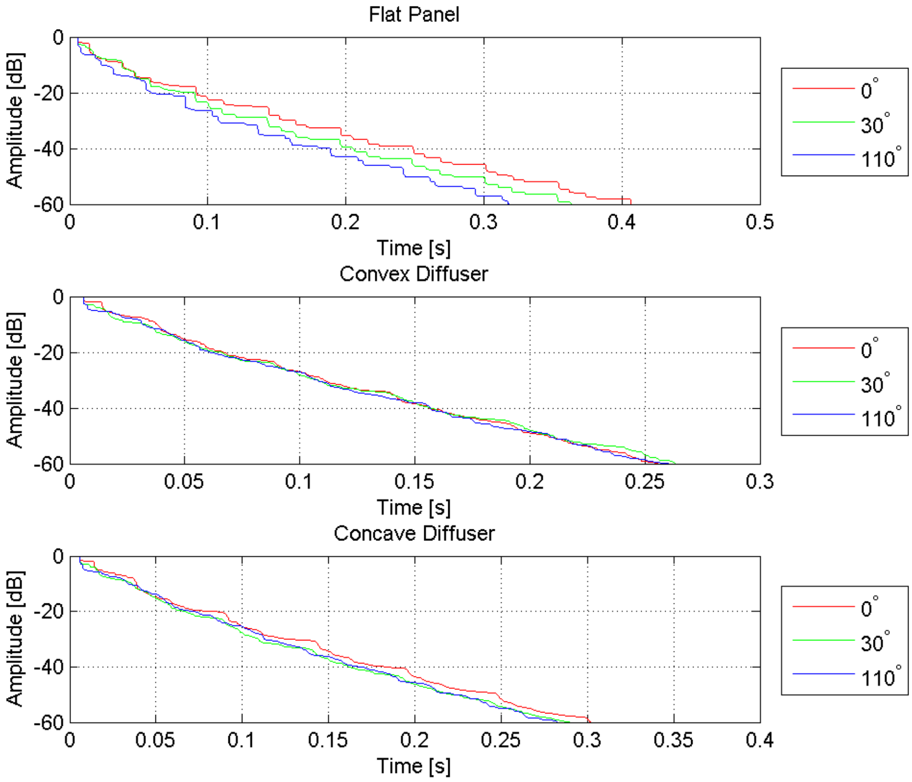

Figure 6.8: These are the schroeder curves for the Flat Panel, Convex Diffuser and Concave Diffuser. Each line plot uses a separate coloured line for each source position.

Figure 6.8 illustrates that the Flat panel gives the widest variation of reverberation times, about a 100 ms range. This is not surprising as the reflections are not diffused. These graphs show that for a given diffuser geometry, one could expect similar decay times no matter where the source position was placed, as evidenced by the tighter grouping of the Schroeder Curves. The most varied of these diffuser geometries is the Schroeder Diffuser which has a max variation of about 50 ms. This time difference is unlikely to be noticed in subjective tests according to [Cox et al., 1993]. The reason why it may vary more in the range of reverberation values is due to the fact that this design is most similar to a series of flat panels and therefore, the diffraction effects for different angles of incidence are what lead to different reverberation times. Something else to note in these figures is that the reverberation time varies from diffuser geometry to diffuser geometry. However, for a given diffuser geometry and varying source positions, the reverberation time does not change to values outside of a 50 ms time window.

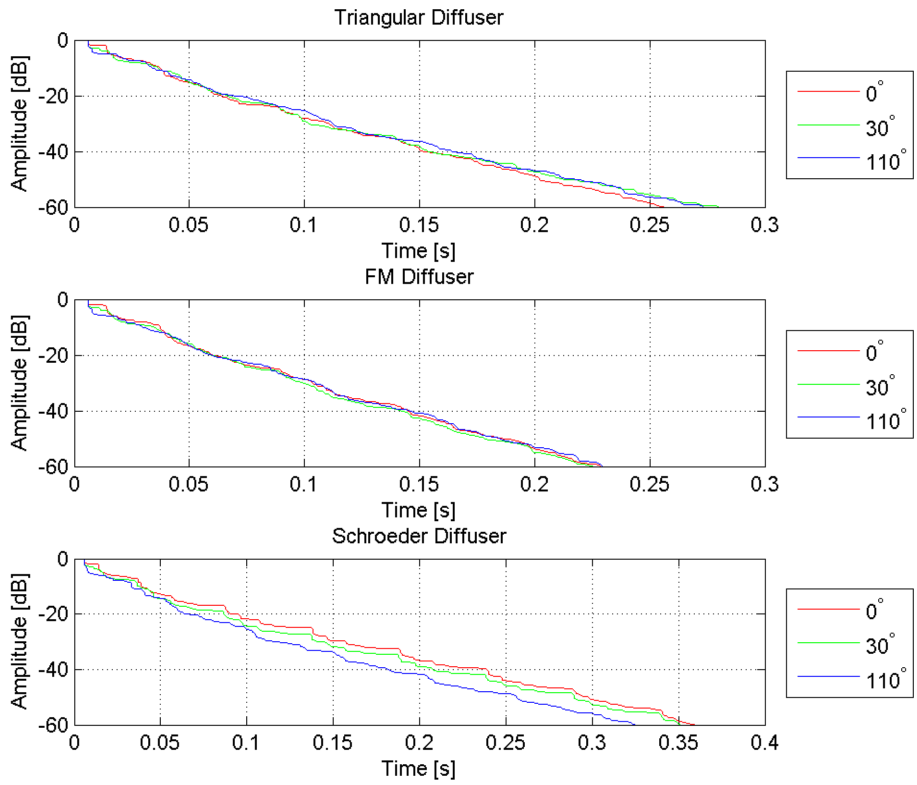

Figure 6.9: These are the schroeder curves for the Triangular Diffuser, FM Diffuser and Schroeder Diffuser. Each line plot uses a separate coloured line for each source position.

