MASTER

Hybrid acoustic model for sound propagation in a street canyon

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Abstract

In this project, a hybrid model for the propagation of sound is proposed and evaluated. The hybrid method combines the image source method, a geometrical acoustics method, and the diffusion equation method, an energy based method. The image source method is used to calculate the direct sound and early reflections while the diffusion equation method is used to calculate the late part of the impulse response. The stand-alone methods are used to obtain individual results for two cases: a rectangular room and a street canyon. The hybrid method involves combining the results from the individual methods to obtain the impulse response for the investigated cases.
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Chapter 1

Introduction

1.1 Urban Acoustics

With the rapid urbanization of cities, increasing importance is being given to the field of urban acoustics. A significant amount of research is concentrated in the area of noise reduction and more work is being done in the area of ‘sound environment design’ [18], integrating sound quality and acoustic atmospheric perception of urban spaces.

In October 2018, the World Health Organization (WHO) released a document titled *Environmental Noise Guidelines for the European Region* [41] signifying the growing concern of the hazards of noise on the physical and mental well-being of people living in European cities. Prolonged exposure to noise has been linked with various health issues including hearing impairments, cardiovascular problems, stress, sleep disturbance, cognitive impairments in children, as well as psychological problems that can increase the risk of depression [4, 35, 38, 41]. The document provides recommendations for protection from exposure to transportation noise (specifically traffic, railway and aircraft noise), wind turbine noise and leisure noise.

In relation to urban acoustic perception, Yang et al. [42] conducted nearly 9200 surveys in seven cities in five different European countries in order to evaluate the acoustic comfort perception in urban areas. While there was a positive correlation between the measured sound level and a qualitative evaluation of the sound level (noisy to quiet), the correlation between the acoustic comfort and the sound level was less apparent. Hong and Jeon [12] tried to further map out the subjective nature of the perception of sound by using attributes such as pleasant, chaotic, exciting, uneventful, calm, annoying, eventful, and monotonous. They attempt to build a soundscape map to provide a better understanding of the perceived and actual acoustic environment in northern Seoul, Korea.
CHAPTER 1. INTRODUCTION

Both urban noise reduction and the need to design urban areas that are acoustically appealing require a better understanding of urban sound propagation. One of the ways to achieve this understanding is through computational modeling of sound propagation which is used to predict or model the sound field. These predictions can aid in the design of urban areas by improving the overall acoustic quality of a space.

1.2 Computational Modeling of Sound Propagation

This section explains the main modeling methods that are used to describe sound propagation. Understanding the propagation of sound is an important part of the field of acoustics, both in indoor and in outdoor environments. There are several methods of prediction that help to design and construct spaces that are acoustically more appealing or considered to have a higher acoustic quality. There are three overarching prediction methods that are widely referred to: wave-based, geometrical acoustics, and energy-based methods [3, 34, 22, 9]. Figure 1.1 [40] shows a breakdown of the modeling methods for sound propagation.

1.2.1 Wave-based Methods

Wave-based methods solve the fundamental equations governing the propagation of sound in air. Examples of wave-based methods are the finite-element method (FEM), boundary-element method (BEM), and finite-difference time-domain (FDTD) among others, that approximate the solution of the wave equation. FEM and BEM work by discretizing the space being modeled into small volume or surface elements [28]. A major advantage of wave-based methods is that they are able to model sound propagation with a high degree of accuracy [13]. Their main limitation, however, is that they require significant computational power. These methods are also better suited to low frequencies because solving for higher frequencies increases the amount of discretization required to obtain an accurate solution, thereby further increasing the computational load.

Wave-based methods have been used to model urban sound propagation. For instance, Iu and Li [16] investigated the propagation of sound in a narrow street canyon. They proposed a simple analytical model based on the Green’s function, and compared their model against measurements in an anechoic chamber as well as in a typical alley. Their main interest was to study the interference effects caused by reflected rays in a street canyon with a width smaller than 10 m.
CHAPTER 1. INTRODUCTION

Figure 1.1: Classification of models for simulation of sound propagation. Extended to include Energy-based methods. [40].

1.2.2 Geometrical Methods

Geometrical Acoustics (GA) methods have been derived as a result of the similarities between the properties of light and sound [25]. GA methods consider the sound wave as rays, describing straight paths between the source, the boundaries, and the receiver. The main assumption with GA methods is that the wavelengths are small compared to the surfaces of the modeled space, thereby it is better suited to larger spaces and mid- to high-range frequencies. In GA methods, the sound ray is understood to be ‘a small portion of a spherical wave with vanishing aperture which originates from a certain point’ [20]. It has a well-defined direction and the intensity of the sound ray decreases with $1/r^2$, where $r$ indicates the distance between the receiver and the sound source. Diffraction and interference effects are not implicitly taken into account in GA methods. Popular GA methods include the image source method (ISM), ray-tracing, and beam tracing.

The image source method (ISM) draws a lot of attention due to the simplicity of its implementation; much of the research is focused on improving the accuracy of the method. For instance, Brinkmann et al. look into extending the classical ISM for a rectangular room to include directivity [5]. Another paper focuses on the inclusion of phase information to the image source method [24]. As one of the reference methods for this project, ISM is explained in Chapter 2. The applicability of ISM is limited mostly to the early reflections and to relatively simple geometries. This is mainly because of the exponential increase in the number of image sources when increasing the order of reflection of interest, requiring the use of visibility or audibility checks to remove invalid image sources.
1.2.3 Energy-based Methods

The acoustic diffusion equation method, which is an energy-based method, works on the assumption that the propagation of sound energy is analogous to heat transfer or to that of particles moving in a gas. Typically, it has been successfully used to model the sound field in indoor environments that have diffusely reflecting boundaries. The main advantage of the diffusion equation method is that it accurately predicts the late part of the sound energy decay [22]. Navarro et al. [26] investigated the implementation of the diffusion equation method, in a cubic room with four different combinations of absorption coefficients for the walls, floor, and ceiling, using finite difference schemes to solve the differential equations. They studied the accuracy of the simulations in comparison to geometric methods and the computational complexity and calculation time.

