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Virtual Acoustics for Product Design and Prototyping Process

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Abstract

In the last years Product Design is taking more and more advantage of new technologies for the optimization of the different steps of the processes from the concept to the final product.

Physical prototypes are usually expensive and not flexible enough to perform different kinds of tests. Virtual Prototypes can be used to evaluate the product during the design process. Therefore the production of physical prototypes becomes useless, leading to a strong reduction of the costs related to their production and validation.

Virtual Prototyping mainly focuses on the simulation and evaluation of visual, haptic and tactile aspects of the products. However there are some categories of industrial products that need to be evaluated also from an acoustic point of view, since they generate sounds while working.

The sound can be an important aspect of an industrial product, and it needs to be studied and evaluated, since it can influence the customers' choices between similar products.

The research work described in this thesis concerns the acoustic evaluation of industrial products supported by the development and the use of Virtual Acoustic Prototypes. More in detail a method for integrating the use of Virtual Acoustic Prototypes in the Product Design Process has been defined and analyzed in all its aspects. The method consists in a process that can be divided into three different phases, which are the analysis of the acoustic requirements of a given industrial product, the implementation of a Virtual Acoustic Prototype and the evaluation of the sound generated with the help of the Virtual Prototype.

For each phase a specific tools has been identified. While the definition of the phases related to the analysis of the acoustic requirements and the evaluation of sounds concerns the use of a well-known procedure for the sound quality evaluation, a new software tool has been designed and implemented to support the definition of the Virtual Acoustic Prototypes.

The software tool, called Virtual Acoustic Environment, has been designed and developed after a deepened study of the literature in the field of Virtual Acoustics and the simulation of sound fields, in order to identify and use the most effective algorithms and techniques. The Virtual Environment, whose core is based on an algorithm for the simulation of the propagation of sound waves, can be described as a tool able to reproduce the sonic response of a product within its working environment.

Two testing sessions have been performed to validate the Virtual Acoustic Environment and to evaluate the level of accuracy of the simulation, both from a numerical and from a perceptual point of view. The numerical test has been conducted for evaluating the differences, in terms of sound power, between sounds recorded in real environments and corresponding sounds simulated with the Virtual Acoustic Environment. The aim of the perceptual test was to investigate if the Virtual Acoustic Environment is able to reproduce the acoustic feedback perceived by people during the use of an industrial product.

The results of the numerical test showed that the Virtual Acoustic Environment is able to simulate the sonic response of industrial products with an adequate level of detail, except for low frequencies. Moreover the results obtained with the perceptual test confirmed that the Virtual Acoustic Environment is able to reproduce sounds that are comparable with sounds audible in a real situation.

On the basis of the results obtained during the testing sessions, it is likely to hypothesize the use of the Virtual Acoustic Environment in the industrial context: it could be used for performing the acoustic validation during the development phase.

Nevertheless further developments are possible and necessary. The simulation algorithm needs to be improved to solve the issues related to the simulation of low frequencies propagation. Moreover the integration and the use of the other senses - i.e. vision and touch - is useful to create a multi-modal environment that will contribute to increase the interaction of the users with the environment and, thus, the level of users' immersion.

Sommario

Nel corso degli ultimi anni, il Design di Prodotto sta facendo sempre piuúso delle nuove tecnologie, per riuscire ad ottimizzare le varie fasi dei processi di sviluppo prodotto, dal concept al prodotto finale. Lo sviluppo di prototipi fisici risulta essere molto costoso. Inoltre, i prototipi fisici non sono sufficientemente flessibili per poter effettuare differenti tipologie di test. I prototipi virtuali, invece, possono essere utilizzati per valutare il prodotto durante il processo di progettazione. Ne consegue che non vi epiuĺa necessitádi creare prototipi fisici, e questo porta ad una forte riduzione dei costi per la loro produzione e validazione. La prototipazione Virtuale si concentra principalmente sulla simulazione e la valutazione degli aspetti visivi, aptici e tattili dei prodotti. Tuttavia vi sono alcune categorie di prodotti industriali che necessitano di una analisi anche dal punto di vista acustico, poichégenerano dei suoni durante il loro utilizzo. La qualitÃă del suono che deriva da un prodotto eún importante aspetto che richiede essere studiato ed esaminato perchépotrebbe influenzare le scelte dei consumatori difronte a prodotti simili. Il lavoro di ricerca descritto in questa tesi, riguarda la valutazione acustica dei prodotti industriali supportata dallo sviluppo dell'utilizzo dei Prototipi Acustici Virtuali. Piuín dettaglio un metodo per integrare l'uso dei Prototipi Acustici Virtuali all'interno del Processo di Product Design éstato definito e analizzato in tutti i suoi aspetti. Il metodo consiste in un processo che puoéssere diviso in tre fasi differenti, analisi dei requisiti acustici di un dato prodotto industriale, realizzazione di un Prototipo Acustico Virtuale e valutazione del suono generato con l'aiuto del prototipo virtuale. Per ogni fase, sono stati identificati una serie di stru-

menti specifici. Mentre la definizione delle fasi riguardanti l'analisi dei requisiti acustici e la valutazione dei suoni riguardano l'uso di un procedimento noto, per la valutazione della qualitÃă del suono, eśtato progettato e realizzato un nuovo strumento software, per supportare la definizione dei Prototipi Acustici Virtuali. Lo strumento software, chiamato Ambiente Acustico Virtuale, eśtato progettato e sviluppato dopo un approfondito studio della letteratura nel campo dell'acustica virtuale e della simulazione di campi sonori. Tale studio eśtato condotto con l'obiettivo di individuare e utilizzare gli algoritmi e le tecniche piuéfficaci. L'ambiente virtuale, il cui nucleo ébasato su un algoritmo per la simulazione della propagazione di onde sonore, puoéssere descritto come uno strumento in grado di riprodurre la risposta sonora di un prodotto nel suo ambiente di lavoro. Sono state eseguite due sessioni di test per convalidare l'Ambiente Acustico Virtuale e per valutare il livello di precisione della simulazione, sia dal punto di vista numerico, sia da un punto di vista percettivo. Il test numerico eśtato condotto per valutare le differenze, in termini di potenza sonora, tra i suoni registrati in ambienti reali e i suoni corrispondenti, simulati con l'Ambiente Acustico Virtuale. Lo scopo della prova percettiva era indagare se l'ambiente acustico virtuale eín grado di riprodurre il feedback acustico percepito dalle persone durante l'uso di un prodotto industriale. I risultati del test hanno dimostrato che l'ambiente acustico virtuale eín grado di simulare la risposta sonora di prodotti industriali con un adeguato livello di particolari, eccezion fatta per le basse frequenze. Inoltre, I risultato ottenuti con il test percettivo hanno confermato che l'ambiente Acustico Virtuale riproduce suoni che possono essere comparati a suoni reali.

Sulla base dei risultati ottenuti durante i test, eŕagionevole ipotizzare il possibile uso dell'ambiente Acustico Virtuale nell'ambito industriale per effettuare la validazione acustica durante la fase di sviluppo.

Ciononostante, ulteriori sviluppi sono possibili e necessari. L'algoritmo di simulazione deve essere migliorato per poter risolvere le problematiche relative alla simulazione della propagazione delle basse frequenze. Inoltre, l'integrazione e l'uso degli altri sensi, vale a dire vista e tatto, eńecessaria per poter creare un ambiente multimodale che possa contribuire ad incrementare l'interazione degli utenti con l'ambiente e, dunque, il livello di immersione degli utenti.

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CHAPTER 1

Introduction

Product Design is taking more and more advantage of new technologies for the optimization of the different steps of the processes from the concept to the final product.

The concepts developed in the design phase need to be analyzed before their approval, in order to guarantee the quality of the final product [70]. Traditionally, the evaluation phase consists in building and analyzing a large number of physical prototypes in order to evaluate different characteristics of the product, such as functionality, usability, aesthetics, comfort and so on. Most of times physical prototypes are expensive and not flexible enough to perform different kinds of tests. As a consequence, the practice of Virtual Prototyping is spreading [48].

A Virtual Prototype consists in a digital model of the product, usually the CAD model, conveniently expanded with additional information, such as functional parameters and physical properties, which can be easily represented and modified. Virtual Prototypes can be used to evaluate the product concept during the design process, thus reducing the needs of producing physical prototypes and the costs related to their production and validation [20]. The kind of analyses that can be performed on a Virtual Prototype depends on the information the prototype is enhanced with. Material properties as surface finishing offer information that can be used for the aesthetic evaluation of the bodywork of a car. The physical parameters of linking elements, such as springs and dampers, are useful to perform interaction tests focusing on different industrial products, as for instance household appliances [19]. A more complex system described in [18], based on haptic technology, offers the possibility to evaluate the shape of aesthetic products by physically touching a strip that is able to deform itself, thus reproducing some section of the surface of the virtual object.

So far, the research works addressing Virtual Prototyping have mainly focused on visual, haptic and tactile aspects. However, some industrial products need to be evaluated also from an acoustic point of view.

There are some categories of industrial products, e.g. vehicles, household appliances, power tools and so on, that generate different kinds of sounds when users work or just interact with them. The *sound quality* [16] can play an important role in customers' choices, and can discriminate between similar products [49]. Sound can be an important aspect of an industrial product. However, without its validation during the early design phase, it could be likely to obtain inaccurate results, which may lead to negative evaluations from the customers' point of view.

The research work described in this thesis is about the acoustic evaluation of industrial products supported by the development and the subsequent use of Virtual Acoustic Prototypes.

1.1 Objectives of the research

Customers' opinion about the quality of a product can be influenced by the acoustic feedback given by the product itself. The design process of a product should take into account what is the *expected* sound for the corresponding category of products.

Usually, the sound generated by a product can be analyzed when the final product, or at least a physical prototype of it, is made available. Sound quality evaluation can lead to the identification of design errors that imply modifications in the design process with consequent waste of time and money. Therefore it arises the necessity to evaluate the sound quality of products early in the product design process. In 1997 Keiper [49] wrote that:

> *"At the product specification stage, where prototypes of the new product do not exist, decisions on target sounds have to be based*

on existing older, comparable products (including the competitors'), and possibly on sound simulations"

This thesis reports the results of a research work aimed at defining a method for integrating the use of Virtual Acoustic Prototypes in the Product Design Process. The method mainly consists of three different phases: the analysis of the acoustic requirements of a given industrial product (i.e. the expectations of customers about the desired sound generated by the product) , the implementation of a Virtual Acoustic Prototype and evaluation of the sound generated with the help of the Virtual Prototype.

The three phases have been deeply analyzed and for each phase a specific tool has been identified. The research has been conducted with the aim of identifying, defining and validating each used tools individually.

It has been decided to use the same sound quality descriptors both to define the acoustic requirements and to perform the evaluation tests on sounds with the Virtual Acoustic Prototype, in order to easily compare the expectations of the users with the perceived sound quality.

More in detail the literature related to procedures for sound quality evaluation has been studied and, on the basis of the information achieved, the Semantic Differentials procedure, that consists on the evaluation of the characteristics of a sound through the use of pairs of bipolar adjectives, has been chosen.

For what concerns the development of the Virtual Acoustic Prototype, a Virtual Acoustic Environment has been entirely developed and implemented. The state of the art on the tools used in the field of Virtual Acoustics has been largely studied, in order to identify the most effective techniques and algorithms used for the simulation of sound fields.

The Virtual Acoustic Environment consists of an interactive environment where users can hear sounds produced by virtual models of products. Users can change some characteristics of the virtual environment, as adding objects, changing material properties. The core of the system is based on the simulation of the propagation of sound waves using a ray-tracing algorithm.

The major innovative aspect of the Virtual Acoustic Environment, if compared to canonical commercial software used to perform acoustic simulations, is related to the kind of output obtained from the implementation of the Virtual Acoustic Prototypes, and consequently to the potential users that can exploit the functionality of the system. While the outputs of the simulations performed with commercial software are generally complex numerical data that require to be analyzed by engineers, the Virtual Acoustic Environment provide an audible feedback, which can be immediately perceived and evaluated by common users in a natural way.

Moreover, since the Virtual Acoustic Environment has been designed as interactive, the implementation of the algorithm has been performed trying to minimize the computation time. Therefore the parallel computing architecture CUDA [12], developed by NVIDIA, has been used for the implementation of the ray-tracing algorithm.

1.2 Structure of the thesis

The thesis is structured as follows:

In **Chapter 2** the role of Sound generated by industrial products is analyzed. We will see how the acoustic feedback given by a product can influence the users' choices. The concept of *sound quality* in the context of Product Design is deepened. The chapter ends with an overview of the main methodologies used for the characterization and evaluation of industrial sounds. Both the main differences and advantages for the several methodologies are deeply analyzed.

In **Chapter 3** the definition of a Virtual Acoustic Method, aimed at the construction and the use of Virtual Acoustic Prototypes inside the several steps of the product design process is provided. The chapter starts with an overview of a canonical product design process, then it presents the different steps that lead from the product concept to the final product. The use of Physical and Virtual Prototypes during the process is analyzed. Then the Virtual Acoustic Method is presented. The method is mainly based on three phases: the definition of the acoustic requirements for a given product, the development of the Virtual Acoustic Prototype and the evaluation of sounds obtained with the Virtual Prototype. The chapter ends with a description of the tools used in the different steps of the method. Semantic Differential are used for the definition of the acoustic expectations and for the evaluation of sounds, while a new Virtual Acoustic Environment, which can be used as a tool for the building up of the Virtual Acoustic Prototype, has been developed. The concept of the Virtual Acoustic Environment is described.

In **Chapter 4**, an overview of the various techniques used in the field of Virtual Acoustics is described. The simulation of sound fields is a very large research context. In this chapter, the global context has been separated into three macro-areas, one related to the generation of sound, one related to the propagation of sound waves into the environment and the last one related to the sound reproduction techniques. The chapter ends with a description of how acoustics simulations are commonly used for product design purposes.