The next set of graphs hope to reveal if the diffuser designs have audible frequency domain effects when utilized within this small room simulation. The frequency response is shown for every 3rd octave band instead of showing the narrow band frequency response because this resembles the approximations of human hearing (namely critical bands). Therefore, changes in timbre can be identified by using the frequency domain to highlight temporal effects. There are a number of challenges when testing audibility. Human perception of audibility is not constant for a given sound pressure level across all frequencies. In order to establish an audible threshold, it may be best to see if (for a given critical band) a given diffuser creates a 3 dB or greater difference compared to a flat panel. This would correspond with the threshold of disturbance at 50 ms offered by Kuttruff. The reason why the "ball-park" method of 10 dB is not used is because we can expect a 10 dB drop in level after 50 ms (according to the Schroeder curves). The data presented is the response from 300 Hz to 5 kHz because these represent the lowest possible wavelength to diffract and the upper usable limit of the scale model (Experiment 3).

Figure 6.10 shows the 3rd octave band normalized frequency response for all diffuser designs with the source located at the 0° position. Overall, it can be said that there is a possible

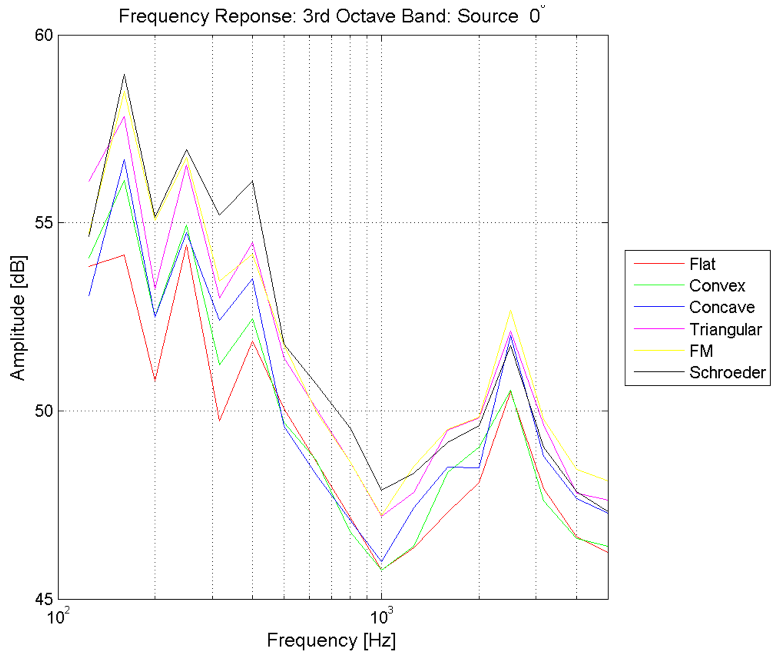

Figure 6.10: 3rd octave frequency response of the room with the source at 0°Ṅormalized to the 3rd octave frequency response of the source function.

audible difference between the different diffuser designs. The range in magnitude when comparing adjacent 3rd octave bands is decreased when using a diffuser compared to a flat panel. Despite following the same trend, the Schroeder and triangular diffuser designs display a consistent audible difference compared to the flat panel (no diffuser). The convex diffuser has the closest relationship to the flat panel. The concave and FM (broad curve) diffusers exhibit an inconsistent audible difference compared to the flat panel. One possible reason why these results occur is because while two of the diffusers are not the interacting with the wave along their design axis, the diffuser on the back wall is interacting with the wavefront along its design axis (arguable this might be enough).

Figure 6.11 shows the 3rd octave band normalized frequency response for all diffuser designs with the source located at the 30° position. This graph illustrates that when the angle of incidence changes there is no audible difference between the different diffusers (for this given source position). For this given source position, +30° , none of the geometries sound different than a flat panel. This graph illustrates that, for a given, 3rd Octave Band, the different diffuser geometries do not yield a difference beyond 1 dB when compared to each other or the flat panel. The basic reason as to why is because the wavefront does not interact with any of the diffuser geometries along their design axis. Therefore, each diffuser is not disturbing the wavefront as efficiently as it is intended to.

Figure 6.12 shows the 3rd octave band normalized frequency response for all diffuser designs with the source located at the 110° position. This graph illustrates that when the angle of incidence changes again, there is a whole new relationship. As with the 30° position, the type

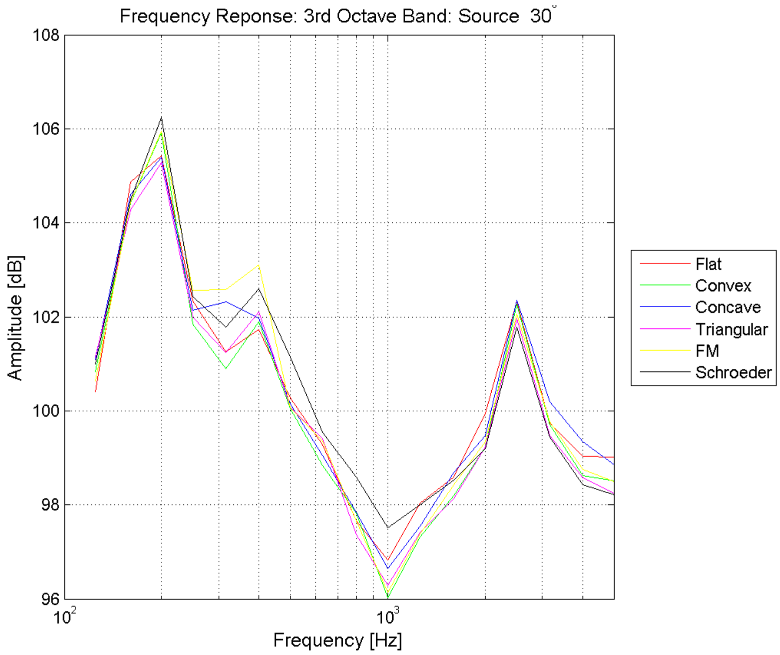

Figure 6.11: 3rd octave frequency response of the room with the source at 30°Ṅormalized to the 3rd octave frequency response of the source function.

of diffuser geometry does not offer a significant audible difference across these 3rd octave bands compared to a flat panel. However, at the 300 Hz 3rd octave band, the concave, FM and Schroeder diffusers do offer an audible difference (compared to a flat panel).