While majority of the modeled cases that make use of the diffusion equation are indoors, it has also been used for predictions in outdoor environments like city streets and street canyons. The application of the diffusion equation method to urban scenarios is based on the assumption that the irregular surfaces of the building façades resemble a diffuse boundary [32]. Picaut [30] presented the numerical implementation of the diffusion equation method in a rectangular street and validated the results with an analytical solution. The paper explained how real urban scenarios are much more complex than a rectangular street with a mostly rectangular building arrangement. The main contribution in [30] was the derivation of the finite-difference equations for nodes on the building façade as well as the corners.

The main limitation of this method is in the inherent assumption that requires that the sound reflections are diffuse. This method cannot be used to predict the direct sound propagation nor specular reflections, and it cannot model diffraction [29]. The diffusion equation method is detailed in Chapter 2.

1.2.4 Hybrid Methods

Recent research has shown the development of hybrid methods to be important in overcoming the limitations of the other stand-alone methods. In the context of fast and accurate predictions in the urban environment, Pasareanu [28] proposed a hybrid method that considers a combination of solving the wave equation, through the use of a finite-difference time-domain numerical approximation, and the diffusion equation method. Other hybrid methods focus on modeling reflections that are both specular and diffuse. Tenenbaum et al. [37] presented a hybrid method combining an improved ray-tracing algorithm (a geo-
metrical acoustics method) for modeling specular reflections and a slightly modified energy transition method (an energy-based method) to model the diffuse reflections. Alarcão and Coelho [1] presented a method of combining the impulse responses generated by the image source method for specular reflections and by the radiosity method for diffuse reflections in the case of arbitrarily shaped geometries. The combination of the image source method and the radiosity method was also investigated for urban squares in [17]. The main idea the hybrid method, as it pertains to this investigation, is the understanding that an impulse response is comprised of two parts (Figure 1.2), an early response and a late response. The early response consists of the direct sound component and the early (specular) reflections, the late response contains the late (diffuse) reflections.

1.3 Research Objective

The main objective of this research is to develop a hybrid method that combines the image source method, a geometrical acoustics method, and the diffusion equation method, an energy-based method in order to provide a more efficient way to calculate the prediction of sound in an urban context. The urban environment considered in this project is a rectangular street canyon.

In the course of this project, the main question being addressed is HOW TO DEVELOP A HYBRID SOUND PREDICTION TECHNIQUE BY COMBINING GEOMETRICAL ACOUSTICS AND ENERGY-BASED METHODS FOR A STREET CANYON? As a result, this project will also explore (1) how effective the hybrid method is at overcoming the limitations of the individual methods and (2) what the challenges and limitations are in developing this hybrid method.
Chapter 2

Reference Methods: ISM and DEM

2.1 ISM: Image Source Method

Although work with the Image Source Method (ISM) began as early as 1948 [23, 8, 10], Allen and Berkley [2] were the first to show that ISM provides an exact solution to the wave equation for the unique case of a rectangular room with rigid walls [34].

ISM is a geometrical acoustics (GA) method that works by creating a linear path between a source and its receiver through the use of purely specular reflections. A specular reflection is the mirror-like reflection of a wave from a surface; the angle of incidence equals the angle of reflection. This allows for the sound ray to be traced back from the receiver to the source with the help of image sources. In order to explain how an image source is constructed, let us image a horizontal plane. This plane represents a uniform surface. When a sound ray strikes this surface, it is reflected (in a specular manner) towards an arbitrarily located receiver. We can think of the reflected path as being originated from another source i.e. a virtual source or an image source ‘behind’ the surface. This image source is the same distance from the surface as the original source. It is constructed by mirroring the original source against the surface. Figure 2.1 [11] illustrates how an image source is constructed where the co-ordinates of the original source are given by \((x_0, y_0)\), the receiver by \((x, y)\), and the image source by \((x_0, -y_0)\). We can observe that the distance along the line from the image source to the receiver is the same as that of the path from the original source to the receiver.

When the original source is mirrored against a surface, it creates what is known as a first order image source. This means that a single reflection has taken place. When a sound ray has been reflected more than once, against multiple surfaces, the path of reflection is determined by higher order image sources. A higher order image source is constructed by
CHAPTER 2. REFERENCE METHODS: ISM AND DEM

Figure 2.1: Construction of an image source. The cross at co-ordinates \((x_o, y_o)\) depicts the original source, the dot at \((x, y)\) depicts the receiver, and the cross at \((x_o, -y_o)\) depicts the image source. \(\theta_i\) is the incident angle of the sound ray and \(\theta_r\) is the reflected angle. Figure extracted from [11].

Mirroring the first order image source against the surface.

The geometry of the room has great impact on the resulting positions of image sources. For a rectangular room, the room dimensions are described in 3D cartesian coordinates as

\[
L = \begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix},
\]

(2.1)

where \(L_x\), \(L_y\), and \(L_z\) are the length, width, and height of the room in meters. Similarly, the position of the source and the receiver are defined as

\[
s = \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix}, \quad r = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix},
\]

(2.2)

There are six first order image sources and their positions are given by

\[
p = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} iL_x + (-1)^i s_x \\ jL_y + (-1)^j s_y \\ kL_z + (-1)^k s_z \end{bmatrix}.
\]

(2.3)
where \( i, j, \) and \( k \) are indices representing the normal to the plane of reflection. For a rectangular room, there are six planes of reflection i.e. the six surfaces of the room. The set of indices for the first order image sources, \([i, j, k]\) is given by Equation (2.4) for each of the six planes of reflection. Note that the notation used here is slightly different than that used by Lehmann and Johansson [21] and the positions of the resulting image sources have been verified as accurate. The main difference between the Lehmann and Johansson approach and the one presented here is the location of the origin \([0, 0, 0]\) in the geometry; the former assumes that an origin at the front facing bottom left corner of the cuboid while this method assumes that the origin is in the center of the cuboid.

\[
[i, j, k] = \begin{cases} 
[1, 0, 0] \\
[-1, 0, 0] \\
[0, 1, 0] \\
[0, -1, 0] \\
[0, 0, 1] \\
[0, 0, -1] 
\end{cases}.
\] (2.4)

The positions of the higher order image sources are calculated by treating each of the first order image sources as a source. Figure 2.2 illustrates the resulting image source positions for a room in two dimensions with a rectangular geometry.