Chapter 5 describes in details the development of the Virtual Acoustic Environment, that is one of the results of the present research work. The first part of the Chapter shows the modelling techniques chosen to define the Virtual Acoustic Environment. The use of a ray-tracing algorithm for the simulation of the propagation of sound waves will be described, including all its benefits and limitations. Subsequently, the architecture and the implementation of the Virtual Acoustic Environment will be given. The system consists of two separated modules, one related to the ray-propagation and one related to the digital signal processing of the sound data. We will see how the two modules have been defined, in terms of software used and implementation tasks. Then we will see how the modules have been connected in order to work in a synchronized manner.

In **Chapter 6** the testing session performed to validate the Virtual Acoustic Environment is described.

The testing session is based on the comparison between different working setups of a hairdryer, both real (directly recorded in different working environments) and virtual (simulated using the Virtual Acoustic Environment). More in detail, two different validations have been performed: a numerical comparison between real and simulated sounds, aimed at the evaluation of the level of accuracy of the simulation, and a perceptual equivalence validation, whose puropose was to investigate if the Virtual Acoustic Environment is able to reproduce the acoustic feedback perceived by people during the use of an industrial product. In addition, the obtained results are presented and analysed.

Finally in **Chapter 7** some conclusions and remarks are drawn. The effective usefulness of the present research, for product design purposes, is described: in particular, the benefits and the limitations of the method are described, as well as possible applications and improvements are provided.

CHAPTER 2

The role of Sound generated by Products

2.1 Sound Quality of Industrial Products

In the twentieth century large attention has been paid to the study and the design of the sounds generated by industrial products.

The first studies have been conducted in the field of the automotive industry, and the research of sound engineers was aimed to the reduction of the noise generated by vehicles, trains and so on.

From the 80s sound designers and engineers realized that the sound pressure level of the noise generated by a product was not the only characteristic that had to be taken into account [28]. Sound frequency and pitch began to be studied and designed.

In the recent years, the concept of *sound quality* has been extended to all the categories of industrial products that generate sounds when users work or just interact with them. The sound quality can play an important role in customers' choices for products such as vehicles, power tools, household appliances and so on. It and can be considered as a key element leading the customer to discriminate between similar products [49].

The term sound quality usually refers to the quality and the level of accuracy of the output audio of electronic devices [87]. In the context of

Industrial Products the term “sound quality" assumes a different meaning. Blauert and Jekosch described the sound quality of Industrial Products in the following way [16]:

> *“Product-sound quality is a descriptor of the adequacy of the sound attached to a product. It results from judgements upon the totality of auditory characteristics of the said sound - the judgements being performed with reference to the set of those desired features of the product which are apparent to the users in their actual cognitive, actional and emotional situation."*

We can describe the adequacy as the ability of a product to satisfy, while working, the typical acoustic expectations of his product class.

The expectations, which we can call acoustic requirements can be very different from a product to another one, and they depend on the kind of usage, on the working environment, on the potential buyers and so on. Sometimes, it happens that similar products have different requirements.

An example is related to car design. During the last years many studies have been carried out to reduce the sound perceived from the interior of the car. This sound is mainly generated by the car engine, by the wind and the noise of the wheels rolling on the tarmac. For what concerns the engine, we can imagine that a sound as smooth and quiet as possible is required. This is definitively true for some categories of cars, as sedans, while for sport cars the loudness and the roughness of the engine sounds are peculiarities.

For some kind of products the analysis of the acoustic requirements can be more complicated and sometimes can lead to a contradiction. Even if most consumers prefer quiet products, the reduction of the loudness of sounds is not always the best solution.

For example, the sound generated by a drill should not be too loud or annoying, but at the same time a feeling of good performance is required: in this case, the sound should elicit in the user the sensation of “power”. Another example is related to the sound coming from a coffee machine, which should not be too loud but it should not even be reduced too much because of its usefulness. It usually warns users about the state of the coffee preparation.

Industrial products can generate different kinds of sound and with different purposes.

The field of Product Sound Design studies all the different typologies of product sounds together with tools and methods for the development of product sound specifications.

2.2 Sound Design

When approaching to the Product Sound Design, it is necessary to analyze all the different aspects and characteristics of the sounds that usually are generated by industrial products. First of all, It could be useful to introduce a preliminary consideration about the meaning of the two words *noise* and *sound*. The word sound is extremely generic. His main meaning refers to mechanical waves obtained by a pressure oscillation in a propagation medium. In the life of every days the term sound is used to describe all the physical phenomena that result to be audible by humans. The word noise is commonly associated to an unwanted sound, i.e. an unpleasant sound that should be avoided. The work of sound designers and engineers aims to the reduction of the noise component of the sound coming from Industrial Products. The big difference between sounds and noises depends on the level of pleasantness perceived by humans. Since the pleasantness is a qualitative attribute of a sound, and moreover it is strictly subjective, it is not possible to define a limit between noise and acceptable sound. Therefore many studies have been conducted to define methods and tools for the evaluation of the quality of product sounds. The most effective procedures are described in Section 2.3.

In the field of Product Sound Design it becomes necessary to distinguish between different typologies of sounds that can be generated. In particular it is possible to define three main categories of industrial product sounds:

- Sounds generated by products while working (that we will call *working sounds*)
- Sounds generated by the interaction of the user with the product (*interaction sounds*)
- Sounds generated to give some information to the user (*communication sounds*)

Working sounds can be described as the sounds that the mechanical components of a product produce during operation. Examples of working sounds can be the sound of the motor of a vehicle, rather than the fan of a hairdryer or the compressor of a fridge. In many cases those sounds result to be unpleasant (and therefore they are described as noises) but, since they cannot be completely avoided, the work of sound engineers is to identify the annoying characteristics of the sounds (such as a specific frequency, or a ticking) and to reduce them. However there are some examples of working sounds that have been intentionally designed to be different from the competitors, and that becomes a distinctive element of a specified brand (e.g. Harley Davidson filed a sound trademark application for the distinctive sound of the Harley-Davidson motorcycle engine [86]).

Interaction sounds are the sound that are generated when a user interacts with a product. The design of those kind of sounds is usually studied analyzing all the senses that are involved in the interaction phase. Usually the senses of sight, sound and touch are used by humans when they interact with a product. The design of interaction sounds can affect the overall perceived sound quality of a product. We can consider the example of interaction with the door of a fridge. A dry or an attenuated sound can provide the feeling of stiffness and solidity of the fridge, while a crackling sound probably provide a sensation of bad quality.

There is a specific line of research, called Sonic Interaction Design [69], that studies the design of interaction sounds through the use of interactive simulations.

Communication sounds are usually artificial sounds that are inserted with the scope of providing the users with information. One example can be the alarm user to inform drivers about the level of gasoline. Communication sounds can be control the status of a process, can be inform user about something wrong, and so on. Usually communication sounds are designed to be very clear distinguishable, in order to avoid mistakes and sense of confusion of the users.

2.3 Tools for Sound Quality Evaluation

The concept of *product sound quality* is nowadays commonly accepted in industrial applications and the design of the *appropriate* sound for a given industrial product has gained importance in the overall design and development processes.

Therefore, the correct evaluation of the sound quality of an industrial product became a necessary task for the identification of possible acoustic problems of the product, rather than for the comparison with similar products developed by competitors.

Different studies have been carried out to define different tools and procedures to quantify the sound quality of products. In this section, the most common used tools will be described, mainly underlining the differences and the advantages of each tool.

An initial distinction has to be made between quantitative and qualitative tools for the sound quality evaluation.

Quantitative magnitudes are used to numerically characterize sounds.

Those magnitudes are generally used to analyze the physical characteristics of the sound waves as loudness, frequency, pitch and so on.

Qualitative tools allow to evaluate the sound quality of a product using human subjects, that are first exposed to various sounds and subsequently asked to judge different characteristics of those sounds.

2.3.1 Quantitative Tools for sound quality evaluation

The first analyses on product sounds have been done by using weighting filters to obtain an approximation of the loudness of sounds [28]. More precisely the A-weighting filter has been long used for such purposes, but it resulted to be inadequate to correctly evaluate the loudness of sounds because it does not take into account parameters, such as duration and bandwidth of the sounds. Nowadays the A-weighting filter is mainly used for the evaluation of industrial noises and environmental noises [85].

A variety of psychoacoustic indices have been defined to correlate the physical magnitudes of sound to the human perception and are used for sound quality evaluation. Some of them, described in detail by Fastl in 1997 [38] are international standards:

- **Loudness** represents the human perception of sound volume. Loudness is the dominant metric in psychoacoustics and it is measured in sone.
- **Sharpness** is used to evaluate the timbre of the sound. It is related to frequency and not related to loudness. High-frequency sounds have a higher level of sharpness. It is measured in acum.
- **Roughness and Fluctuation Strength** represent the temporal variation of sound. More precisely, they represents the loudness variation. Fluctuation strength is the metric used for very low frequencies, while roughness is used for higher frequencies. Even if there is no a defined limit between those two metrics, it is common usage to use roughness for frequencies higher that 30 Hz and fluctuation strength for lower frequencies. Roughness is measured in asper and fluctuation strength is measured in vacil.

Those magnitudes resulted to be very useful for the scaling of some characteristics of the sounds and correctly correlate the physics of sounds to subjective evaluations. The research carried out by Lion [58] discovered that sometimes the psychoacoustics indices are not enough to completely define a sound in all its aspects and that it is necessary to determinate the sound quality using subjective evaluations.

2.3.2 Qualitative Tools for sound quality evaluation

A deepened research has been conducted, mainly by Fastl [10] and Otto et al. [62], about the use of human subjects for the evaluation of the sound quality of products. This kind of procedures, also known as jury tests because they are conducted using a group of subjects(a jury), have been studied to categorize in ranks, rather than in several scales, the opinions that subjects form when they listen to the sound coming from a product. Several kind of tests have been defined. In the following, the most used tests for the evaluation of the sound quality of industrial products will be described.

Rank Order Procedure

The rank order procedure [62] is a very simple sound quality evaluation procedure. The subjects are asked to order N sounds, from 1 to N. The ranking can be based on some criteria, such as magnitude, annoyance and so on, or it can be based on the general concept of *perceived sound quality*. Figure 2.1 shows an example of user interface used for the rank order procedure. Subjects have the possibility to listen to a sound as many times as they want, only by clicking the loudspeaker icon.

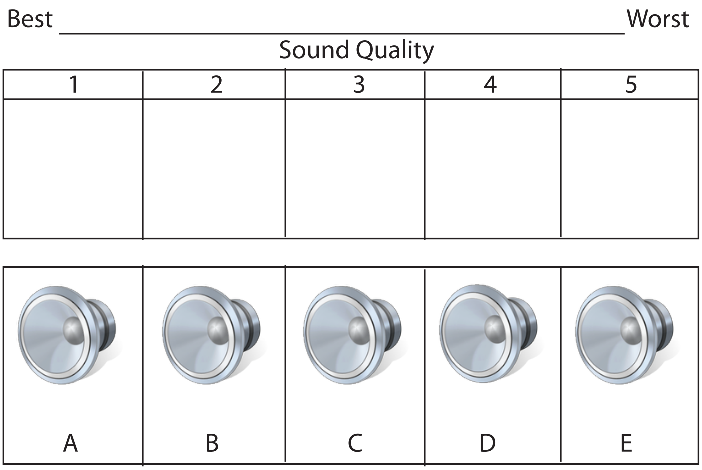


Figure 2.1: *Rank oder procedure interface for 5 sounds*

It is common usage to do not use more than 6 sounds with this procedure, in order to avoid too much complexity of the test.

A great disadvantage of this procedure is that subject are not asked to use a scale to evaluate the sounds. Therefore, even if it results that one sound is preferred to another one, it is not possible to know *how much* it is preferred.

Unidimensional Category Scaling

Unidimensional Category Scaling is used to evaluate a single characteristic for a set of sounds. Subject are asked to evaluate the characteristic of the sound (loudness, annoyance, pleasantness, etc.) using a predefined scale (see Figure 2.2).

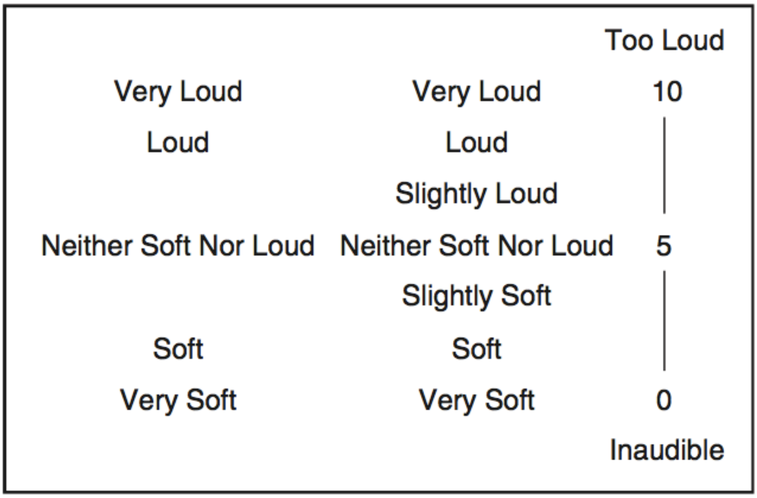


Figure 2.2: *Unidimensional Category scaling for the evaluation of Loudness with 5 verbal categories (left), 7 verbal categories (center) and 10 numerical categories(right)*

The scale can be defined in verbal categories (left and central columns in Figure 2.2) or with numbers, only defining the upper and the lower verbal values (right column in Figure 2.2).

Magnitude Estimation

The magnitude estimation procedure is based on the comparison of two sounds. Sounds are compared taking into account one attribute, such as loudness. One of the two sounds, named *anchor sound* has a fixed value, chosen according to an arbitrary scale. Usually the anchor sound has a symbolic value of 100. The subjects are asked to evaluate the magnitude of the second sound, giving a relative ranking, that can be greater or smaller that the anchor sound. The greatest advantage of this procedure is that the subject can choose any possible value, and therefore there is no ceiling in the ranking scale.