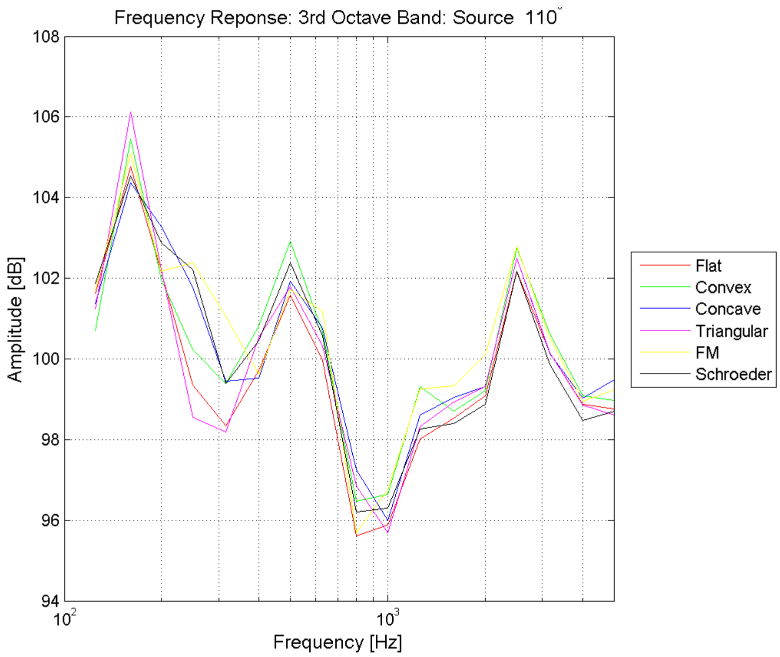

Figure 6.12: 3rd octave frequency response of the room with the source at 110°Ṅormalized to the 3rd octave frequency response of the source function.

A superficial examination would convey that there is no audible difference for different diffusers. If only the standard positions for a stereo configuration were tested, then these graphs would illustrate that there is no audible difference between diffuser designs. However, these graphs also illustrate that a diffuser can effect the response of a room as the angle of incidence changes. Further contemplation reveals that over the broader scope, these graphs seem to dictate that the diffuser designs create audible differences when the wave propagation interacts along the appropriate design axis.

This is in alignment with the behaviours dictated by the previous anechoic simulation results. At the steeper angles of incidence, created by moving the source position, the ability to diffuse the reflection is greatly diminished and even the most varied geometry exhibits behaviour similar to a Flat Panel.

As shown in Figure 6.10, if the wave propagation is on-axis, the Schroeder design demonstrated more effectiveness than the other designs. While the FM, triangular and concave designs demonstrate the ability to sound different than a flat panel, they do not exhibit the same degree of consistency between adjacent 3rd octave bands and can be deemed as offering less ability to reduce colouration.

This is not to say that one diffuser sounds worse than another. The data dictates that these diffusers must be used with the correct orientation of the face towards the incident propagation in order to achieve the maximal effect. This orientation should be identified as the combination of yaw and pitch as to not be confused with face orientation which will be identified as roll. That is to say, that the typical method of mounting a diffuser flush or flat with a wall or boundary is not always the best way to utilize these diffusers. Therefore, if one was to use these diffuser in this typical manner then there is little audible effect.

6.3 Experiment 3: Data and Analysis

This section will present and examine the data produced by a 3D scale model. Figures 6.13 - 6.15 illustrate the 3rd octave band Frequency Response of the scale model. The scale model offers the ability to experiment with face orientations (face orientations which will be identified as roll) of the diffuser as well as the type. For each graph, the triangular diffuser is represented as red, the convex diffuser is green the concave diffuser is blue. Lastly, each frequency response is limited to the range of 300 Hz - 2 kHz (full scale).

Figure 6.13 illustrates the response of the room for the various orientations of the diffusers with the sources located at the 0° position. The first thing to notice is that the frequency response for each diffuser of a given orientation is similar. The exception to be noted is the response of the Convex Diffuser when all diffusers are in the horizontal orientation. This