### 2.1.1 Impulse Response

The impulse response, \( h(t) \), is calculated as the sum of the contribution of individual image sources in the form of Dirac pulses, delayed by time \( \tau_m \), and weighted by amplitude \( A_m \). This is shown in Equation (2.5).

\[
h(t) = \sum_{m=1}^{M} A_m \cdot \delta(t - \tau_m),
\] (2.5)

where \( M \) is the total number of image sources, \( \tau_m \) is the time delay and is calculated based on the distance \( d_m \) between each image source and the receiver and the speed of sound \( c \). They are calculated by Equations (2.6) and (2.7).

\[
\tau_m = d_m / c,
\] (2.6)

\[
d_m = \sqrt{(p_x - r_x)^2 + (p_y - r_y)^2 + (p_z - r_z)^2}.
\] (2.7)
Figure 2.2: Image sources for a rectangular room in 2D.
Figure 2.3: Impulse response for a rectangular room with image sources calculated up to the third order. (a) shows the rectangular room with the source, receiver and image source positions while (b) shows the corresponding impulse response.

The direct sound component is also added when calculating the impulse response. The real source can be considered as an image source of order 0 and the distance between the source and the receiver is calculated by substituting $p_x$, $p_y$, and $p_z$ for $s_x$, $s_y$, and $s_z$ respectively.

The amplitude $A_m$ represents the attenuation due to reflections with the walls of the room. It is calculated as

$$A_m = \frac{\prod |\kappa|^{|\kappa|}}{4\pi d_m} = \frac{\beta_1^{|\kappa|} \beta_2^{|\kappa|} \beta_3^{|\kappa|} \beta_4^{|\kappa|} \beta_5^{|\kappa|} \beta_6^{|\kappa|}}{4\pi d_m},$$

where $\beta_w$ is the reflection coefficient of the walls of the room. The subscript $w$ is used as a way to identify the walls. The exponent $|\kappa|$ represents the number of times that a particular wall, $w$, was reflected.

The resulting impulse response, $h(t)$, for a rectangular room with image sources calculated up to the third order and with arbitrarily chosen source and receiver positions is shown in Figure 2.3.
2.2 DEM: Diffusion Equation Method

Diffusion is a physical process that describes the movement of particles from a region of high concentration to a region of low concentration. The diffusion equation is best described in [25]: The diffusion equation is a parabolic partial differential equation which describes physical processes such as heat conduction in a solid body, population dispersion, and other similar processes. It has been used to model sound propagation by assuming a similarity with the movement of particles in a gas.

The diffusion equation is derived based on Fick’s law of diffusion which states that the diffusion flux is proportional to the negative concentration gradient of the particles in motion. It is described by (2.9) [39].

\[ F = -D \nabla C \]  

(2.9)

where \( F \) is the diffusion flux, \( C \) is the concentration of the diffusing particles, and \( D \) is the diffusion constant.

Applying Equation (2.9) to the propagation of sound results in Equation (2.10) [25]

\[ J(r, t) = -D \nabla w(r, t) \]  

(2.10)

where \( J(r, t) \) is the sound energy flux vector, \( w(r, t) \) is the sound energy density, \( D \) is the diffusion coefficient in \((m^2s^{-1})\), \( r \) denotes the source-receiver distance, and \( t \) denotes the time instant.

The diffusion equation is stated in Equation (2.11) [25].

\[ \frac{\partial}{\partial t} w(r, t) = D \nabla^2 w(r, t) - \sigma w(r, t) \]  

(2.11)

There are two main terms:

1. \( D \nabla^2 w(r, t) \)  
a spatial term which accounts for the room geometry, where \( D \) is the diffusion coefficient as in (2.12).

2. \( \sigma w(r, t) \)  
an absorption term that accounts for the absorption at the room boundaries where \( \sigma \) is the coefficient as shown in (2.13).

\[ D = \frac{\lambda c}{3} = \frac{4Vc}{3S} \]  

(2.12)
\[ \sigma = \frac{c\bar{\alpha}}{\bar{\lambda}} = \frac{c\bar{\alpha}S}{4V} \]  

(2.13)

where \( c \) is the speed of sound in air, \( \bar{\alpha} \) is the mean absorption coefficient, \( V \) is the volume, and \( S \) is the surface area of the domain. \( \lambda \) is the mean free path which in classical acoustic theory is defined as the path length between two successive reflections.