Pairwise Comparison

Pairwise comparison test is based on the comparison of two sounds. Subjects are asked to give a relative evaluation of the two sounds. Various evaluation tests can be performed for different purposes. Here, thee different kind of tasks will be described:

- **Evaluation task**: subjects are asked to evaluate the two sounds comparing them on a given characteristic, such as loudness or annoyance. Subjects will decide which of the two sounds possesses more of the given characteristic.
- **Detection task**: subjects are asked to identify which of the two sounds contain a required signal (that can be, as example, a particular frequency). This kind of test is normally used to detect a threshold of a signal in a set of sounds.
- **Similarity task**: subjects are asked to evaluate the degree of similarity between different pairs of sounds.

Semantic Differentials

The main difference between Semantic Differentials and the other qualitative procedures analyzed in this section, is that the Semantic Differential procedure is the only where subjects are asked to analyze more than one attribute of the sounds during the testing session.

In this procedure, which has been first defined by Osgood [61], the evaluation of the sounds is performed by using pairs of bipolar adjectives. Table 2.1 shows an example of bipolar adjectives that can be used for a Semantic differential test [10].

The comparison is usually performed on a five, seven or nine point scale. One of the advantages of this procedure is related to the choice of the adjectives. It is possible to choose different kinds of adjectives in order to analyze some characteristics of the sound of a product rather than others. Moreover it is possible to personalize the set of adjectives in relation to the kind of product that has to be analyzed.

A different approach has been defined by Lyon [58], that found 62 words to be used as descriptors for sound grading.

Table 2.1: *Example of bipolar adjectives used in the Semantic Differential scale*

Loud	Soft
Deep	Shrill
Frightening	Not Frightening
Pleasant	Unpleasant
Dangerous	Safe
Hard	Soft
Calm	Exciting
Bright	Dark
Weak	Powerful
Busy	Tranquil
Conspicuous	Incospicuous
Slow	Fast
Distinct	Vague
Weak	Strong
Tense	Relaxed
Pleasing	Unpleasing

CHAPTER 3

Virtual Acoustic Method for Product Design

The research work described in this thesis has been carried out in the area of the Product Design Process. In the last years the Product Design process has been strongly influenced by the fast development of the Information Technologies.

The use of CAD software to create digital models of the products is extended to every field of industrial design by now. The digital models mainly provide information about the different components that form the products and about the shape of those components.

The research area of Virtual Prototyping [83] focuses on the use and the integration of Virtual Reality (VR) and Mixed/Augmented Reality technologies (MR/AR) in the Product Design Process.

Virtual Prototypes can be described as digital models enriched with additional informations, such as the surface finishing of the materials used or the mechanical behaviour of some dynamic components. Virtual Prototypes can be used to perform specific tests and analyses, as for instance ergonomics and usability test, rather than aesthetic analyses, during the different phases of the Product Design Process, without the necessity to build physical prototypes of the product.

As anticipated in Chapter 2, there are some categories of products, such as household appliances, vehicles, power tools, air-conditioning systems and so on, that need to be evaluated also from an acoustic point of view, since the sound generated by those products, while working, plays a key role in the overall perceived quality.

The focus of this research is the definition of a method for the validation of the acoustic feedback of Industrial Products. The method describes a way to perform this validation on the Virtual Prototypes of the products, and therefore it describes also a way to simulate the acoustic behavior of the prototype before the final product is ready.

Through the use of this method it will be possible to evaluate different characteristics of the sound perceived by customers during the use of a product (e.g. the level of annoyance), compare the results with the ones obtained with similar products and identify and solve possible acoustic problems.

In order to understand how to apply the method it is necessary to analyze how a Product Design Process works, explaining the different steps that lead from a concept idea to the final product. Subsequently, it will be possible to identify how the method for the evaluation of sound quality of Industrial Products can be integrated into the overall design process.

3.1 Product Design Process

The Product Design Process has been extensively studied [29, 70, 76], and many different representations are available in literature. Roxenburg and Eekels [70] proposed the model shown in the block diagram in Figure 3.1.

This representation is quite simple and shows only the macro-steps involved in a typical product design process without going into the details of the different steps.

The process generally starts with an **analysis** of the problem. The analysis concerns the definition of product objectives, requirements and attributes. Some requirements are based on the customers' needs, which can be collected with interviews with potential buyers.

The **design** task is definitely the most complex of the entire process. Due to the complexity of this task, it is common usage to spilt-up the Design phase into different parts.

It starts with the **concept design** step, in which designers and engineers develop one or more product concepts on the basis of the requirements defined in the analysis step. Those concepts, as the name suggests, usually contain only few information about the product, such as the shape, but technical contents are still not available.

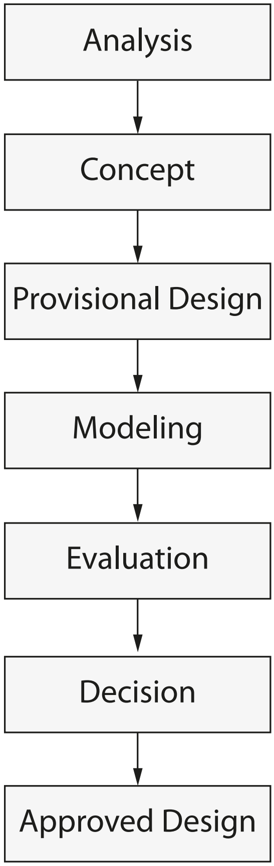


Figure 3.1: *Schematic representation of the Product Design Process [70]*

Afterwards, a more detailed design will be developed for the selected concept (**Provisional Design** in Figure 3.1). This task consists in designing the architecture of the product, including the definition of detailed functional information.

The **modeling** part of the process, known also as engineering or design to manufacturing, usually consists in the definition of all the technical characteristics of every component of the product. Structural analyses, dynamic and kinematic simulations are performed. Feasibility studies and production costs are analyzed. Finally, the production process is defined. Once the design process is completed, prototypes are built and tested to validate the product.

The **evaluation** can involve different aspects of the product, both related to the behaviour of the different components and to the interaction with users, e.g. aesthetics, usability and ergonomics.

Decisions and product modifications are performed on the basis of the results obtained during the tests, before to bring the product to market.

3.1.1 Evaluation of products

The testing phase plays a very important role in the product design process for obvious reasons. It is necessary to evaluate the correct working of a product before starting the production.

But the development of a product that “correctly works" is no longer enough, especially because customers can choose between a large variety of similar products made by different brands, and probably all consumer products work good enough.

Therefore, the new challenge is to find out what customers really look for when they buy a product, what makes the difference against the competitors. Aspects as ergonomics, aesthetics, functionality need to be evaluated and, in order to obtain satisfying results, potential buyers should be involved in the testing phase.

Through the users’ tests different kinds of problems can be discovered, and not all of these problems can be easily solved with few modifications of the design of the product.

Even if the schematic model of the product design process shows a linear flux from the analysis of the problem to the approved design of the product, in a real process the different phases may intersect each other and the process can be more complicated. Once a prototype of a product has been evaluated and the design has been modified on the basis of the results of the analyses, it will probably be necessary to perform again the evaluation, in order to check if the problems arisen have been solved.

Bordegoni described the process that involves design, engineering and testing phases as a spiral [20] that converges to the optimal products (see Figure 3.2).

3.1.2 Physical and Virtual Prototypes

Since different aspects of a product need to be evaluated during the different phases of the product design process, several kinds of prototypes are usually built to allow designers to perform tests before the final product has been carried out. Prototypes differ depending on the purpose of the tests that have to be performed.

Let us take car design as an example. The evaluation of the aesthetic characteristics of the car exterior can be performed by using a prototype of

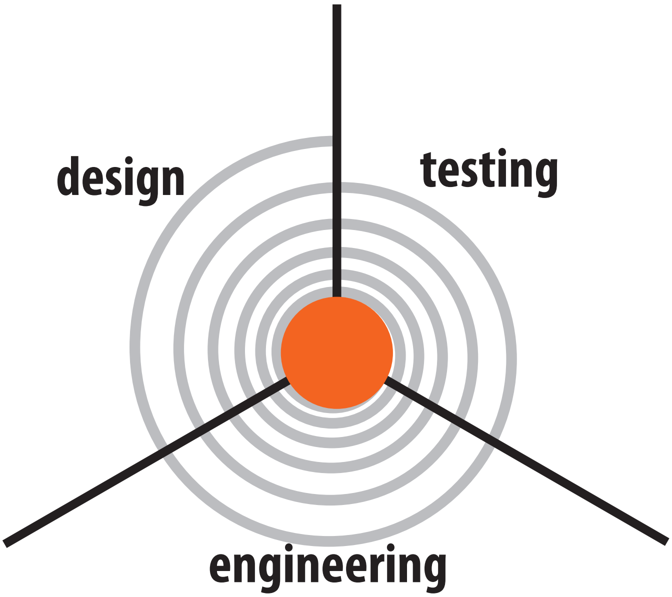


Figure 3.2: *Design, testing and Engineering phases of a Product Design Process [20]*

the body of the car with the correct surface finishing and painting, while a prototype of the dashboard of the car can be used to perform usability tests.

However, physical prototypes have some limitations. First of all, their production is very expensive, and, moreover, they are not modifiable and consequently they cannot be used if the design of a product is changed.

The research field of Virtual Prototyping [68] aims at solving those kinds of problems by giving the possibility to create digital prototypes of the product (called Virtual Prototypes) through the use of Virtual Reality technologies. Virtual Prototypes are interactive prototypes, and therefore they allow to be used as real prototypes do. Moreover they are extremely flexible and they can be used to evaluate the product since the concept phase to the full design. Those technologies allow creating virtual environments that involve multiple senses, as the sense of sight, hearing and touch.

3.2 Virtual Acoustic Method

In this Section, a general method to integrate the use of Virtual Acoustic Prototypes in the Product Design Process, in order to evaluate the acoustic characteristics of the industrial product starting from the first steps of the process will be described.

As explained in Section 2.2, the sound design of Industrial Products concerns several aspects. First of all, it is necessary to distinguish between the sound made by a product during operation (e.g. the noise generated by the fan of a hair dyer or by the motor of a washing machine) and the sound made during the interaction of the user with the product (opening and closing of the door of a fridge, interaction with the user interface of a microwave oven). The first category of sounds, in most cases, cannot be completely avoided, and therefore the sound design process is aimed at reducing the level of annoyance perceived by users and at increasing the perceived sound quality. The design of interaction sounds concerns, instead, different aspects. Usually interaction sounds are designed taking into account the other senses involved in the interaction of the user with the product (senses of sight and touch).

The method described in this research work is focused of the analysis and the evaluation of the sounds that are generated by products while working. Interaction sounds are not taken into account.

The method consists in turn of a process, which can be called Virtual Acoustic Prototyping Process (VAP Process). It describes how the sound generated by industrial products should be analyzed from the beginning of the Product Design Process. Figure 3.3 shows the principal steps of the VAP Process, which are the analysis of the acoustic requirements of the product under review, the implementation of one or more Virtual Acoustic Prototypes and the evaluation of the sound quality of the sounds generated with the help of the Virtual Acoustic Prototypes.

In the next sections, the phases of the VAP Process will be analyzed more in detail.

3.2.1 Acoustic Requirements

The acoustic requirements of a product can be described as the expectations of the users about the sound quality of a given product. The definition of the acoustic requirements of Industrial Products becomes necessary very early in the Design process. Figure 3.4 shows how the VAP process can be integrated with a canonical Product Design Process. From the diagram it is possible to see that the analysis of the acoustic requirements should be performed during the analysis of the product attributes, and those requirements should be taken into account during the whole design process.

Different methods can be used to estimate the acoustic requirements of a product. Actually one of the most effective solutions is to obtain feedback directly from the possible buyers [49].

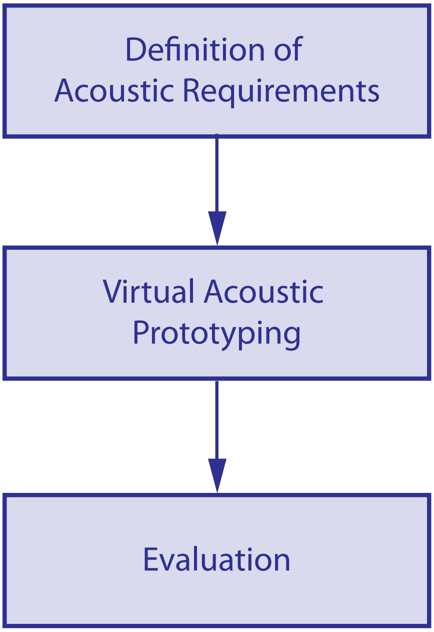


Figure 3.3: *Virtual Acoustic Prototyping Process*

Customers' opinions can be simply obtained with interviews. A different problem is to find out what to ask them. A question like "what is the sound you expect from this product?" can be too generic, and people can answer in many different ways, using a wide variety of adjectives, which makes a subsequent rearrangement of the results impossible. Another solution can be asking them about specific features of the sound: "how much powerful should be the sound of this product?". In this case the interviewer can choose what kind of semantics should be used to characterize the sound.

The analysis of the literature related to the procedures for the evaluation of sound quality has proved that Semantic Differentials is one of the most suitable procedures to define the characteristics of industrial sounds and schematize the users' opinion.