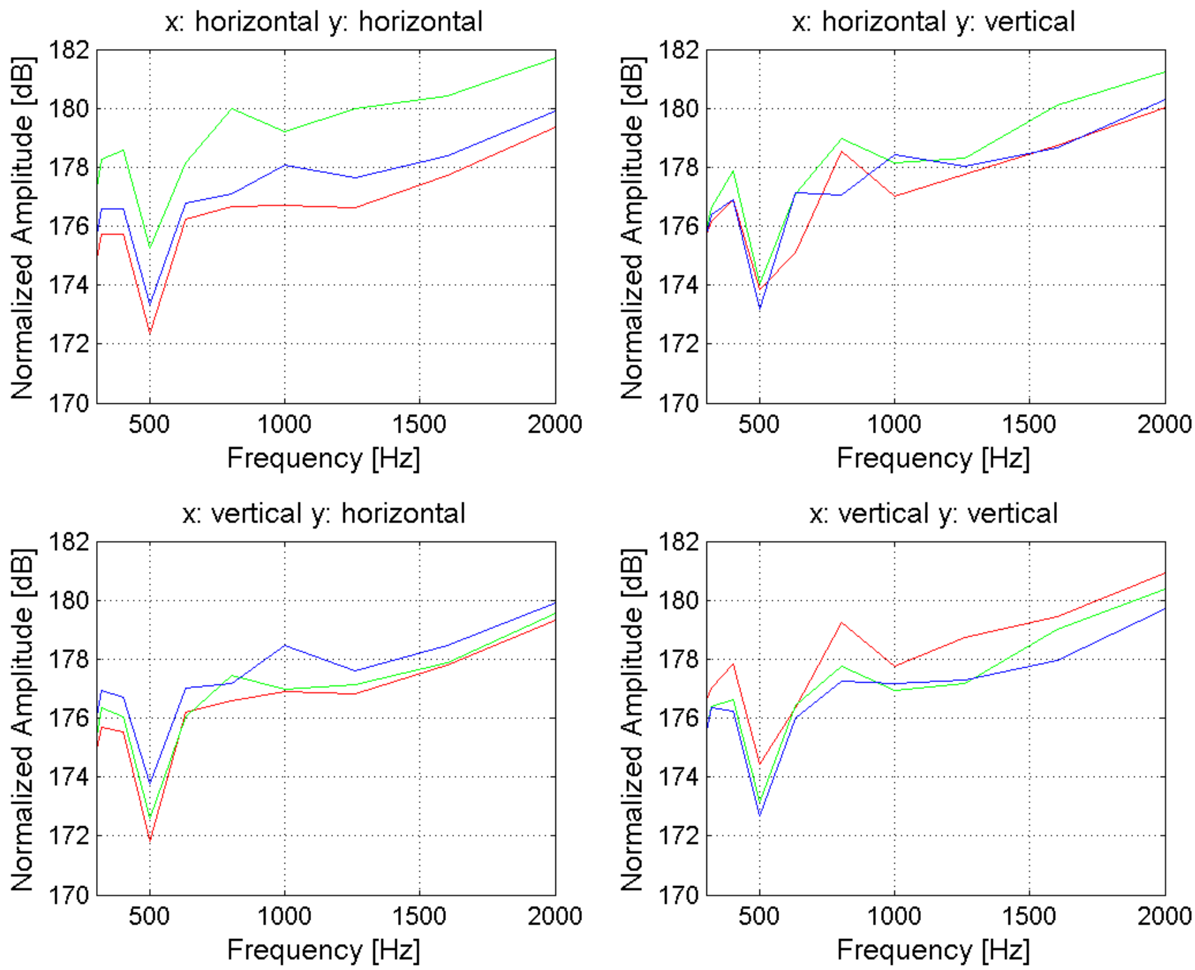

Figure 6.13: This is the 3rd octave band frequency response for the different orientations with the source position at source 0° (on axis). Red represents the triangular diffuser. Green represents the convex diffuser. Blue represents the concave diffuser. The response is normalized in order to remove the response of the transducer.

appears to be the only audibly different diffuser. From graph to graph, the orientations seem to effect the frequency responses in minor ways. For the Triangular Diffuser (red) , a vertical orientation for the "y-axis" yields a 2 dB gain at 800 Hz and a 2-3 dB gain at 500 Hz.

Figure 6.14 illustrates the response of the room for the various orientations with the source located at the 30° position. The frequency response for each diffuser of a given orientation is similar. The exception to be noted is the response of the Triangular Diffuser when all diffusers are in the horizontal orientation. From graph to graph, the orientations seem to effect the frequency responses in minor ways as no difference beyond a 1-2 dB difference occurs.

Figure 6.15 illustrates the response of the room for the various orientations with the source located at the 110° position. The frequency response for each diffuser of a given orientation is not as closely comparable. Again, the response of the Convex Diffuser (when all diffusers are in the horizontal orientation) is audibly louder but the basic behaviour is similar to the other diffusers for that orientation. The graph with a horizontal "x-axis" and vertical "y-axis"