### 2.2.1 Application of the diffusion coefficient to urban cases

The diffusion equation method was traditionally developed for rooms but the model was extended to streets in [32]. Typically, in a rectangular room, the assumption that the walls are uniformly diffuse results in the use of a single value for the diffusion coefficient. In a street, the assumption that the boundaries are uniformly diffuse is not valid. The building facades do not provide uniformly diffuse boundaries and that is also different from the diffusion by the street pavement. In addition, there are no reflections at the ‘ceiling’ of the street or at the beginning or the end of the street. As a result, it is not reasonable to use a single diffusion coefficient to represent the entire street. Rather a set of diffusion coefficients should be used [32, 33]. Having stated that a set of diffusion coefficients should be used, this project does not delve into the investigation of appropriate diffusion coefficients for a street canyon. For the purpose of the development of this hybrid model, a single diffusion coefficient will be used. It is assumed that using appropriate diffusion coefficients for a street will improve the prediction of the reverberation tail thereby improving the accuracy of the hybrid model.
Chapter 3

Developing the Hybrid Method

The image source method and the diffusion equation method are used in this investigation as stand-alone solvers and the solutions are combined to obtain a hybrid impulse response. The early response accounts for the specular reflections simulated using the image source method and the late response provides the contribution of the diffuse part using the diffusion equation method. The hybrid impulse response is obtained by combining the results from the individual methods. This chapter outlines the hybridization process.

3.1 The Early Response

In this section, the steps taken using the image source method to obtain the early response which consists of the direct sound and the specular reflections are described. The entire process of generating the early response is summarized in a block diagram in Figure 3.1 with the relevant equations for different steps in the process.

3.1.1 Visibility check

The total number of image sources, \(\text{num}\), for order \(K\) is given by equation (3.1) where \(N\) is the number of surfaces of the geometry [34]. For a rectangular geometry with six surfaces, calculating up to order \(K = 2\) results in 36 image sources, \(K = 3\) results in 186 image sources and so on. It is easy to see that this process results in an exponential increase in the number of image sources as the order of the calculation increases. Not all these image sources, however, are visible from the position of the receiver. This means that not all these image sources contribute to the final impulse response at the receiver position. A visibility check, sometimes also called an audibility check [9], is necessary to discard invalid
CHAPTER 3. DEVELOPING THE HYBRID METHOD

Figure 3.1: Process of obtaining the early response using the image source method. Each block describes a process and lists the relevant equation(s) in parentheses.
Table 3.1: Number of image sources for a cuboid where $K$ is the order of calculation, $num$ is the total number of image sources, and $num_{valid}$ is the number of valid image sources.

<table>
<thead>
<tr>
<th>$K$</th>
<th>$num$</th>
<th>$num_{valid}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>186</td>
<td>38</td>
</tr>
<tr>
<td>4</td>
<td>936</td>
<td>66</td>
</tr>
<tr>
<td>5</td>
<td>4686</td>
<td>102</td>
</tr>
</tbody>
</table>

The number of valid image sources, $num_{valid}$, for a rectangular geometry is given by equation (3.2) [36]. It is also worth noting that for a rectangular geometry, each valid image source has a unique position i.e. no two valid image sources have the same position. Table 3.1 shows the total number of image sources obtained for different orders and how many of those are actually valid.

\[
num = \sum_{k=1}^{K} N(N - 1)^{k-1}, \quad (3.1)
\]

\[
num_{valid} = 4K^2 + 2, \quad (3.2)
\]

The visibility check involves tracing back the path of reflection from the receiver to the source [9]. Consider the geometry in Figure 3.2 with source $S$ and receiver $R$. Reflecting the source against the wall on plane A results in the image source $S_2$ and a reflection against the wall on plane B results in the image source $S_1$. $S_1$ and $S_2$ are first order image sources and are therefore valid. The image source $S_{1A}$ is a second order image source that is created by reflecting $S_1$ against plane A. To determine the validity of $S_{1A}$, we look at the intersection point between the direct line from $R$ to $S_{1A}$ and the plane of reflection, plane A; the intersection point lies outside the wall polygon (Figure 3.2a). Thus, $S_{1A}$ is not a valid image source. In contrast, the intersection point between the direct line from $R$ to $S_{2B}$ and plane B lies inside the wall polygon (Figure 3.2b) making $S_{2B}$ valid.

3.1.2 The image source method for a simplified urban case

The simplified geometry of a street canyon can be considered a long cuboid. When modeling the image sources for a room, the source is mirrored against all six surfaces of the cuboid. For a street, however, the assumption is that there are no reflections against the top surface.
Figure 3.2: Visibility check for image sources. (a) shows an invalid image source while (b) shows a valid image source. Image adapted from [9].

Hybrid acoustic model for sound propagation in a street canyon
Table 3.2: Number of image sources for a simplified rectilinear street.

<table>
<thead>
<tr>
<th>Order</th>
<th>Number of image sources for a room</th>
<th>Number of image sources for a street</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>66</td>
<td>15</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
<td>19</td>
</tr>
</tbody>
</table>

and two of the smaller side surfaces. The positions of the image sources are still calculated using equation (2.3) but the values of the indices $i$, $j$, and $k$ are given by (3.3). Since the image source positions are calculated as a result of mirroring from three surfaces, the number of valid image sources, as compared to that of a room, is reduced (Table 3.2). Figure 3.3 shows the image source positions for a three-dimensional room and a street.

$$[i,j,k] = \begin{cases} [0,1,0] \\ [0,-1,0] \\ [0,0,-1] \end{cases}$$ (3.3)

3.1.3 Frequency dependent absorption coefficients

There seems to be limited information related to the absorption coefficients of building facades. Most research [15, 14, 32] use values in the range of 0.1. This is more or less consistent with the absorption coefficient of a standard brick wall. For the modeling of a street canyon, [32] used $\alpha = 0.05$ and [6] looked at the impact of varying the facade and ground sound absorption coefficient from $\alpha = 0$ to 0.3 on the sound attenuation. While $\alpha = 0.3$ is considered a high value in comparison to other literature, their study suggests that varying the ground absorption from $\alpha = 0$ to 0.3 results in about a 2 dB difference. Onaga et al. [27] concluded, through reasonable agreement between measured values and simulations, that absorption values of facades in actual urban streets range from about $\alpha = 0.1$ to 0.25.