3.2.2 Virtual Acoustic Prototyping

As we can see in Figure 3.4 Virtual Acoustic prototypes can be implemented during the different phases of the Design Process. They will differ from a phase to another and their accuracy will depend on the stage of development of the design. In the concept phase only few information of the product are available, and for this reason some hypotheses about the shape

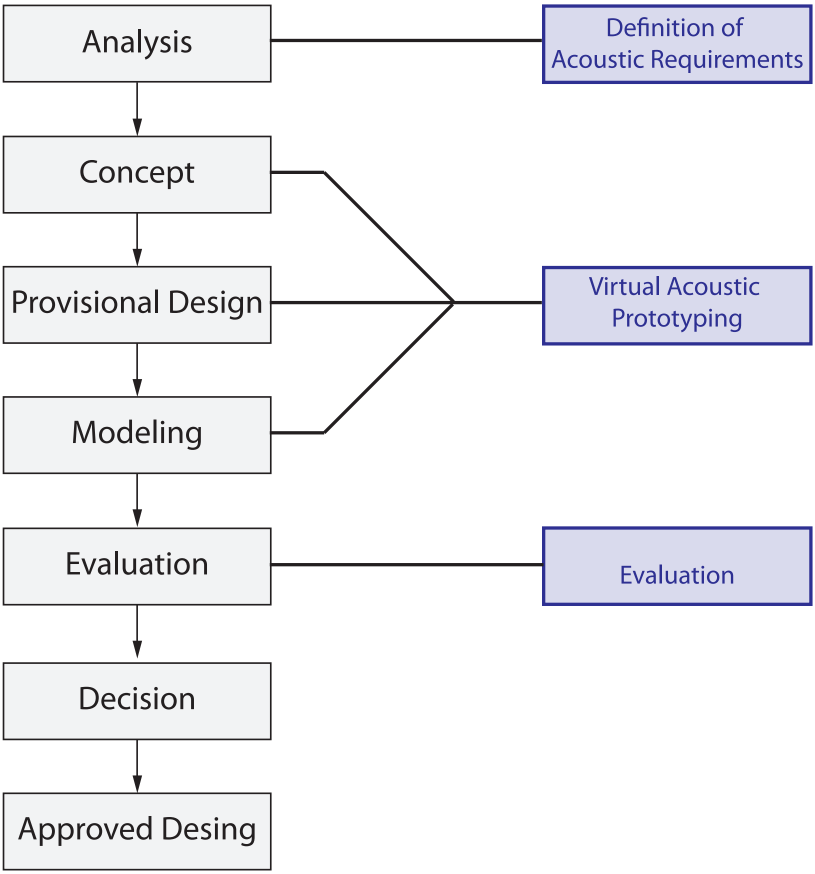


Figure 3.4: *Virtual Acoustic Prototyping in the Product Design Process*

of the product and the different components have to be done.

Since no physical prototype is available in the first steps of the Design process, it is necessary to find a way to simulate the sound produced by the product.

Therefore the first step consists in the identification of the components of the product which contribute to create the overall sound emitted during operation. If we consider, as example, an hairdryer, the noise is generated by the motor, by the internal fan and by the movement of the air going out from the nozzle.

Once the "noisy" components have been identified, the corresponding sounds should be collected and mixed in order to create the overall sound of the product. If the physical process that generates the sound, e.g. impact, friction, is simple, it is possible to use a physically-based synthesis (see section 4.1.2) to obtain a realistic output sound. However in many cases the complexity of the physical phenomena involved in the generation of sounds of industrial products is too high to be simulated with an adequate level of detail. A different method, which can be used both with simple and complex sounds is to record the noise components from similar products already on the market. For some components this approach is adequate enough. Coming back to the example of the hairdryer, it is reasonable to imagine that a manufacturer will choose, for a new product, the same motor present in the previous product line. Also in those cases, some approximations are needed, because some noise components cannot be the same of the previous products, otherwise the sound quality analysis does not make sense.

Another aspect that cannot be avoided during the implementation of a Virtual Acoustic Prototype is related to the working environment of the product. The sound perceived by users differs from the one generated by the product, and this difference is related to the propagation of the sound waves into the environment. Therefore an appropriate Virtual Acoustic Prototype should also be able to simulate the sound propagation into different working environments.

In Section 3.3.2 the concept of a Virtual Environment that can be used as a tool for the construction of Virtual Acoustic Prototypes has been described. The environment, whose implementation is part of the research work described in this thesis, combines the use of sounds recorded from noise components of Industrial Products with an algorithm to simulate the propagation of sounds.

3.2.3 Evaluation

The final purpose of the overall VAP Process is the evaluation of the sound generated with the implementation of the Virtual Acoustic Prototypes. Also in this case potential buyers should be involved in the process, since they are the final users of the product. With the use of Virtual Prototypes it is possible to easily evaluate different configurations for the same product, e.g. it is possible to evaluate the sound perceived by users in different working environments.

Once the Virtual Acoustic Prototypes have been defined, and one or more different configurations have been simulated, a jury test is performed. Users are asked to hear one or more generated sounds and evaluate them. The results of the evaluation tests can be compared with the acoustic requirements collected. In this way it is possible to analyze which characteristics of the product, in terms of acoustic feedback, differ from the expected ones. Moreover, an evaluation of the influence that the working environment has on the perception of sound quality can be made.

More interesting results can be obtained including some expert customers in the evaluation phase. Expert customers are people that have more experience with a specific product. This experience can be acquired if the product is involved in their everyday jobs. A canonical user of hairdryers mostly use the product once a day, while hairdressers hear the noise generated by the hairdryer during all the working day. They can certainly give more precise impressions about how annoying can be the sound and which characteristics should be avoided.

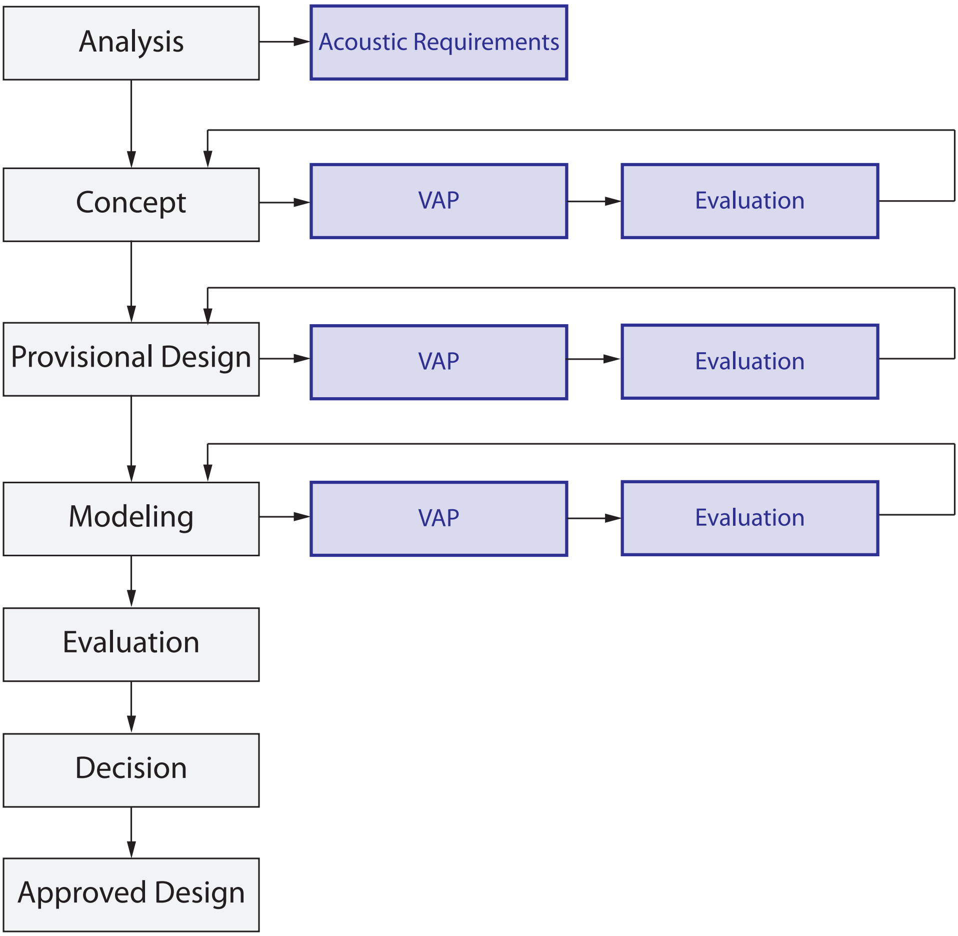


Figure 3.5: *VAP and evaluation in the different phases of the Product Design Process*

A final consideration is related to the integration of this method into the Product Design Process. As Virtual Prototypes can be implemented since the Concept phase, test and evaluations should be performed early in the process.

Figure 3.5 shows a reorganization of the overall Product Design Process that includes a VAP method. Different Virtual Prototypes, with different levels of details are implemented since the very beginning of the Design. Through their evaluation possible problems can be discovered and solved early in the process, thus reducing costs and time-to-market.

3.3 Tools for the Virtual Acoustic Prototyping Method

For each phase of the VAP Process it has been necessary to define an appropriate tool. In Figure 3.6 the three phases of the VAP Process and the corresponding tools are shown. We can notice that for both the Acoustic Requirement phase and the evaluation phase it has been decided to use the Semantic Differentials procedure as sound quality descriptors. In this way it is possible to easily compare the expectations of the users with the perceived sound quality.

Virtual Acoustic Prototyping Method

Phases	Tools
Definition of the Acoustic Requirements	Semantic Differentials
Implementation of the Virtual Acoustic Prototype	Virutal Acoustic Environment
Sound Quality Evaluation	Semantic Differentials

Figure 3.6: *Phases of the Virtual Acoustic Prototyping Method and corresponding tools*

The Virtual Acoustic Environment, which can be described as the tool used for the implementation of the Virtual Acoustic Prototypes, has been entirely defined and implemented inside the research work described in this thesis, while Semantic Differentials is a well-known tool for the sound quality evaluation, and it has been chosen between a large number of other procedures for its peculiarities.

3.3.1 Semantic Differentials

The comparison of the different qualitative tools used for the sound quality evaluation showed that the Semantic Differentials procedure is the only one that takes into account more than one characteristic of the sounds.

In this method it has been decided to use the set of bipolar adjectives proposed by Zeitler [89] that is suitable for the analysis of industrial sounds. Moreover a seven-point scale is used, since resulted to be the most effective scale to be used for the Semantic Differentials procedure [40].

calming	___	___	___	___	___	___	___	agitating
dark	___	___	___	___	___	___	___	bright
dull	___	___	___	___	___	___	___	sharp
flat	___	___	___	___	___	___	___	rumbling
muffled	___	___	___	___	___	___	___	shrill
pure	___	___	___	___	___	___	___	impure
smooth	___	___	___	___	___	___	___	rough
soft	___	___	___	___	___	___	___	hard
steady	___	___	___	___	___	___	___	unsteady
ugly	___	___	___	___	___	___	___	beautiful
unpleasant	___	___	___	___	___	___	___	pleasant
weak	___	___	___	___	___	___	___	strong

Figure 3.7: *7-point based scale to compare pairs of adjectives*

Customers are asked to fill in a form, shown in Figure 3.7. The same form is used both for the definition of the acoustic requirements and for the evaluation of the sounds generated with the Virtual Acoustic Prototypes.

Since the Semantic Differentials procedure is normally used only for the evaluation of the sound quality of products, it is possible to consider this procedure also as a tool to extrapolate users' opinions and expectations about the sound that a product should generate, and to classify those opinions in a structured model, that can be analyzed and compared.

3.3.2 Virtual Acoustic Environment

The Virtual Acoustic Environment reproduces the sonic response of a product within its working environment.

Through an accurate modeling of the environment, and an appropriate propagation algorithm, it is possible to simulate how a sound generated by a product, during its operation, is modified by all the surrounding elements.

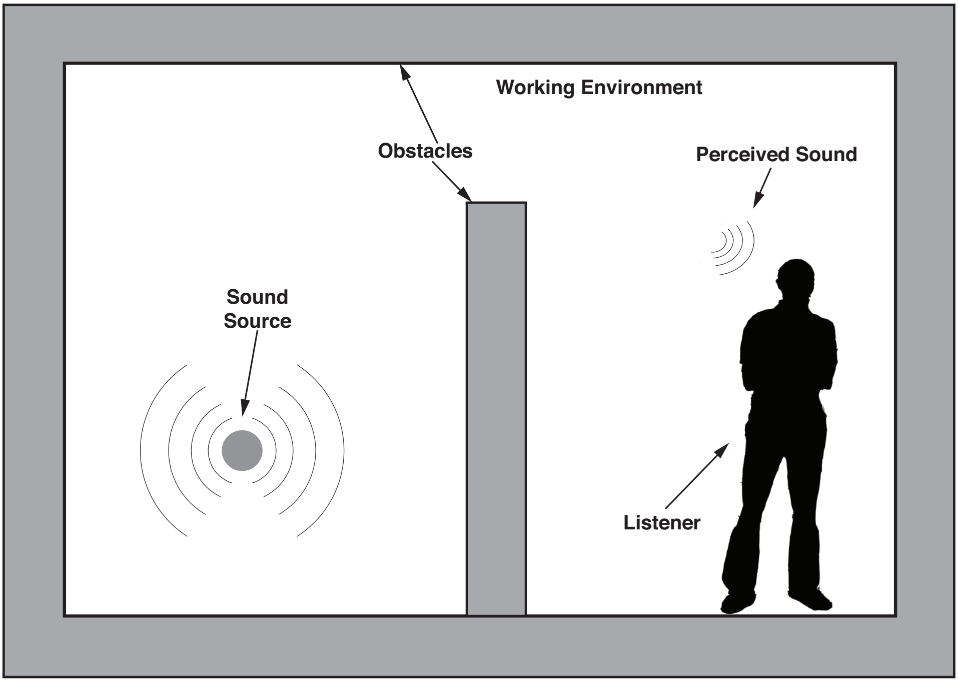


Figure 3.8: *Concept of the virtual environment*

The "obstacles" in the Figure 3.8 represent all the physical elements that are present in the scene, i.e. in the environment where the sound propagates. They can surround both source and listener (e.g. the walls of a room) or they can stay between them (e.g. tables or chairs). Users are able to modify the virtual environment just adding objects in the scene, or editing the characteristics of the objects, such as thickness or material, and feel how those modifications can influence the perceived sound.

It is important to underline that also the Virtual Prototype of an Industrial Product can be partly considered as an obstacle. In most cases, only a part of the product contributes to the generation of the sound. The other components can be assumed as obstacles. Figure 3.9 can be used to clarify this concept.