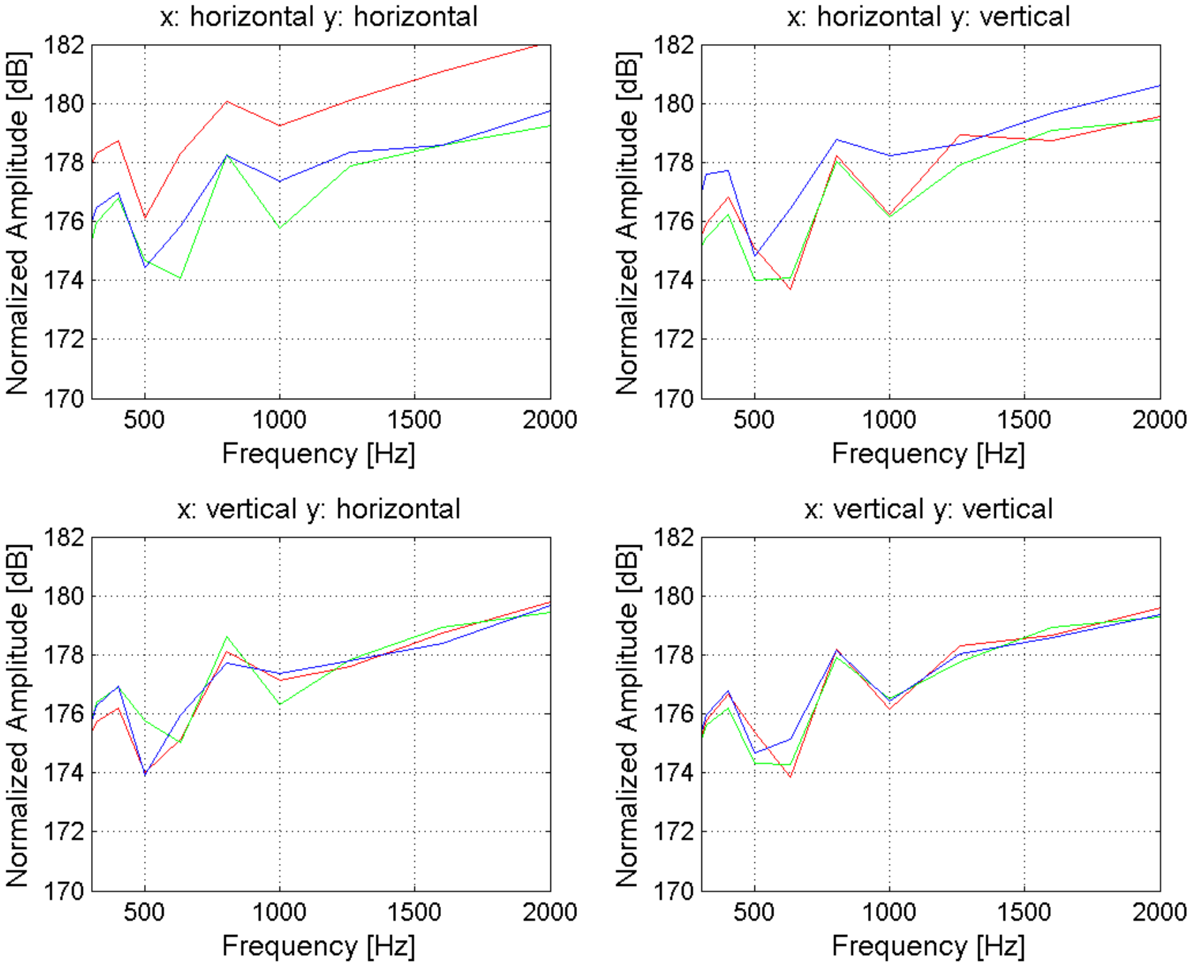

Figure 6.14: This is the 3rd octave Band frequency response for the different orientations with the source position at source +30° (off axis). Red represents the triangular diffuser. Green represents the convex diffuser. Blue represents the concave diffuser. The response is normalized in order to remove the response of the transducer.

demonstrates a unique occurrence where the basic behaviour is not followed. The Triangular Diffuser (red) exhibits an audible boost at the 800 Hz band which yields a 3dB+ difference between the other diffusers.

So what do these results infer? The first question to ask is: Does this data reaffirm what could be expected by the 2D simulation? The second question to ask is: Does this data dictate and audible difference between diffuser types? Does Orientation make a difference?

According to this Scale Model Experiment, there is almost no difference between the frequency response of this room when these different diffuser designs are implemented. This is in concurrence with the 2D Simulation. According to this experiment, there are certain frequency bands that may be audibly attenuated or boosted however, it is not clear whether or not this would be perceived by most listeners as it is a small deviation from the general tonal behaviour. Another factor that this experiment tested is diffuser orientation. This experiment shows that orientation does create measurable differences in the response of a room but not

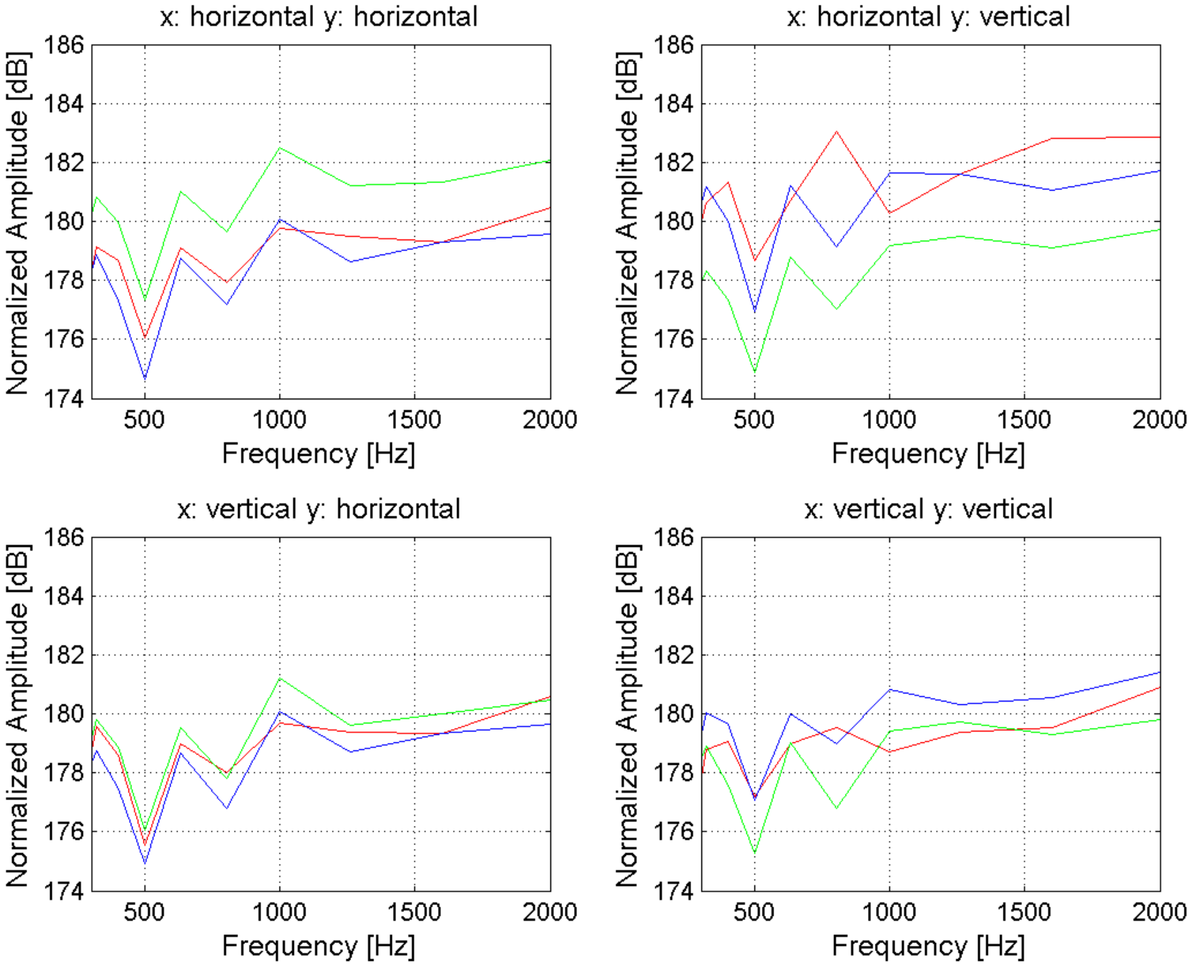

Figure 6.15: This is the 3rd octave band frequency response for the different orientations with the source position at +110° (off axis). Red represents the triangular diffuser. Green represents the convex diffuser. Blue represents the concave diffuser. The response is normalized in order to remove the response of the transducer.