The attenuation due to reflection with the boundaries is calculated according to equation (2.8). The reflection coefficient, $\beta$, is the average reflection coefficient for each surface and it is not frequency dependent. $\beta$ and the absorption coefficient, $\alpha$, for materials are related by $\beta = \sqrt{1-\alpha}$ and they are defined for a particular octave band. To obtain
Figure 3.3: Image source positions calculated up to order 3 for a rectangular geometry; a room in (a) and a street in (b). The axes show the displacement in meters.
values for a higher frequency resolution, interpolation was used to estimate the reflection coefficients between octave band frequencies. Additionally, for every image source, we can trace the path of reflection from the source to the receiver. This indicates which surface has been reflected and the sequence in which they were reflected. The attenuation due to reflection with the boundaries, originally given by Equation (2.8), is now given by

$$A_m(f) = \prod \frac{\beta_{\text{tot}}(f)}{4\pi d_m}$$

(3.4)

where $\beta_{\text{tot}}(f)$ is the frequency dependent reflection coefficient for each surface in the reflection sequence.

The early response is then calculated by Equation (2.5). An example of the early response after applying the frequency dependent absorption coefficients is shown in Figure 3.4.

3.2 The Late Response

The late response can also be called the diffuse reverberation tail. This section describes the process of obtaining this diffuse reverberation tail as a result of using the diffusion equation method. A simple diagram summarizing the process of obtaining the diffuse
CHAPTER 3. DEVELOPING THE HYBRID METHOD

3.2.1 Diffuse Reverberation Tail

The Diffusion Equation Method (DEM) solves for the sound energy density $w(r, t)$. The energy decay curve for a particular octave band (Figure 3.6) can be obtained by

$$EDC_f(t) = 10 \log_{10} \left( \frac{w(r, t) \rho c^2}{(2 \times 10^{-5})^2} \right), \quad (3.5)$$

where $f$ denotes the frequency band, $\rho$ is the density of air in $kg/m^3$, and $c$ is the velocity of sound in air in $m/s^{-1}$.

In order to combine the results from the diffusion equation method with the impulse response obtained from the image source method (ISM), the energy decay curve for the diffuse part of the sound field must be transformed into an impulse response. The process of obtaining the energy decay curve from an impulse response is accomplished using Schroeder integration [21]. The reverse process, reverse Schroeder integration, will then provide the envelope of the impulse response, $d_f(t)$.
This envelope, $d_f(t)$, is then normalized so that the maximum amplitude is 1. The normalized envelope is $d_f^*(t)$ given by

$$d_f^*(t) = \frac{d_f(t)}{\max(d_f(t))}.$$  \hfill (3.6)

The diffuse reverberation tail is modeled by using the normalized envelope of the impulse response, $d_f^*(t)$, to shape white noise, $G(t)$, [43]. This is accomplished by first filtering white noise per frequency band. The filtered white noise, $G_f(t)$, is then multiplied by $d_f^*(t)$, the normalized envelope of the impulse response. This is described in equation (3.7).

$$h_{\text{late}}(t) = \sum_f d_f^*(t) \cdot G_f(t),$$  \hfill (3.7)

where $f$ denotes the frequency band and $h_{\text{late}}(t)$ is the diffuse reverberation tail. An example of the resulting late response is shown in Figure 3.7.
CHAPTER 3. DEVELOPING THE HYBRID METHOD

3.3 The Hybrid Response

The hybrid response is a combination of the early response obtained from the image source method which solves for direct sound and the specularly reflecting sound, and the late response from the diffusion equation method which solves for the diffusely reflecting sound. The hybrid response is ultimately accomplished by combining the two individual responses by adding them together. Before they can be combined, however, the late response undergoes two main modifications:

1. The early part of the late response is removed

2. The amplitude of the late response is scaled to fit with the early response

The time delay from the last reflection of the early response is used to determine when the diffuse field should start. This time delay is referred to as the transition time $t_c$ in the remainder of the report. The late response before time, $t_c$, constitutes the early reflections where the diffusion equation method is not accurate. This first part - the late response before time $t_c$ is therefore removed. The late response is then scaled using the ratio of the rms-value of the early response to the late response. The rms-value of the early response, $h_{e,rms}$, is calculated using a fixed time interval, $t_{int}$. This time interval is determined by an adequate number of reflections of the early response. The rms-value of the late response, $h_{l,rms}$, is calculated using the same time interval, $t_{int}$, of the late response after time, $t_c$. 

Figure 3.7: The late response $h_{late}(t)$. 

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Figure 3.8: Representation of the process of creating the hybrid impulse response.

The scaled late response, $h_{\text{late, scaled}}(t)$, given by equation (3.8), is then added to the early response.

$$h_{\text{late, scaled}}(t) = h_{\text{late}}(t) \times \frac{h_{e,\text{rms}}}{h_{l,\text{rms}}} \tag{3.8}$$

The entire process of combining the early and late response to obtain the hybrid response is schematically represented in Figure 3.8.
Chapter 4

Evaluating the Hybrid Method

4.1 Scenarios

Two scenarios were studied during the course of this project. They include an indoor (small room) and an outdoor environment (street canyon). The main idea behind modeling an indoor environment is due to the use of a single diffusion coefficient for modeling the late part of the impulse response. Section 2.2.1 explains that in the case of an outdoor environment, a non-homogeneous diffusion coefficient is needed. However, this project makes use of a constant value of the diffusion coefficient, since currently there are no analytical expressions to derive the non-homogeneous value. The goal of this study is to model the outdoor environment with the intention of exploring the proposed hybrid methodology assuming that the diffusion equation method is adequate for urban cases. The scenarios are described below and their geometry and configuration are illustrated in Figure 4.1.