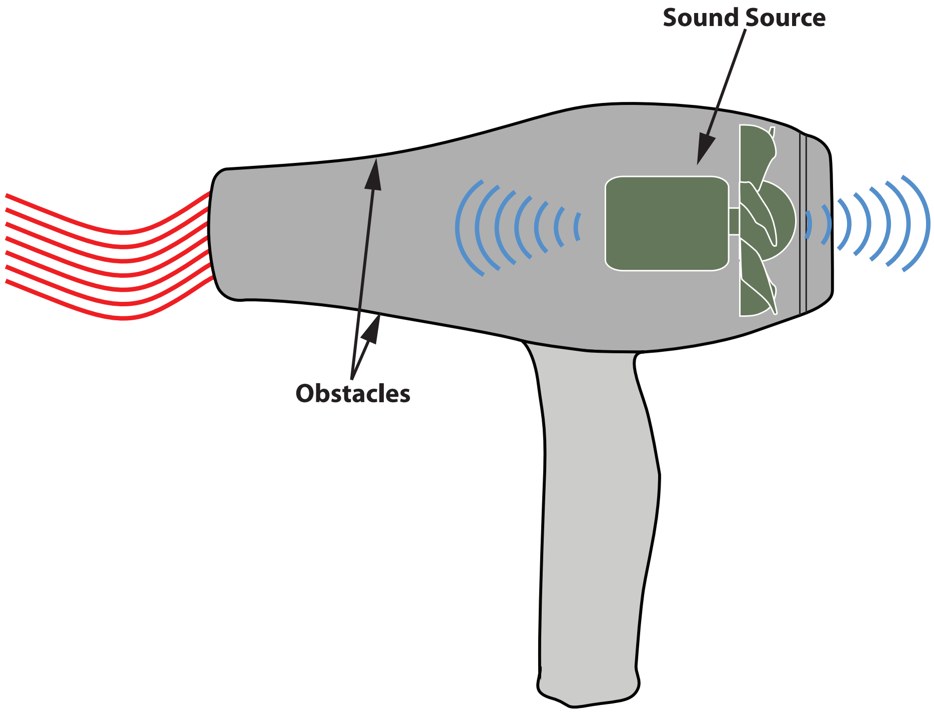


Figure 3.9: *System conception of the virtual environment*

The principal noise component of a working hairdryer is the motor and the connected fan. The other components, such as the cover, can be assumed as obstacles. The propagation of the sound waves is influenced by the shape and the material of those components. The Virtual Acoustic Environment allow users to modify the characteristics of those components (e.g it is possible to increase the thickness of the cover, rather than the material or the shape), and the output sound will be modified on the basis of those changes.

CHAPTER 4

Related Works

The research field of Virtual Acoustics concerns all the methods and the techniques that simulate physical laws with the purpose of creating virtual sound fields [14]. Generally sound fields are described by:

- **Sound source**: The objects that start the motion of air molecules, activating the propagation of sound waves.
- **Environment**: Everything surrounding the sound source. Sound waves are modified by the presence of other items (obstacles) in their wave field.
- **Listener**: the person or the object that receives and acquires the sound waves.

Savioja et al. [73] defined a conceptual model of a virtual acoustic environment modeling structure, named Virtual Acoustic Display (VAD) (see Figure 4.1) that illustrates the process of implementing Virtual Acoustic Environments. The process consists of three modeling tasks that have to be analyzed separately.

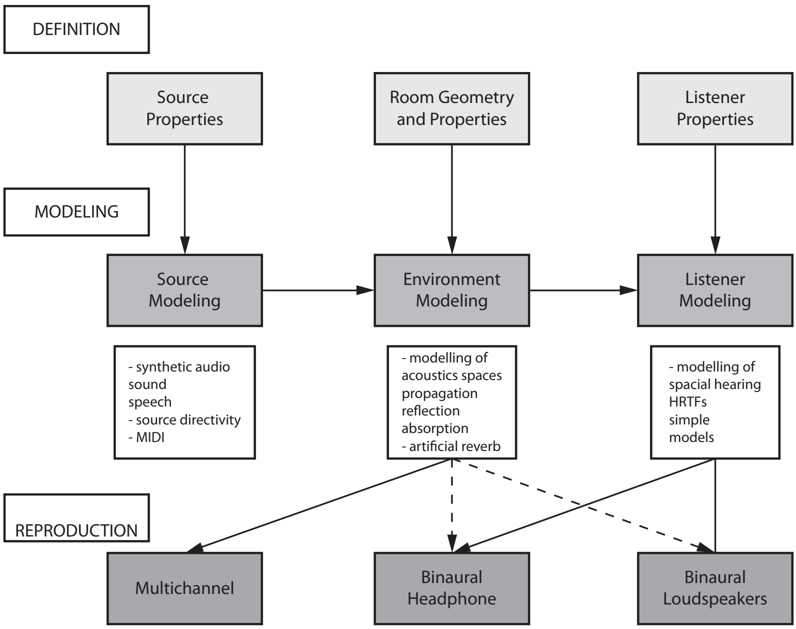


Figure 4.1: *Coneptual model of Virtual Acoustics (Virtual Acoustic Display [73])*

The research field of Virtual Acoustics can be organized into three macro-areas, using the same classification defined in the VAD:

- Source Modeling
- Environment Modeling
- Listener Modeling

In this chapter, a description of the latest technologies and results obtained in the research field of Virtual Acoustics is presented.

4.1 Source Modeling

The basis of sound rendering is the synthesis of sounds that have to be reproduced by virtual sources. Many research regarding sound synthesis has been done, especially for music applications [26]. In spite of this, in virtual environments acoustic synthesis rarely includes musical sounds; moreover, aiming to create an immersive environment, it is necessary to simulate "natural" sounds, like ones obtained by collisions.

Method	Working Principle
Sample-based Synthesis • Sampling • Sound Texture	Recorded Sounds
Physically-based Synthesis	Sounds obtained by simulating the physic laws of interaction between objects

Figure 4.2: *Source Modeling techniques*

Sound Synthesis (see Figure 4.2) process can be split into two categories: a sample-based synthesis, in which registration of sounds are used, and a physically-based synthesis, in which sound is generated starting from physical and mathematical models.

4.1.1 Sample-Based Synthesis

One approach for sound synthesis is based on the use of pre-registered corresponding sounds (sampling) that have to be reproduced by virtual sources. This method allows us to create desired sounds by combining different registrations, generally monophonic, and by editing parameters like volumes and sound spectrum. Even if sounds obtained with sound sampling are generally very realistic, there are many troubles related to the use of this methodology, as the necessity of a big amount of memory to store samples or the complexity of analyses and parameters necessary to define correctly the desired sound.

Moreover, a big problem of sample-based sounds is that they are always finite sounds; therefore, in order to create a continuous signal, sounds have to be repeated, creating an artificial sensation of loop.

In order to solve problems like those, sound texture techniques have been defined [13, 63, 71].

Those techniques aim at synthesizing a signal similar to a desired sound, and different approaches have been used. In 2000 Desainte-Catherine and Hanna [30] defined a statistic approach based on parametric model of the signal adapted on the statistical parameters of the target sound. In 2002 Dubnov et al. [33] defined a statistical learning algorithm for sound texture based on the decomposition of the signal in wavelets. Another approach, studied by Lu et al. [57], consists of synthesizing long audio stream according to a given short example audio clip. The example clip is first analyzed to extract its basic building patterns. An audio stream of arbitrary length is then synthesized using a sequence of extracted building patterns. In sample-based synthesis and sound texture sounds must be recorded in anechoic chambers in order to obtain only the direct sound generated by the sound source and avoid sound modifications caused by to the environment - e.g. sound reflections, reverberation and so on.

4.1.2 Physically-Based Synthesis

Sounds are generally created by the interactions between objects. The study and the simulation of the physic laws related to those interactions, like impacts and frictions [66], is known as physically-based synthesis. This approach is generally used when integrating sound in virtual reality environments, due to the possibility of simulating the interaction of users in a virtual environment. In 1998 van den Doel and Pai [80] described a framework for the simulation of sounds obtained by collisions.

Physically-based simulations are generally based on the evaluation of mechanical properties of the objects, like natural frequencies and mode shapes; those properties are function of the shape of the object, materials, impact point and impact magnitude. Sounds can be modeled as combination of harmonic functions (sinusoids).

In 2001 van den Doel et al. [79] expanded sound simulation taking into account other interaction models, like rolling and sliding.

In 2004 [78] they arrange results to simulate complex audio environents. In order to obtain a real-time simulation of rigid-body interaction sounds, O'Brien et al. [60] pre-calculated a mode shapes matrix using a 3D mesh of the object. The simulation of deformable objects [59] needs a more complex algorithm; at first the motions of the objects are computed, then their surfaces are analyzed to determine how the motion will induce acoustic pressure waves in the surrounding medium.

More complex algorithms for sound synthesis have been developed by James et al. [47]. They start by pre-computing the linear vibration modes of an object, and then relate each mode to its sound pressure field, or acoustic transfer function, using standard methods from numerical acoustics.

Moreover, in 2008 Bonnell et al. [17] defined a fast sound synthesis approach, based on short-time Fourier Transforms. This approach allow us to perform mode-based computations when many objects are impacted simultaneously.

Other studies have been done investigating different natural phenomena; aerodynamics, like wind blowing or swinging swords [31], and turbulent field, like fire vortices [32] have been analyzed by Dobashi et al.. They proposed a method for creating sound textures for aerodynamic sound by making use of computational fluid dynamics. Next, they used the sound textures for real-time rendering of aerodynamic sound according to the motion of objects or wind velocity or vortexes distribution. This method can be defined as a hybrid approach between sample-based and physically-based synthesis.

More about fluids sound simulations, in 2005 van den Doel [77] validated a physically based liquid sound synthesis methodology; he used a simplified sound model for isolated single bubbles and then a stochastic model for the interactive synthesis of complex liquid sounds based on the synthesis of single bubble sounds.

A similar work has been carried out by Zheng and James [90], in 2009, in which they proposed a practical method for automatic procedural synthesis of synchronized harmonic bubble-based sounds from 3D fluid animations.

One of the most evolved approach for a physically-based sound synthesis is developed in 2009 by Chadwick, An and James [24]; they propose a procedural method for synthesizing realistic sounds due to nonlinear thin-shell vibrations. They used linear modal analysis to generate a small-deformation displacement basis, then join the modes together using nonlinear thin-shell forces.

4.2 Environment Modeling

In order to properly model sound wave propagation in a closed environment, a very large number of variables need to be taken in account. In time, different models have been developed, but none has resulted in a proper and efficient solution for both low and high frequencies. The number of parameters to be considered has proved so high that in the end the real behavior can only be approximated. It is possible to approach the problem with three different kinds of methods, from a computational point of view: statistical methods, wave based methods and geometrical methods [72]. Figure 4.3 shows a summary of the different methods used to simulate the propagation of sound waves.

The first ray-tracing sound model has been developed in 1968 by Krokstad et al [52]. It referred to sound waves distribution in the audience area of

Method	Working Principle
Statistical Methods	No simulation, but estimation of sound pressure level and reverberation time
Wave-based Methods • FEM • BEM • FDTD	Numerical approximation of wave equation
Geometrical Methods • Ray-tracing • Image-source • Particle tracing • Cone and pyramid tracing	Enegy approach. The loss of energy, during the propagation path of sound waves, is computed.

Figure 4.3: *Environment Modeling techniques*

a concert hall. They fully understood the fact that the advent of digital computation would have dramatically improved the modeling of sound reflections. Since then, a lot of different models and approaches have been developed.

4.2.1 Statistical Methods

Statistical methods, offering quite approximate results, are empirical implementations used to predict in octave bands parameters like sound pressure level and reverberation time. The most famous statistical methods are the ones developed by Eyring and Sabine. These methods are used most of all to calculate diffuse parameters, e.g. noise level in closed environments [42]. In fact, they do not consider shapes and positions of objects in the environment, but only the dimensions of the room and the absorption level. Furthermore, these methods have a large number of limitations, and cannot be used to predict sound levels in rooms of every shape, material and dimension [44]. For example, they cannot be applied in rooms that present very high levels of absorption. The application of this methods in the model of a room that falls out of the limits of application can give erroneous results. Many have tried to refine and improve these methods, for example Hodgsons [43] and Cotana [27], but the limitations of this approach are intrinsic, and as for now there has not been one single model suitable overall.

4.2.2 Wave-based Methods

Wave-based methods are numerical approaches used to approximate the solution, and do not solve the wave equation itself. These implementations are applications of well-known generic numerical methods such as Finite Element method (FEM) [45], Boundary Element method (BEM) [51] and Finite-difference time-domain method (FDTD). In these implementations, the space is not treated as a continuum, but as a series of small adjacent elements that interact with each other according to the laws of wave propagation. When used to solve the problem for a single frequency, wave-based models give very accurate results. The limitation of this methods is in the fact that they have an extremely high computational cost. In fact, at least six nodes for every frequency need to be used to model the wavelength in order to obtain realistic results. At high frequencies, this can generate a huge amount of data to be considered, as the natural modes in a room increase with the third power of the frequency. In FEM, the space is represented by small elements that only interact with the adjacent ones. This technique is mostly used to simulate wave propagation in a closed space. As for BEM, not all the space is discretized, but only its boundaries. All the nodes discretized in BEM interact with each other. This method can be used to simulate interior acoustic fields, exterior acoustic fields or both at once. The FDTD method is based on the substitution of the derivatives in the wave equation with the corresponding differences. As said, all these methods have a very high computational cost, therefore they are only used in the simulation of small environments, for example the cockpit of a car.

4.2.3 Geometrical methods

These methods are based on sound paths in an environment. They basically use a physical representation of sound, represented not as waves but as straight lines. They use different techniques to simulate sound diffusion by tracing rays, pyramids, particles or other similar artifacts, and taking in account the effects of reflection, diffusion and diffraction. These methods are based on approximations and therefore none of them provides exact results, but they can prove useful in the prediction of the temporal and spatial reflections of sound, thus being suitable for auralization [55]. There are four main geometrical methods to be presented.