consistent possibly audible differences. These results should not be considered as comprehensive as this experiment only tested half of the designs tested in the FDTD model.

These figures dictate measurable difference in room response. Part of this is due to how large these geometries are within this scale model. However, part of this may be due to change in reflection directions when the diffusers are reoriented. When a particular axis is denoted as horizontal, then the 2D dispersion happens perpendicular to that axis. In other words, x-vertical means that the diffusers on the x axis will disperse reflections laterally in relation to the listening position. According to Cox et al. [1993]:

> It was found that when changes are made to concert halls, the audience are most likely to perceive the changes as ones of spatial impression rather than clarity. Also acoustician can gain the most from a hall by paying the attention to lateral sound levels.

If this is true for concert halls, then it is difficult to know if this is true for small rooms. This is partly due to the fact that this experiment was unable to conduct subjective measurements and the scale model did not have enough physical space to get measurements to be used for subjective evaluation and binaural simulation.

However, it is possible (and this is speculative) that the data from this experiment may point towards a similar conclusion. In these measurements in Figure 6.13 - Figure 6.15 show that when the x-axis diffusers were arranged in such a way that they did not effectively address lateral reflections (when x = horizontal) then the response of the different diffusers was more varied. The change of the y-axis diffusers seemed to have had little influence on the response of the room. Is this audible in terms of timbre? Probably not, as stated above. However, perhaps one problem with this experiment is that some of these diffuser designs may be better than others and therefore, this can cause different effects in terms of spatial impression. Again, this is not something that can be really discussed without the use of subjective tests.

Chapter 7

Conclusion

This research was conducted to better understand how diffusers interact with a wave in the context of small rooms. The fundamental question was: Can one hear the difference between different diffusers? To test this, a number of experiments were conducted to see how different diffuser designs affected the acoustic characteristics of a small room. All of the diffusers tested are meant to be wall mounted and therefore, are subject to a cuboid constraint as the distortions of the surface take place along one principle design axis.

The first experiment tested the behaviour of a single diffuser in an anechoic environment in order to establish an understanding of the dispersion characteristics for each design. This test revealed that more distortions in the surface may yield more temporal disturbances provided that the surface distortions actually change the path length of wave propagation from the source to the receiver. These disturbances in the surface will affect the manner in which a given geometry scatters sound spatially because the protrusions and corrugations will impede the propagation of a wave and the laws of diffraction dictate the filtering characteristics that will be experienced. The most important finding from this experiment is that the ability for a diffuser to scatter sound spatially or temporally (whatever it is designed for) will not hold consistent over all angles of incidence. In fact, the diffusers tested work most efficiently when wave propagation is on axis. For the cases where the source is located at the extreme angles off axis (oblique incidence), the behaviour is no different from a flat panel. This is because the flat panel and diffusers do not change wave propagation temporally or spatially at those angles due to the simple fact that no distortions in the surface interact with the wave.

The second experiment tested the behaviour of multiple diffusers in a studio environment in order to establish an understanding of how these different diffuser designs affected colouration. The impulse response of each simulation was divided into 3rd octave bands in order to identify changes in timbre. The Finite Difference Time Domain Room Simulation shows the results of these considerations of the anechoic tests in a more complicated scenario. It appears, that for this given room configuration, the diffusers yield an audible difference when wave propagation is on axis. Otherwise, the effects are negligible.

The third experiment used a scale model in order to test the behaviour of multiple diffusers in a 3D studio environment. The Scale Model was far more limited in scope as discussed in the section labelled "Further Work". The major limitation is that it did not test all of the different diffuser designs used in the FDTD simulations. The scale model did yield some results that seem to dictate that the face orientation ("roll"), may cause some differences in the frequency domain but, they are unlikely to be consistently audible.

All of these experiments demonstrate that the differences between diffuser types is measurable but not necessarily audible and that there are likely to be other considerations that are far more important than simply which diffuser to use. Not surprisingly, each diffuser design may yield an audible difference compared to a Flat Panel or the absence of a diffuser. Furthermore, The temporal scattering aspects of a diffuser design may reduce colouration however, if the wave propagates at an angle towards the diffuser that is incompatible with its design, then it is unlikely to operate any differently than another diffuser or (at times) a flat panel. Lastly, different diffusers may address colouration more effectively than a flat panel, but this does not necessarily, yield a consistently audible difference between each other.

7.1 Further Work

This project has demonstrated that Finite Difference Time Domain offers a viable solution for simulating a small room. The data gathered by the simulation and the scale model experiment point in a concurrent direction with implications. However, there are a number of limitations to the project that must be addressed before any further work may continue to verify these implications.

The FDTD simulations used in this thesis were limited to two dimensions and humans observe sound in three dimensional space. Therefore, the FDTD simulation should be expanded to three dimensions. Furthermore, these experiments only tested diffusers designed to scatter along a single plane. A quadratic residue sequence, such as the one used for the Schroeder diffuser, can be expanded along another dimension which may allow for more complex scattering behaviour. Curved diffusers using bi-cubic design can also be expanded to two dimension. This experiment did not address any of these geometries as this extended variation was beyond the scope of the project. The reason it would be interesting to investigate the designs is because, even though they are subject to the same cuboid constraint, the more complex scattering behaviour may be more robust and address colouration more effectively.