1. Small Room - The small room measures 7 ($L_x$) $\times$ 5.3 ($L_y$) $\times$ 2.7 ($L_z$) m as seen in [7]. The source is located at one end of the room, 0.5 m away from the west wall and 2.65 m away from the north wall. Table 4.1 indicates the source and receiver coordinates. All surfaces in the room are modeled as rough concrete with the absorption coefficients $\alpha = [0.02, 0.03, 0.03, 0.03, 0.04, 0.07]$ for octave band frequencies from 125 to 4000 Hz. The image sources were calculated up to the fifth order.

2. Street Canyon - A street canyon is a term used to describe a narrow street with tall buildings on both sides of the street. The street canyon in this paper measures 50 ($L_x$) $\times$ 7.9 ($L_y$) $\times$ 18 ($L_z$) m. Table 4.1 indicates the source and receiver coordinates. The model for this street is derived from Kervegan street in downtown...
CHAPTER 4. EVALUATING THE HYBRID METHOD

(a) Small room plan and elevation

(b) Street canyon plan and elevation

Figure 4.1: Geometry and configuration of the modeling scenarios.

Nantes, France where an experimental sound propagation study was conducted [31]. Table 4.2 details the values of the absorption coefficients used to model the surfaces of the street canyon. The image sources were calculated up to the tenth order i.e. twice that of the small room because the street canyon has fewer image source per calculation order when compared to a small room. This means that once could calculate up to a higher order for a street canyon without added computational load.
Table 4.1: Parameters of the modeling scenarios presented in Figure 4.1. \( L \) denotes the dimensions of the room, \( s \) and \( r \) denote the source and receiver positions as defined in equations (2.1) and (2.2).

<table>
<thead>
<tr>
<th></th>
<th>Small Room</th>
<th>Street Canyon</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L )</td>
<td>7.0</td>
<td>50.0</td>
</tr>
<tr>
<td>( s )</td>
<td>-3.0</td>
<td>-23.0</td>
</tr>
<tr>
<td>( r )</td>
<td>2.7</td>
<td>18.0</td>
</tr>
</tbody>
</table>

Table 4.2: Absorption coefficients \( \alpha \) used to model a street canyon. The absorption coefficients for the side surfaces were derived from [33].

<table>
<thead>
<tr>
<th>Octave Band (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom surface (ground)</td>
<td>0.05</td>
<td>0.04</td>
<td>0.02</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Side surfaces (facade)</td>
<td>0.01334</td>
<td>0.1932</td>
<td>0.2254</td>
<td>0.1429</td>
<td>0.1355</td>
</tr>
<tr>
<td>Top and end surfaces (ceiling and openings)</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

4.2 Results

4.2.1 Hybrid Impulse Response

The resulting normalized impulse responses in Figure 4.2. In the case of a small room, the transition from specular to diffuse reflections takes place at time \( t_c = 0.0723 \) s. It is not as clearly visible as in the case of a street canyon where the transition occurs at time \( t_c = 0.2670 \) s.
CHAPTER 4. EVALUATING THE HYBRID METHOD

4.2.2 Energy Decay Curve

The energy decay curve (EDC) is approximated by integrating over the impulse response as shown in equation (4.1). This is known in literature as the Schroeder integration method [21].

\[
EDC = 10 \log_{10} \left( \frac{\sum_{i=0}^{\infty} h_i^2}{\sum_{0}^{\infty} h^2} \right) \tag{4.1}
\]

where \( h \) represents the time-domain impulse response generated by the hybrid method.

The sound pressure level is a logarithmic quantity used to describe the strength of a sound signal. It is calculated as:

\[
L_p = 20 \log_{10} \left( \frac{h}{h_0} \right) \tag{4.2}
\]

where \( h_0 = 2 \times 10^{-5} Pa \), a standardized value for reference pressure. The resulting energy decay curves and sound pressure levels for each octave band are normalized to the maximum value and are shown in Figures 4.3 for a small room and 4.4 for a street canyon.
Figure 4.3: Sound pressure level, $L_p$ in black, and energy decay curve, $EDC$ in red, for the small room scenario for octave bands 125 Hz (a), 250 Hz (b), 500 Hz (c), 1000 Hz (d), 2000 Hz (e), and 4000 Hz (f).
(a) 125 Hz
(b) 250 Hz
(c) 500 Hz
(d) 1000 Hz
(e) 2000 Hz

Figure 4.4: Sound pressure level, $L_p$ in black, and energy decay curve, $EDC$ in red, for the street canyon scenario for octave bands 125 Hz (a), 250 Hz (b), 500 Hz (c), 1000 Hz (d), and 2000 Hz (e).

CHAPTER 4. EVALUATING THE HYBRID METHOD

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CHAPTER 4. EVALUATING THE HYBRID METHOD

4.3 Observations and evaluation

4.3.1 Assessment Criteria

The main acoustic parameter used to assess the hybrid impulse response in this instance is the reverberation time. Reverberation time is defined as the time taken for the sound energy to decay by 60dB. It is calculated from the energy decay curve obtained through reverse Schroeder integration. In most cases, it is not easy to get the range required for the sound energy to decay by 60dB, so the reverberation time is usually obtained through a 30dB decay from -5dB to -35dB from the maximum; this is referred to as $RT_{30}$. Reverberation time is often estimated using Sabine’s formula (4.3) which is valid for rooms with low absorption boundaries where the average absorption is around 0.2 or lower.

$$RT_{60} = 0.161 \frac{V}{S\bar{\alpha}}$$  \hspace{1cm} (4.3)

$V$ is the volume of the room; $S$ is the surface area and $\bar{\alpha}$ is the mean absorption of the surface.

A comparison is drawn between the results obtained through the hybrid method and those calculated by ODEON version 12.12. It is worth noting that ODEON also uses a hybrid method to estimate various acoustic parameters for a given geometry. The method is a combination of three geometric methods, the image source method (ISM) and early scattering rays (ESR) for the early reflections, and the ray-tracing method (RTM) for the late reflections. The transition from early to late reflections is specified by a transition order [44].