Ray-tracing Method

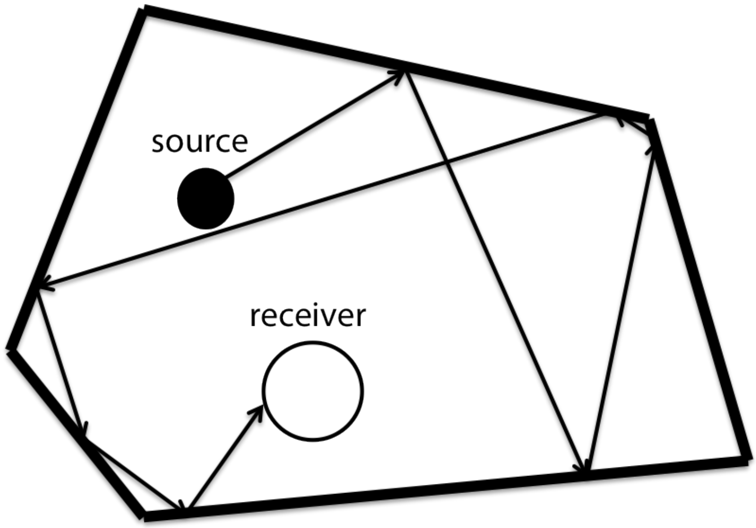


Figure 4.4: *Ray-tracing method*

This method is based on the substitution of sound waves with power-carrying rays (see Figure 4.4). These rays cross the space, bouncing on the objects they meet on their path. All this path needs to be modeled, considering every ray as a single vector that changes direction with every impact. The energy of the rays constantly decreases because of sound absorption (due to air, collisions or other materials). When finally the rays reach a predefined volume (called receiver), the residual energy is calculated and the data is stored, along with its temporal delay. Obviously, residual energy depends on the length of the path. Adding all the data collected, it is possible to obtain all acoustic parameters for every receiver considered. The receiver must also be modeled, in order to simulate its effect on the acoustic of the room and to achieve more accurate information on the direction the sound comes from. The preferred shape used to model a receiver is a sphere, as it is omni-directional, but theoretically a receiver can be of every shape, even planar. The rays can be emitted in a pre-determined or random way [53]. This method gives good results, except for low frequency, and it is often used to predict noise levels with good accuracy [8, 9].

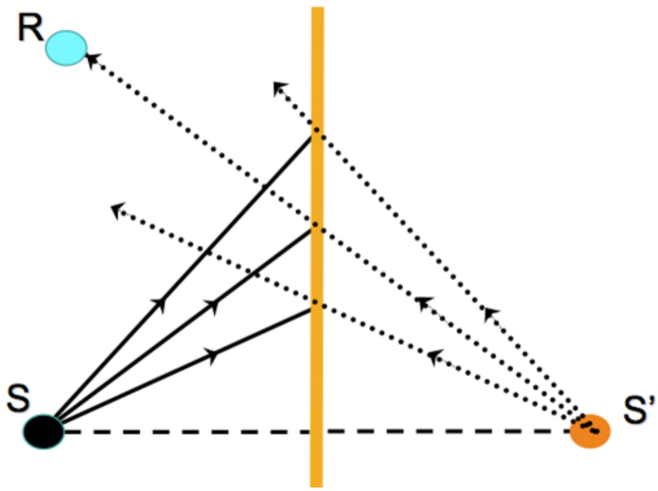


Figure 4.5: *Image-source method*

Image-source method

This method is a more complex, but also accurate, version of the ray-tracing method. In this model, every time a sound path is reflected on a surface, the sound source is mirrored on the impact point (S' in Figure 4.5) .

At this point, the reflected path is replaced by a virtual path that connects the newly found virtual source with the receiverâĂŹs position.

It is quite evident as, with the increase of the complexity of the environment, the computational cost increases exponentially. Therefore, a hybrid method is often used: the image-source method is used for early reflections, while the ray-tracing method is used for subsequent reflections [88]. These hybrid methods can be further augmented by the use of some wave-based methods in order to improve the accuracy at lower frequencies.

Anyway, the image-source method can give very accurate results in terms of level, arrival time and direction of the early reflections [67], which are known to be the most important in the subjective hearing feeling of listeners [46]. Usually, for regular spaces simple algorithms are used [54], which can be extended to the generic polyhedral environment as described by Borish [21].

Particle-based method

This method is a simplification of the ray-tracing method. Instead of tracing the paths of rays, these are substituted with particles. The energetic charge of rays is also absent: in order to simulate the loss of energy, particles can disappear with every impact.

At every collision with a surface, a random number between 0 and 1 is generated. This number is then compared with the absorption coefficient of the surface and, if it is smaller, the particle disappears. If it is higher, the particle continues its path.

This method is much more simple than the ray-tracing method and it is computationally much more affordable, but it is also rather inaccurate. Acceptable results can only be obtained with a number of particles tending to infinite.

Cone or pyramids tracing method

In order to reduce computation time, it is also possible to trace cone or pyramids spreading from the sound source with the axis traced as in ray-tracing. One of the first applications of this method was carried out by Farina with the commercial software Ramsete [37], where triangular beams were generated at the sound source. The central axis of each pyramid was traced as in ray tracing, being specular-reflected when a surface was hit. The three corners follow the axis, all being reflected at the same plane. It considers point receivers, and detection occurs when the receiver is inside the pyramid being traced.

4.3 Listener Modeling

Another fundamental task for a correct definition of a virtual audio environment is the spatial reproduction of sounds.

Research about 3D sound reproduction is very active, especially due to the integration of more immersive tools in the common multimedia environments like video games or home cinema. In the same way, a correct reproduction of 3D sound in virtual reality environments contributes to increase the sensation of immersion of users [54]. Figure 4.6 shows a summary of the techniques used for the spatial reproduction of sounds.

Systems for spatial hearing generally aim to simulate the correct three-dimensional output sound for users ears, taking into account both positions of users and virtual sound sources. It is possible to distinguish two categories of spatial sound methodologies.

The first approach is based on the use of two or more independent audio channels that, exploiting a symmetrical configuration of loudspeakers, can create the impression of sound heard from various directions; this approach is the basis of stereophony, and has been extend to multi-channel systems.

Method	Working Principle
Stereophony and multi-channel	Spatial sound obtained by positioning two or more loudspeakers around the user
Binaural Techniques	Spatial sound obtained by simulating the physics of the acoustic waves that come to user's ears.

Figure 4.6: *Listener Modeling techniques*

The second approach is targeted to the physical simulation of the acoustic field around the user; the most used method is known as binaural hearing and studies the differences, in terms of time and magnitude, between the two ears of the user.

4.3.1 Stereophony and multi-channel systems

How explained before, the first category for spatial sound consists of the use of two or more loudspeakers that create a sound field around the user.

Stereophony is still the most used method for sound reproduction; it is based on the use of two loudspeakers, generally situated in front of the user [75]. Working on the delay and the gain of the two speakers, it is possible to create a "phantom" source, giving therefore the sound direction desired in the range between the two speakers.

When using loudspeakers each ear hears sound from both speakers. Different recording method are based on the use of more than two microphones, and mixing then recordings down to two tracks, so that the separation of the instruments can be increased, and the mixture that occurs when listening via speakers can be compensated.

An extension of stereophony is obtained using more than two loudspeakers. The best example of multi-channel systems is represented by the surround sound technology, generally used in most of multimedia applications, like cinema and home theater systems, personal computers, video game consoles and other platforms. It is possible to use a multi-channel environment defining different configurations of the loudspeakers; at the moment most of commercial systems use a "5.1" or a "7.1" configuration.

Those configurations generally schedule three front channels, two of them in the front-left and front-right corners and one in the center (generally used to increase the acoustic of dialogues), and two back channels, called *surround channels*. In the 5.1 4.7 configuration the two surround channels are positioned in the back-right and back-left corner, instead in the 7.1 configurations a central back channel and others two lateral channel are added.

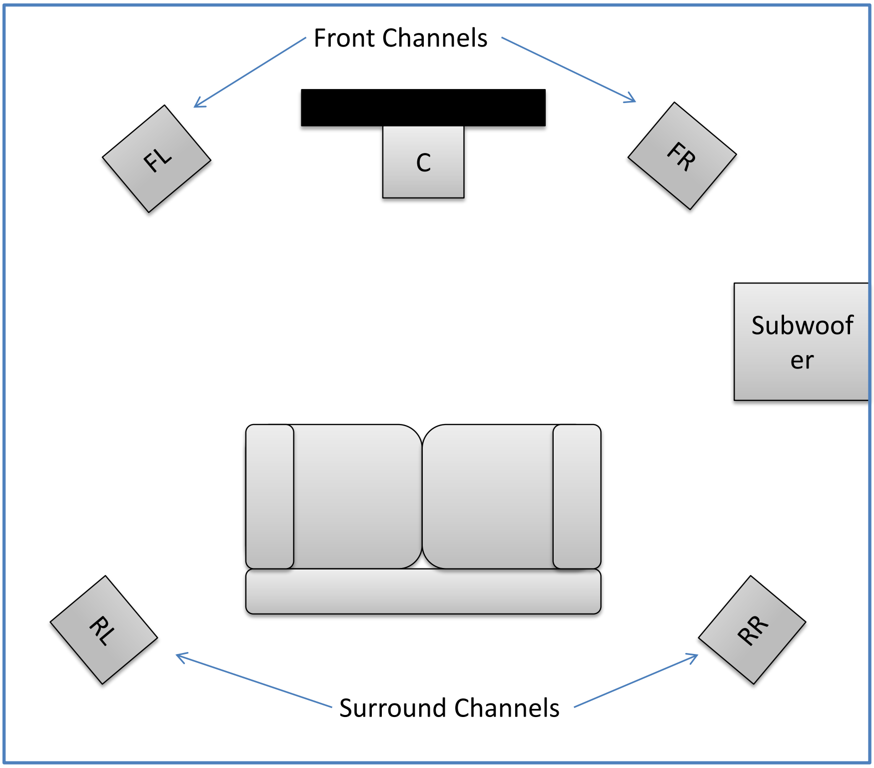


Figure 4.7: *Surround 5.1 configuration*

In this last configuration the separation between the front and the back sounds is more clear. In both configurations there is another channel used only to transmit low frequencies (generally up to 80/100 Hz), and it is usually positioned on the floor, to increase the transmission of vibrations.

Surround systems can therefore create an immersive acoustic field around users, but generally the results is different related to real three dimensional sounds; this kind of problems occur usually because in those systems the spatialization is obtained only separating output in different channels without taking into account the real position of the users.

4.3.2 Physical sound field

The second typology of approaches for spatial sound reproduction, known as binaural techniques, starts from analysis of the physics of acoustic waves that come to user's ears. When speaking about binaural technology it is necessary to introduce:

- Interaural Time Difference (ITD)
- Interaural Level Difference (ILD), also known as Interaural Intensity Difference (IID).

ITD represents the phase difference between ears; sound, in fact, travels a different distance to each ear. Sound localized in direction of ear receiving the leading wave front; the bigger the difference in phase, the bigger the shift in perceived location.

ILD instead represents the difference in Sound Pressure Level (SPL) between ears, as result of obstruction by the head. While ITD is more noticeable at low frequencies, IID is in inverse proportion with the length of the waves, so it is noticeable only for high frequencies (> 1500 Hz). Moreover the diffraction of sound waves by the human torso, shoulders, head and outer ears (pinnae) modify the spectrum of the sound that reaches the ear drums [15].

The head-related transfer function (HRTF) [14] are filters that can be applied to monophonic input sounds, returning stereophonic outputs; those filters take into account the changes of the spectrum of the sound described before but are also dependent on the morphology of the user [84].

HRTF represent the relationship between the sound pressure level close to the eardrum and the sound pressure level of the sound source, in open field.

Once known the transfer functions for the two ears $h_L(t)$ and $h_R(t)$ in Figure 4.8 (related to a specific relative position between sound source and listener), it is possible to apply those functions (filters) to a monophonic input $x(t)$ to obtain a binaural output, $x_L(t)$ and $x_R(t)$

Richard O. Duda studied different methods to define an analytic model of HRTFs. In 1993 [34] he used a spherical model of the head to define analytical HRTFs; in 1998 Brown and Duda [22] defined a parametric structural model, where parameters are directly related to the size and shape of the listener's torso, head and outer ears.

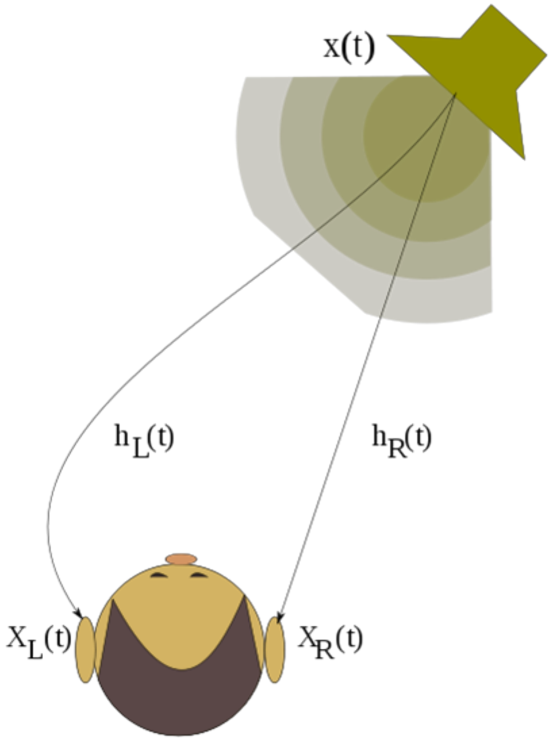


Figure 4.8: *HRTF filtering create binaural output from a monophonic input*

Moreover, in 1999 [35] a simplified ellipsoidal head model has been defined to analyze the ITD variation from person to person.

However the most used approach for spatial sound reproduction consists of the direct measurement of HRTFs in anechoic rooms. those measurements, that are made for different positions, by changing azimuth and elevation angles (see Figure 4.9) can be obtained on physical models of heads or directly on users.

Measurement procedure is quite difficult; a lot o measurements are available on the web and can be used for research purposes, like KEMAR [50], LISTEN [56], CIPIC [25].