Further work attempted on this project should address a comparison with other room designs. As revealed by the anechoic and room simulations, the pitch and yaw orientation of a diffuser face to an incident wave determined not only how the wave was reflected but also was the main contributing factor to audible differences in colouration effects. This is a strong argument for the use of Reflection Free Zones and other rooms with complex geometries due to the fact that there are boundaries that have a number of orientations to be taken advantage of. The other consideration is that RFZ designs are simply more common than LEDE designs.

However, to continue further work, a different FDTD scheme must be implemented in order to solve these problems. Not only should the simulation be 3D but, a second order accurate scheme should be implemented in order to efficiently described the geometry of the medium at the boundaries as well as spread the dispersion error. As stated earlier, the paper by Konrad Kowalczyk is the most comprehensive summary as to the different FDTD methods and their effectiveness.

Lastly, these experiments yielded certain situations where it was not clear if a human could hear the difference between the different diffusers. Therefore, it would be advisable for any further work to create auralization simulations for subjective testing. To do this, the simulations would have to incorporate a human head with 2 receivers at the ear positions. This head would have to be accurate enough to account for diffraction effects as well as absorption.

There is the possibility that this project was still too large in scope and perhaps it would be advisable to explore only one type of geometry such as Quadratic Residue Sequences, Primitive Root Sequences and the like. However, this project may have indicated the possibility that conventional wall mounted diffuser designs that use a single cuboid constraint are possibly not adequate enough to address diffusion over a number of angles of incidence. Perhaps it is time to look at creating other types of diffusing structures that are more effective at interacting with oblique sound.

References

Jonathan A. Hargreaves. *Time Domain Boundary Element Method for Room Acoustics*. PhD thesis, Acoustics Research Centre School of Computing Science and Engineering University of Salford, UK, 2015.

Daniel A. Russell. *Absorption Coefficients and Impedance*. 1 edition, 2013.

Acoustics.salford.ac.uk. Room sizing tutorial — acoustics, audio and video — university of salford, a. URL `http://www.acoustics.salford.ac.uk/acoustics_info/room_sizing/?content=methods`.

Acoustics.salford.ac.uk. Recording studio design tutorial — acoustics, audio and video — university of salford - a greater manchester university, b. URL `http://www.acoustics.salford.ac.uk/acoustics_info/studio_design/`.

Studios Air. *Studio 2: Image 1*. 2015. URL `http://www.airstudios.com/the-studios/studio-2/images-studio-2/`.

Shen Baoli, Ren Wu, Gao Benqing, and Yang Shiming. The analysis of several diffusers in a reverberation chamber by fdtd method. *International Conference on Microwave and Millimeter Wave Technology*, 3, 2002.

Sylvio R. Bistafa and John S. Bradley. Predicting reverberation times in a simulated classroom. *The Journal of the Acoustical Society of America*, 108(4):1721–1731, 2000. doi: 10.1121/1.1310191.

D. Botteldooren. Finite-difference time-domain simulation of low-frequency room acoustic problems. *J. Acoust. Soc. Am.*, 98(6):3302, 1995. doi: 10.1121/1.413817.

Jennifer Burg, Jason Romney, and Eric Schwartz. *DIGITAL SOUND & MUSIC Concepts, Applications, & Science*. 1 edition. URL `http://csweb.cs.wfu.edu/~burg/CCLI/Templates/curriculum_index.php`.

Simon Chandler-Wilde and Steve Langdon. *Boundary element methods for acoustics*. Department of Mathematics University of Reading, 1 edition, 2007. URL `http://www.reading.ac.uk/sms03snc`.

Nick Clark. *Tiny FDTD v1.0*. 2015.

T. J. Cox and P. DAntonio. Contrasting surface diffusion and scattering coefficients. In *17th International Conference on Acoustics ICA*, 2001. URL http://www.icacommission.org/Proceedings/ICA2001Rome/5_10.pdf.

T. J. Cox, B.I.L. Dalenback, P. D'Antonio, J.J. Embrechts, J.Y. Jeon, E. Mommertz, and M. Vorlnder. A tutorial on scattering and diffusion coefficients for room acoustic surfaces. 2015.

TJ Cox, WJ Davies, and YW Lam. The sensitivity of listeners to early sound field changes in auditoriums. *Acustica*, 79(1):27–41, 1993. URL http://usir.salford.ac.uk/2425/. LU952 ACUSTICA.

Trevor J. Cox. *Acoustic Diffusers: The Good, The Bad And The Ugly*. 1 edition, 2004. URL http://www.rpginc.com/docs%5CTechnology%5CWhite%20Papers%5CAcoustic%20Diffusers_The%20Good,%20The%20Bad%20and%20The%20Ugly.pdf.

Trevor J. Cox and Peter D'Antonio. Engineering art: the science of concert hall acoustics. *Interdisciplinary Science Reviews*, 28(2):119–129, 2003. doi: 10.1179/030801803225010412.

Trevor J Cox and Peter D'Antonio. *Acoustic Absorbers and Diffusers*. Taylor & Francis, 2009.

Michael Dinsmore. Acoustical material modeling parameter sensitivities, 2009.

Professor Steven Errede. *Illinois Phys 406 Lect 10 Part 2*. 2015. URL https://courses.physics.illinois.edu/phys406/lecture_notes/p406pom_lecture_notes/p406pom_lect10_part2.pdf.

F. Alton Everest and Ken C Pohlmann. *Master handbook of acoustics*. McGraw-Hill, 2009.

Angelo Farina, Michele Zanolin, and Elisa Crema. *Measurement of sound scattering properties of diffusing panels through the Wave Field Synthesis approach*. Dipartimento di Ingegneria Industriale, Universit di Parma, 1 edition. URL http://pcfarina.eng.unipr.it.