4.3.2 Analysis of Results

One of the main goals of this thesis was to identify the challenges in developing a hybrid method. These challenges are described below.

Reverberation time for a small room and a street canyon

One of the main observations of the energy decay curve of the hybrid response is the presence of two distinct slopes of the energy decay curve. In essence, the energy decay curve is also divided into an early decay and a late decay. This is illustrated in Figure 4.5. The reverberation times are calculated for every frequency band and are depicted in Table 4.3 for a small room and Table 4.4 for a street canyon.
CHAPTER 4. EVALUATING THE HYBRID METHOD

Figure 4.5: Energy decay curve and reverberation time RT60 for a small room (a) and a street canyon (b). The blue crosses describe the range used to estimate the slope (in green) of the EDC (in red).
Table 4.3: Small Room Reverberation time RT60. Reverberation time RT60 per octave band frequency estimated from the slopes of the energy decay curve. The percentage in brackets indicates the percentage difference from the analytical reverberation time calculated according to Equation (4.3).

<table>
<thead>
<tr>
<th>Octave band (Hz)</th>
<th>Early decay</th>
<th>Late decay</th>
<th>ODEON</th>
<th>Analytical</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>5.59 (2%)</td>
<td>3.76 (34%)</td>
<td>5.27 (8%)</td>
<td>5.73</td>
</tr>
<tr>
<td>250</td>
<td>4.18 (9%)</td>
<td>3.83 (0%)</td>
<td>3.71 (3%)</td>
<td>3.82</td>
</tr>
<tr>
<td>500</td>
<td>0.13 (97%)</td>
<td>3.73 (2%)</td>
<td>3.60 (6%)</td>
<td>3.82</td>
</tr>
<tr>
<td>1000</td>
<td>3.43 (10%)</td>
<td>3.70 (3%)</td>
<td>3.36 (12%)</td>
<td>3.82</td>
</tr>
<tr>
<td>2000</td>
<td>0.33 (89%)</td>
<td>2.94 (2%)</td>
<td>2.28 (21%)</td>
<td>2.87</td>
</tr>
<tr>
<td>4000</td>
<td>0.20 (88%)</td>
<td>1.98 (21%)</td>
<td>1.15 (30%)</td>
<td>1.64</td>
</tr>
</tbody>
</table>

In the case of a small room, the reverberation time calculated from the early decay is significantly lower than the expected reverberation time for a small room. This is generally true of the image source method, it underestimates the reverberation time of a room when calculated up to a low order of reflections. The image source method must be calculated up to a higher order to obtain a more accurate reverberation time. The reverberation time calculated from the late decay is closer to the expected reverberation time for a small room.

In the case of a street canyon, the difference between the slope of the early decay and that of the late decay for each octave band is not visible. Referring to Figure 4.4, the sound pressure level $L_p$ from the early decay is lower than that of the late decay. This causes the energy decay curve, computed by the Schroeder integration method in Equation (4.1), to flatten out at the part of the early decay. The main reason for this is the lack of adequate criteria with which to determine the time interval $t_{int}$ and the transition time $t_c$.

**Systematic approach to determine $t_{int}$**

When combining the early and the late response to obtain the hybrid response, the scaling of the late response is a key factor. This process is described in Section 3.3. The number of reflections of the specular part used to scale the diffuse part is of main importance to obtain accurate results. Using too few reflections results in a low value for the $h_{e,rms}$ (Equation (3.8)). As a result, the late response is scaled inordinately down. The graphs in Figure 4.6 describe what happens when different number of reflections, thereby different values of $t_{int}$, are used in the scaling process illustrating how important it is to use sufficient specular reflections. In addition, this project assumes a single value for $t_{int}$ since the late response
CHAPTER 4. EVALUATING THE HYBRID METHOD

Table 4.4: Street Canyon Reverberation time RT60. Reverberation time RT60 per octave band frequency estimated from the energy decay curve. The percentage in brackets indicates the percentage difference from the reverberation time calculated by ODEON.

<table>
<thead>
<tr>
<th>Octave band (Hz)</th>
<th>EDC</th>
<th>ODEON</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>4.08 (12%)</td>
<td>4.58</td>
</tr>
<tr>
<td>250</td>
<td>2.46 (12%)</td>
<td>2.18</td>
</tr>
<tr>
<td>500</td>
<td>1.96 (1%)</td>
<td>1.98</td>
</tr>
<tr>
<td>1000</td>
<td>2.48 (1%)</td>
<td>2.50</td>
</tr>
<tr>
<td>2000</td>
<td>2.48 (3%)</td>
<td>2.40</td>
</tr>
</tbody>
</table>

is scaled in the full frequency band and not per octave band. Although it has not been investigated in the course of this project, the case might be that the value of $t_{int}$ used for scaling varies with each octave band.

Systematic approach to determine $t_c$

In general, an impulse response contains two parts, an early part consisting of the direct sound and the early reflections, and a late part with late reverberation. The time at which the impulse response transitions from the early part to the late part (shown as $t_c$ in Figure 1.2) should be determined through a systematic approach. One of the main challenges in developing the hybrid method is to determine $t_c$. The hybrid method proposed here assumes that $t_c$ equals the time delay from the last reflection computed by the image source method. The time delay of the last reflection depends, then, on the maximum order of computation of the image source method. This maximum order was arbitrarily set to 5 for a small room and 10 for a street canyon.