The problem that usually occurs when using pre-measured HRTFs is due to the fact that those kinds of filters are strongly dependent of the morphologic properties of the user. However studies have been done [74] for the use of generic filters through a specific calibration on the user.

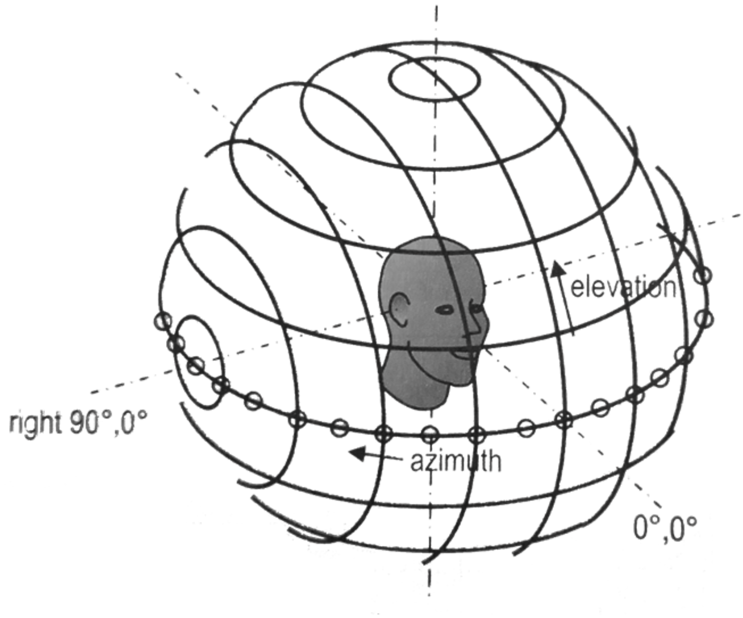


Figure 4.9: *Recording positions for HRTF*

Binaural techniques are usually reproduced by using headphones, since it allows to send separate sounds, opportunely filtered, to the two ears. In the last years, a technique known as cross-talk cancellation, allow the reproduction of binaural sounds by using loudspeakers. This technique is based on the application of filters that remove the unwanted audio components, H_{12} and H_{21} in Figure 4.10 coming from the loudspeakers S_1 and S_2.

4.4 Virtual Acoustic for Product Design

Virtual Acoustics can be described as the study of the various techniques that simulate physical acoustics laws in order to create virtual sound fields. Many studies have been carried out within the context of acoustics simulations, especially concerning gaming and virtual reality applications. Within the field of Virtual Prototyping focused on product development, acoustics simulations can be used for the evaluation of the noise pollution caused by industrial products rather than acoustic comfort perceived by users. COMSOL Multiphysics [2], Altair HyperWorks [1] and other similar commercial software, contain specific modules that allow us to perform acoustic simulations of virtual models in order to predict natural frequencies, evaluate the pressure response and identify vibration hot spots.

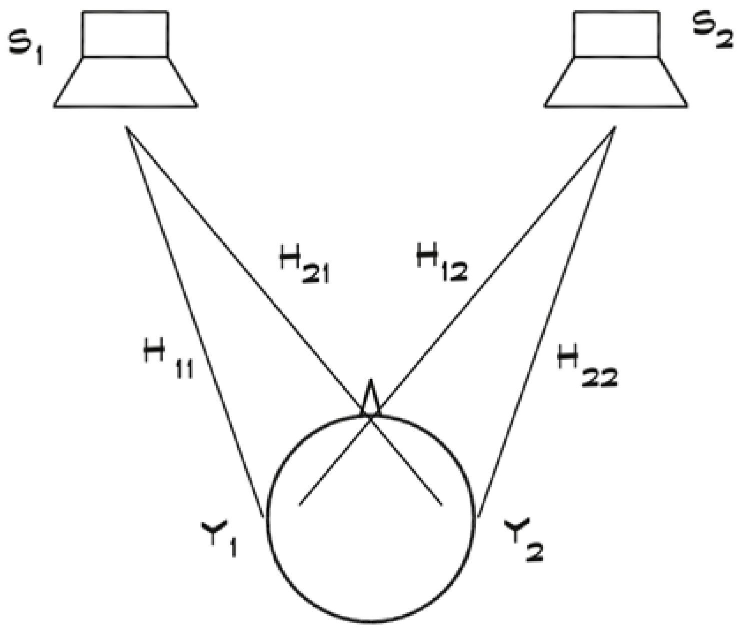


Figure 4.10: *Cross-talk cancellation*

LMS international [4, 81] carried out a deepened research about acoustics analyses on virtual prototypes. LMS solutions contain a large set of software/hardware tools ranging from general purpose to specific applications.

Those kinds of software use numerical methods, e.g. Finite Element or Boundary Element Method (see Section 4.2.2) and the output of the simulations has to be analyzed by engineers to validate the virtual models.

A totally different approach related to the integration of sound in Virtual Prototyping application has been studied in the 5th Framework European Project TOUCH-HapSys [65]. The project research resulted into the development of a multi-modal framework called I-TOUCH, that should allow users to interactively explore digital mock-up and perform usage tests. However the research has been mainly focused on the definition of a haptic tool, and the sound integration has been realized essentially to increase the user's immersion but it is not really used for the acoustic validation of the prototypes. More in detail the framework allows users to perceive 3D positional sounds, but propagation effects have not been simulated.

The major innovative aspect of the research work with respect to the acoustics simulations performed by the above mentioned commercial tools, is related to the kind of output obtained from the implementation of the Virtual Acoustic Prototypes, and consequently to the potential users that can exploit the functionality of the system. In fact, the expected output of the simulations is an audible feedback, which can be immediately perceived and evaluated by common users in a natural way.

CHAPTER 5

Virtual Acoustic Environment: Numerical Modeling and Implementation

In this chapter the development of the Virtual Acoustic Environment is described. The chapter is divided into two The first part shows the modelling techniques chosen to define the Virtual Acoustic Environment. In the second part the architecture and the implementation of the Virtual Acoustic Environment is deepened.

5.1 Numerical Model of the Virtual Acoustic Environment

The sound generated by a sound source travels into a propagation medium in form of a sequence of pressure waves. During their travel, waves are modified (usually attenuated), and the modifications are depending on the characteristics of the propagation medium and on the presence of other objects in their propagation paths.

When a wave impacts against an obstacle, as shown in Figure 5.1, usually a part of the energy carried by the wave is absorbed by the obstacle, a part is reflected into the propagation medium and another part is transmitted through the obstacle.

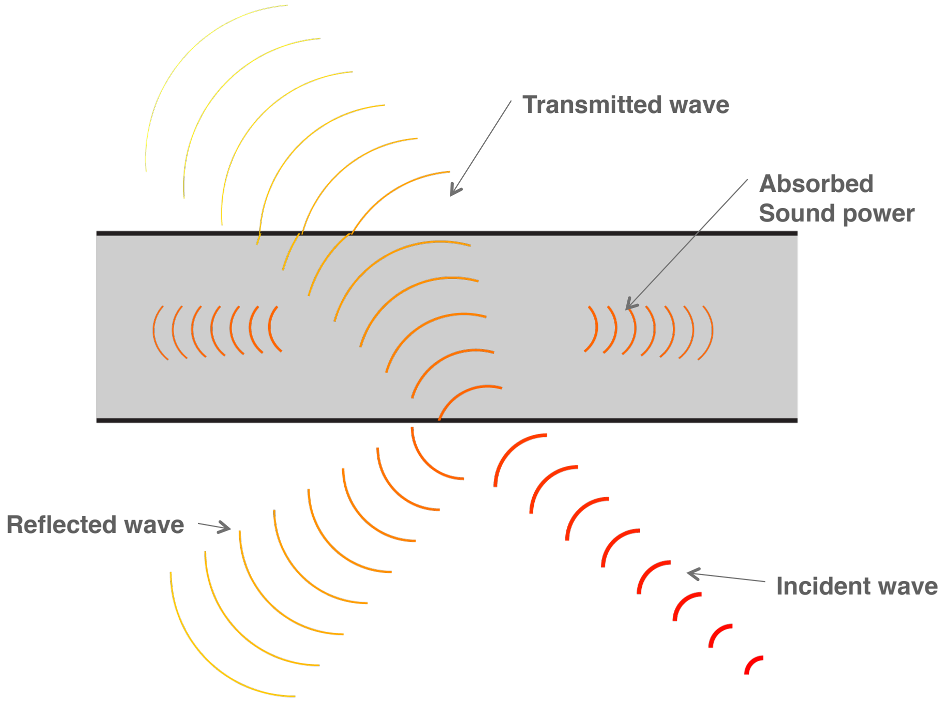


Figure 5.1: *A sound wave impacts against an obstacle*

From the study of the literature about virtual acoustic environments, the geometrical methods resulted to be the more suitable for virtual reality applications. All the geometrical methods are based on an approximation: they do not take into account the wave nature of sound, and they consider the sound waves as traveling through straight lines. The several geometrical methods have been analyzed in Section 4.2.3. The ray-tracing method - that is the method used to implement the core of the Virtual Acoustic Environment - resulted to be one of the most efficient methods, except for the computation time. This problem has been avoided by using a massively parallel computing architecture, as described in Section 5.2.

Figure 5.2 shows the working principle of the algorithm. The sound energy emitted by one or more sound sources is described with a finite number of rays. Each ray carries a part of the global energy. All the rays travel through the space at the speed of sound of the propagation medium (e.g. 343 m/sec in dry air at 20 °C). When a ray hits a surface it is reflected specularly with respect to the surface normal. The energy of each ray de-

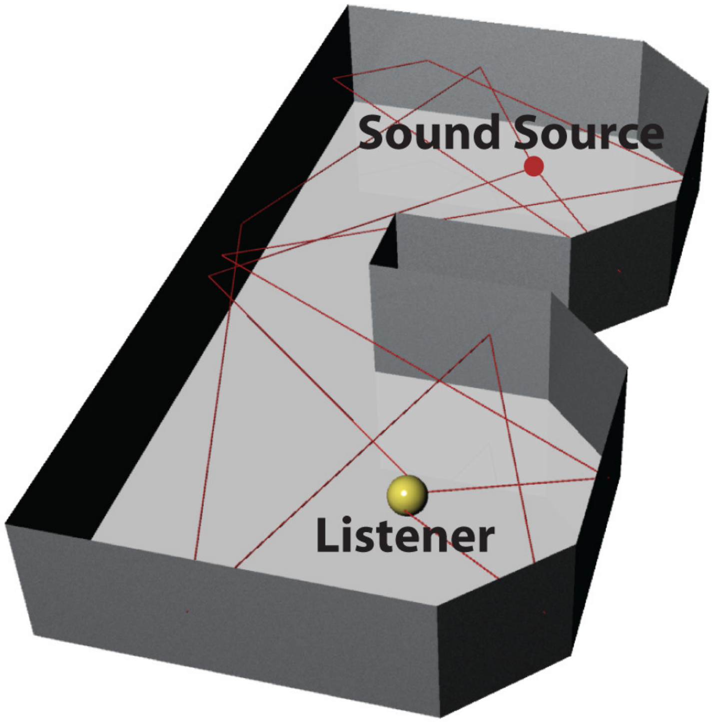


Figure 5.2: *Ray-tracing method*

creases due to sound absorption of the air and of the surfaces (for example, walls) involved in the propagation path. The output sound is obtained by taking into account all the rays that hit the listener, modeled as a volume in the environment.

In reference to Figure 5.3, since the incident wave is modeled as a ray, from the collision point between the incident ray and the surface of the obstacle two other rays will be traced: a reflected ray and a transmitted ray. The reflecting angle Θ_r is equal to the incident one Θ_i(specular respect to the normal of the surface). The transmitted angle Θ_r depends on the sound velocity in the propagation medium, according to the second Snell's law:

$$\frac{Sin(\Theta_i)}{Sin(\Theta_t)} = \frac{c_1}{c_2} \tag{5.1}$$

where c_1 and c_2 represent the sound velocity respectively for medium 1 and 2.

In a typical configuration it is necessary to define one or more sound

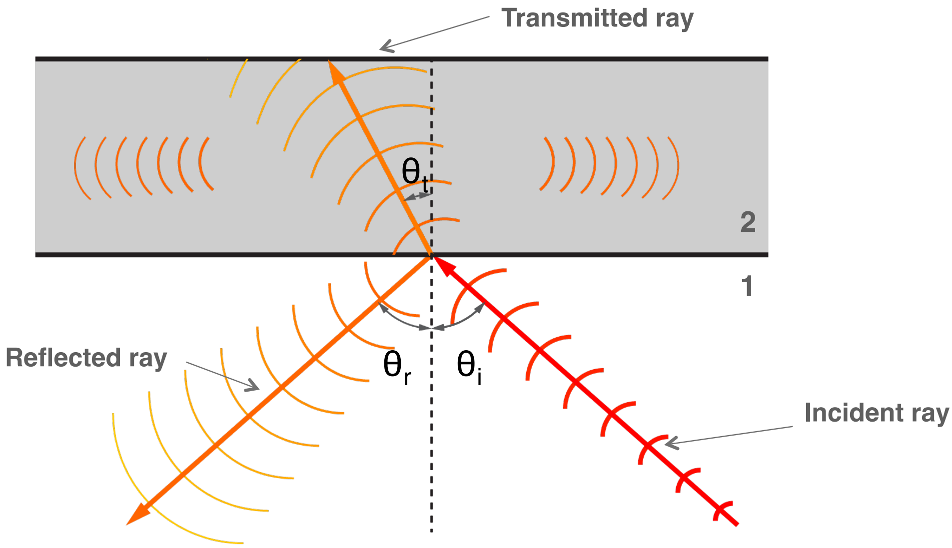


Figure 5.3: *Sound wave impact simulated with a ray-tracing algorithm*

sources, one or more listeners, and the environment, that contains the obstacles with their own materials.