B.M. Fazenda and J.A.S. Angus. Internal acoustic design for a multi-channel control room - measurement and perception. *Institute of Acoustics*, 24, 2002. URL http://usir.salford.ac.uk/9454/1/IOA_Proceedings_Vol24-8_RS18-2002.pdf.

Suzanne Fielding. *The basic equations of fluid dynamics*. 1 edition, 2007. URL http://community.dur.ac.uk/suzanne.fielding/teaching/BLT/sec1.pdf.

Aki Haapaniemi. *Simulation of Acoustic Wall Reflections Using the Finite-Difference Time-Domain Method*. PhD thesis, Aalto University School of Electrical Engineering.

Tor Halmrast. *Coloration Due to Reflections, Further Investigations*. 1 edition, 2015. URL http://www.akutek.info/Papers/TH_Coloration2007.

J. A. Hargreaves and M. Wankling. Implementing wave field synthesis in an itu spec listening room part 2: Bass without modes. *Proceedings of the Institute of Acoustics*, 2011. URL http://usir.salford.ac.uk/19369/1/RS2011_JAHargreaves_paper.pdf.

Jyri Huopaniemi, Lauri Savioja, and Matti Karjalainen. *MODELING OF REFLECTIONS AND AIR ABSORPTION IN ACOUSTICAL SPACES - A DIGITAL FILTER DESIGN APPROACH*. Helsinki University of Technology Laboratory of Acoustics and Audio Signal Processing, 1 edition, 1997.

ITU. International Telecommunications Union, 1 edition, 1997. URL http://www.itu.int/dms_pubrec/itu-r/rec/bs/R-REC-BS.1116-1-199710-S!!PDF-E.pdf.

H Jeong. Source and boundary conditions in finite difference time domain modelling of room acoustics. 2010. URL http://usir.salford.ac.uk/26737/.

Steven G. Johnson. *Notes on Perfectly Matched Layers (PMLs)*. 1 edition, 2010.

Stephen Kirkup. *The Boundary Element Method in Acoustics*. 2007.

R. Kosloff and D. Kosloff. Absorbing boundaries for wave propagation problems. *Journal of Computational Physics*, 63(2):363–376, 1986. doi: 10.1016/0021-9991(86)90199-3.

Konrad Kowalczyk. *Boundary and medium modelling using compact finite difference schemes in simulations of room acoustics for audio and architectural design applications*. PhD thesis, Queens University Belfast, 2008.

Konrad Kowalczyk and Maarten Van Walstijn. A comparison of nonstaggered compact fdtd schemes for the 3d wave equation. 2010. doi: 10.1109/ICASSP.2010.5496043.

Tobias Kufner. Geometrical room acoustics: Raytracing, image sources, 2008.

Heinrich Kuttruff. *Room Acoustics*. Spon Press/Taylor & Francis, 2009.

Knut-Andreas Lie. The wave equation in 1d and 2d.

Nathan Oliveira. *Measurement of the Reverberation Times of a Recording Studio Across the Audio Spectrum*. PhD thesis, 2010.

J. Redondo, R. Pic, B. Roig, and M. R. Avis. Time domain simulation of sound diffusers using finite-difference schemes. *ACTA ACUSTICA UNITED WITH ACUSTICA*, 93: 611–622, 2007.

Thomas D Rossing. *Springer handbook of acoustics*. Springer, 2007.

Per Rubak. *Coloration In Room Impulse Responses*. 1 edition, 2013.

John B. Schneider. Implementation of transparent sources embedded in acoustic finite-difference time-domain grids. *J. Acoust. Soc. Am.*, 103(1):136, 1998. doi: 10.1121/1.421084.

John B. Schneider. *Understanding the Finite-Difference Time-Domain Method*. The School of Electrical Engineering and Computer Science at Washington State University, 1 edition, 2013. URL http://www.eecs.wsu.edu/~schneidj/ufdtd/ufdtd.pdf.

Mike Senior. Armin van buuren producing trance. *Sound on Sound*, 2009. URL https://www.soundonsound.com/sos/aug09/articles/armin.htm.

Sepstanford.edu. The acoustic wave equation, 2000. URL http://sepwww.stanford.edu/data/media/public/sep/prof/bei/fdm/paper_html/node40.html.

J Sheaffer, MV Walstijn, and BM Fazenda. A physically-constrained source model for fdtd acoustic simulation. In *15th International Conference on Digital Audio Effects (DAFx-12)*, September 2012. URL http://usir.salford.ac.uk/23028/.

Jonathan Sheaffer, Maarten van Walstijn, and Bruno Fazenda. Physical and numerical constraints in source modeling for finite difference simulation of room acousticsa). *J. Acoust. Soc. Am.*, 135(1):251–261, 2014. doi: 10.1121/1.4836355.

S. Siltanen, T. Lokki, and L. Savioja. *Rays or Waves? Understanding the Strengths and Weaknesses of Computational Room Acoustics Modeling Techniques*. ISRA, 2010. URL http://www.acoustics.asn.au/conference_proceedings/ICA2010/cdrom-ISRA2010/Papers/O5a.pdf.

A. Varla, A. Makivirta, I. Martikainen, M. Pilchner, R. Schoustal, and C. Anet. Design of rooms for multichannel audio monitoring. *AES*, 16.

Bob Walker. *ROOM ACOUSTICS FOR MULTICHANNEL LISTENING: EARLY REFLECTION CONTROL*. Wave Science Technology Ltd, UK, 1 edition, 2007.

R. Walker. *CONTROLLED IMAGE DESIGN: The management of stereophonic image quality*. BBC: Research and Development Report, 1 edition, 1995.

Kane Yee. Numerical solution of initial boundary value problems involving maxwell's equations in isotropic media. *IEEE Transactions on Antennas and Propagation*, 14(3): 302–307, 1966. doi: 10.1109/tap.1966.1138693.