A better approach to determine $t_c$ would be to calculate the image sources up to an order $n$ such that the specularly reflected sound energy is converted to diffuse energy. According to [20], the specularly reflected sound energy can be described by a factor $(1 - s)^n(1 - \alpha)^n$ and the diffusely reflected sound energy is described by $(1 - (1 - s)^n)(1 - \alpha)^n$ where $n$ is the order of reflection, and $\alpha$ and $s$ are the absorption and scattering coefficients respectively. Relating the specular and diffuse part by a factor $x$ and solving for $n$ gives:

$$n = \frac{\ln \left( \frac{x}{1+x} \right)}{\ln(1 - s)} \quad (4.4)$$

where $x$ is the ratio of specularly to diffusely reflected sound energy. It is easy to see that the order of reflection $n$ is dependent on the scattering coefficient $s$. 

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CHAPTER 4. EVALUATING THE HYBRID METHOD

(a) 2 reflections, 11 ms  
(b) 5 reflections, 41 ms  
(c) 10 reflections, 87 ms  
(d) 15 reflections, 125 ms  
(e) 20 reflections, 145 ms

Figure 4.6: Scaling the late response. The time in ms is $t_{int}$, the time taken for the number of specular reflections used for scaling. For example, in (a), $t_{int} = 11$ ms.
Chapter 5

Conclusion

This project proposes and evaluates a hybrid method for sound propagation that combines a geometrical acoustics method, the image source method, and an energy-based method, the diffusion equation method. The proposed hybrid method, as it stands, requires further work before it is able to be used with a fairly good degree of accuracy. The main premise behind this hybrid method was to make the computational modeling of urban sound propagation more efficient. Since the image source method is computationally intensive for high orders, and the diffusion equation method does not provide accurate results for the direct sound and the early reflections, the hybrid method aims to make up for the inabilities of the individual methods. It works by requiring a lower order of computation of the image source method and using the diffusion equation method to calculate the late reflections.

The hybrid method generates a hybrid impulse response consisting of an early part and a late part. The early part contains the direct sound component and the early reflections, predicted using the image source method. The late part consists of a diffuse reverberation tail which results from using the sound pressure level of the diffusion equation method to shape white noise. The hybrid method combines the early part and the late part in time to create a hybrid impulse response. The process of creating the hybrid impulse response is illustrated in Figure 3.8.

Two main modeling scenarios were explored in the project, a small room and a street canyon. The objective of this project was to develop a hybrid method for an urban scenario i.e. the street canyon. The small room scenario, therefore, was used as a way to validate the hybrid method; the main assumption here was that if the hybrid method results in reasonably accurate results for a room, since the image source method and the diffusion equation method having been individually used successfully in indoor environments, by extending the image source method to an urban case [11] and extending the diffusion
equation method to an urban case [33], results could be obtained more efficiently and with reasonable accuracy. This assumption, however, does not pan out for several reasons.

5.1 Main conclusion

The process of evaluating the hybrid impulse response for the street canyon reveals that a significant outcome of this project is related to the importance of choosing appropriate values for $t_{int}$ and $t_c$; $t_{int}$ is the time interval used to scale diffuse reverberation tail or the late response and $t_c$ is the time at which the sound field transitions from specular to diffuse.

This project assumes a single value of $t_{int}$ for all frequency bands i.e. 145 ms as seen in Figure 4.6. This results in obvious scaling problems when estimating the energy decay curve and the reverberation time. The transition time, $t_{int}$, is expected to vary for each octave band. This means that the diffuse reverberation tail should be scaled per octave band.

In this project, the value of $t_c$ was determined arbitrarily. It was assumed that $t_c$ equals the time delay of the last reflection computed by the image source method and is therefore the same across all octave bands. However, it is likely that the transition time $t_c$ is not a single moment in time but rather a period of time during which the sound field makes the transition from specular to diffuse. By relating the specularly and diffusely reflecting sound energy as shown in Equation (4.4), one could determine the minimum order of reflections required to estimate an appropriate value of $t_c$ for each octave band.

5.2 Future work

There are a few aspects of this project that should be targeted for more research. They relate either to the image source method, the diffusion equation method, or the hybrid method as indicated below.

Image source method

With regard to the image source method, the application of the frequency dependent absorption coefficients was accomplished by interpolating between various absorption coefficients across the entire frequency spectrum. Another way to apply the frequency dependent absorption coefficients would be to filter the impulse response to obtain a time signal
filtered by octave bands and then apply the frequency dependent absorption coefficients to each frequency band without the need for interpolation. While the expected results should not differ too much from each other, the effect of interpolating between various absorption coefficients is not certain.

The image source method used in this project is the method in its most basic form. It does not include phase information of the reflections nor source directivity. It calculates the sound pressure based on distance attenuation, and attenuation due to reflection against the boundaries. Adding more properties to the image source method would be a logical next step.

**Diffusion equation method**

The diffusion equation method used in this project makes use of a single uniform diffusion coefficient. This is typically valid for rooms, however, it is not valid for urban scenarios which require a set of diffusion coefficients that depend on the direction of propagation [32]. The reason to use a single diffusion coefficient, though, was under the assumption that if the hybrid method results in reasonably accurate results for a small room, the extension to an urban scenario with the use of non-homogeneous diffusion coefficients would be the logical next step and fairly straight-forward.

**Hybrid method**

The hybrid method proposed in this paper assumes a single point in time for the transition from specular to diffuse reflections i.e. $t_c$. Determining $t_c$ depends on the order of computation of the image source method. For a small room, the image source method was used to compute the direct sound and the early reflections up to the fifth order while for a street canyon, the computation was carried out to the tenth order. It is expected that a higher order of computation results in more accurate results for the image source method. In this project, the order was chosen to minimize computational time. However, the order can be determined through Equation (4.4) which in turn is highly dependent on the scattering coefficients for the scenario. A significant research area would be to develop a practical way to determine scattering coefficients in urban environments. While [44] provides some values for scattering coefficients for some materials, there is still insufficient information on scattering coefficients in streets. More details on scattering coefficients in urban environments would aid in the process of identifying a good transition time.
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