The sound source is assumed to act in a point, and the tracing of the rays can be omnidirectional or directional, depending on the characteristics of the source. The listener is modeled as a volume. Commonly the sphere is the most used volume for the model of the listener, since it results to be the most performant [88]. The radius of the sphere is variable, and it is proportional to the distance between the source and the listener.

The ray-tracing simulation gives as output all the rays that intersect the listener. The payload of each ray contains the length of the path traveled by the ray to reach the listener, and the residual sound power, calculated in octave bands. It is necessary to compute the sound power in octave bands because some physical phenomena involved in the propagation of sound, have different behaviors for different frequencies. More in detail, for each ray that intersects the listener the following data are calculated:

- Distance delay
- Distance attenuation
- Air Absorption

- Material Absorption

In the following a brief description of those data and their calculation are given.

5.1.1 Distance delay

The delay of a sound wave is depending on the way that the wave travel going from the sound source to the listener. It is possible to calculate the delay of each ray taking into account the length of the ray path and the speed of sound in the propagation medium.

5.1.2 Distance attenuation

Since the propagation of sound waves is in most cases spherical, it is easy to understand how the sound power of the traveling wave is inversely proportional to the distance traveled. The distance attenuation can be modeled as frequency independent, and it follows the inverse-square law [64].

Figure 5.4 shows how the inverse-square equation is obtained from a geometrical point of view.

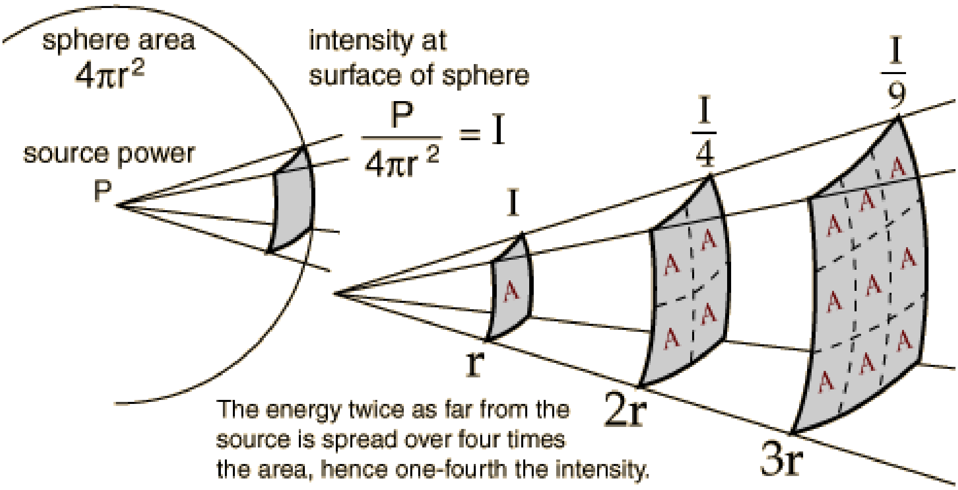


Figure 5.4: *Inverse-square law*

5.1.3 Air absorption

When traveling in air sound waves are subjected to an attenuation. The sound attenuation is calculated using the following equation:

$$W(L) = W_i e^{-\alpha L} \tag{5.2}$$

where W is the sound power at a distance L, W_i is the initial sound power, α is the air absorption coefficient. The coefficient α depends on temperature, humidity and it is also frequency dependent. The equations for the calculation of the coefficient are standardized [11].

Figure 5.5 shows a plot of the coefficient α as function of the frequency, for a temperature of 20°C and a humidity of 60 %.

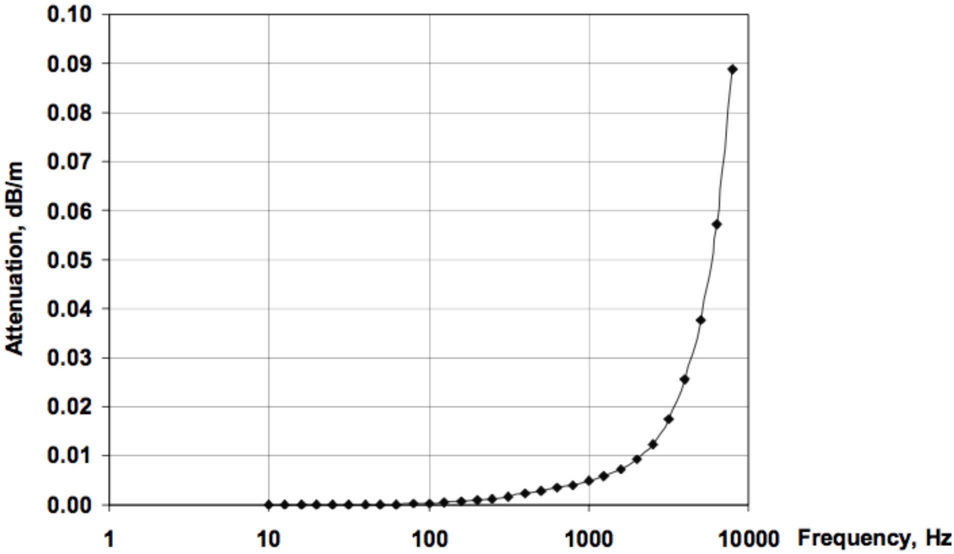


Figure 5.5: *Atmospheric Attenuation of Sound in dB/m (Temperature 20 degC, Humidity 60 %)*

5.1.4 Material absorption

The absorption of sound power caused by the impact of a sound wave against an obstacle is depending on the material of the obstacle and also on the incident angle. In Virtual Acoustics the material absorption simulation is usually simplified. The absorption coefficients (that are frequency dependent) used for the simulations are all angle independent, and scattering and diffraction phenomena are not modeled. The absorption coefficients are available in octave bands. Coefficients for some common materials are reported in Table 5.1.

Table 5.1: *Absorption coefficients for common materials*

Material	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
anechoic	1.00	1.00	1.00	1.00	1.00	1.00
acoustic plaster	0.10	0.20	0.50	0.60	0.70	0.70
acoustic tile average	0.10	0.30	0.80	0.85	0.75	0.65
acoustic tile rigid	0.20	0.40	0.70	0.80	0.60	0.40
brick	0.03	0.03	0.03	0.04	0.05	0.07
concrete (unpaint)	0.40	0.40	0.30	0.30	0.40	0.30
concrete (paint)	0.10	0.05	0.06	0.07	0.10	0.10
ordinary window glass	0.30	0.20	0.20	0.10	0.07	0.04

5.2 System architecture and implementation

This Section will describe the implementation of the Virtual Environment. The virtual environment consists of two separated systems. An acoustic system, that performs the sound simulation and a graphic user interface, used to define the parameters of the simulation.

Figure 5.6 shows how the virtual environment is structured and the software components used to define it.

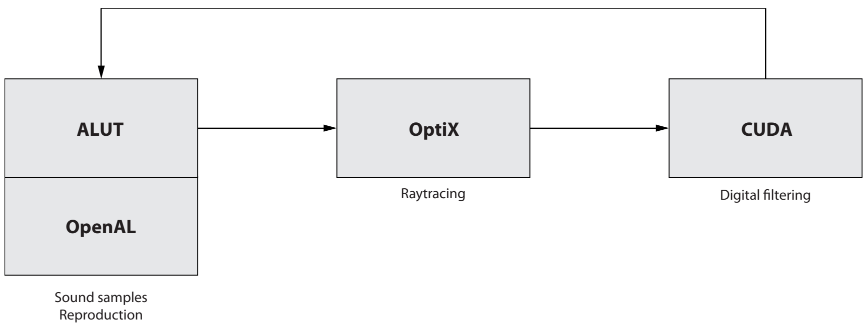


Figure 5.6: *Software components of the Virtual Environment*

A block diagram explaining how the acoustic system works is shown in figure 5.7.

The main steps of the elaboration include the specification of the initial conditions, from which is possible to configure the ray propagation module. The ray propagation module generates the output simulation data which, after a digital filtering process, can be reproduced. Any modification of the initial conditions leads to a restart of the simulation procedure.

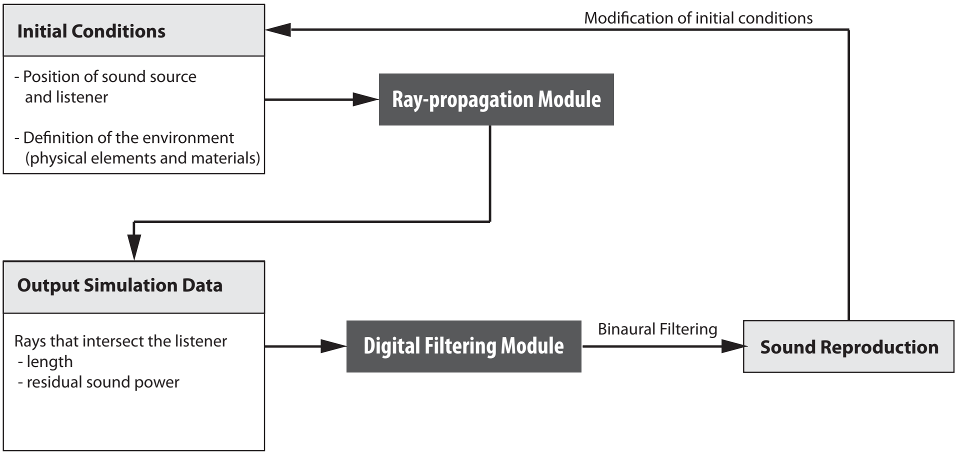


Figure 5.7: *Working principle of the Virtual Acoustic Environment*

Initial Conditions The initial conditions of the system include the configuration of the position of the sound source and the listener, as well as the definition of the characteristics of the simulation environment (i.e. walls).

Ray-propagation A very high number of rays is generated by the sound source, and depending on the characteristic of the environment it is computed the correct path of each ray.

Output simulation data All the rays are filtered, keeping just those which intersect the listener, taking into account maximum length and residual sound power.

Digital Filtering According to the characteristics of the rays, the sound source data must be digitally filtered in order to obtain the result of the simulation.

Sound reproduction After the result of the simulation has been computed, it can be reproduced by the binaural audio system.

By following the logic flow just described, specific software tools, frameworks and solutions have been selected in order to implement the functionalities required.

The implementation is performed using ALUT and OpenAL for audio management, Nvidia Optix as ray tracer and NvidiaCUDA as GPGPU framework for digital filtering of audio data.

In the diagram it is possible to distinguish two main modules: a ray-propagation module and a digital filtering module. The first step of the simulation is the chose of the initial conditions, i.e the position of sound source and listener, and the definition of the environment, both geometries and materials. Then the ray-propagation module performs a tracing of the rays inside the environment. All the data related to the rays that intersect the listener are stored and sent to the data filtering module. This module calculates all the data described in Section 5.1, for each ray. Afterwords the input sound, that is stored as a WAVE file, is conveniently filtered with the data obtained and reproduced.

Considering that the system should allow to perform interactive simulations, the implementation phase has been carried out taking into account the performances of the system. A way to reduce the computational time related to ray-tracing simulations has been studied. It has been decided to take advantage of the recent developments in terms of parallel computing on graphics processing units (GPU) [3].

The ray-propagation module has been defined using the NVIDIA OptiX Application Acceleration Engine [36], a powerful ray-tracing engine based on a C++ code, developed by NVIDIA, that increases ray-tracing speed using the NVIDIA CUDA GPU computing architecture [12]. The engine has been conveniently extended to be used for acoustic purposes. It has been necessary to define a new software library. This library contains data structures (in the form of C++ class objects) like sound source, listener, geometric primitives (parallelogram, sphere, box) and a loader for OBJ files (used to perform simulations on more complex environments). The library allows to easily customize the number of rays and the maximum number of reflections of each ray. All geometries are characterized by a material.

For the digital filtering module, as in the case of the other one, it has been decided to increase the performances using the NVIDIA CUDA GPU computing architecture [12]. The digital filtering module works in the frequency domain. The NVIDIA CUFFT [5] library has been used to perform the fast Fourier transform on the input sound (direct transform) and on the resulting sound after filtering (inverse transform).

For the reproduction of the sounds the OpenAL 3D audio API [6] has been used. Moreover the binaural reproduction is obtained using a commercial driver for OpenAL - Rapture 3D [7] - that uses a HRTF database to perform 3D audio rendering.

5.2.1 Software architecture

The software architecture is designed around the abstraction of geometry entities (class axGeometry), materials (class axMaterial), source (class axSource), listener (class axListener) and scene definition (class axScene). The whole simulation process is controlled by class axSimulation.

Figure 5.8 depicts the UML diagram representing class axGeometry and its relationship with the derived classes axBox, axParallelogram, axSphere, axMesh.

Class axBox represents a thick wall, of which it is possible to set position, orientation and dimensions. Class axParallelogram represents a thin wall, useful in general as border walls or when the computation of wall internal propagation it is not needed, as it is only used as ray reflector. Another geometry primitive defined is the axSphere, whose main use is to represent the listener. This aspect is emphasized by the child-parent relationship between classes axSphere and axListener. A more generic geometry element is represented by the class axMesh, able to load a generic geometry in .OBJ format from an external file.

Using those class entities it is possible to define a series of simple geometrical elements in a single virtual environment in order to simulate the structure of small rooms, apartments or buildings. The availability to load complex 3D objects from a file through the class axMesh is a plus, through which it is possible to add more details to the scene.

In the collaboration diagram depicted in Fig. 5.9 it is highlighted the relationship between the class axGeometry and the entities representing a material (class axMaterial) and the working context (class axContent). The details of the collaboration between those classes will be explained later, after the description of the all the entities, but it is worth to highlight that both axMaterial and axGeometry collaborates with class axContext because in the geometrical entity it is checked the intersection with a ray, and within the axMaterial it is described the behavior of a specific material after a hit.

The entity representing a sound source is defined in class axSource, through which it is possible to define a sound source in terms of position and waveform of the sound produced.

The scene manager is represented by an entity of the class axScene, which is able to hold a collection of geometry items and create the relationship with the current context. The collaboration diagram of class axScene is depicted in Fig. 5.11.

Class axListener represents the listener, in terms of position, ori-

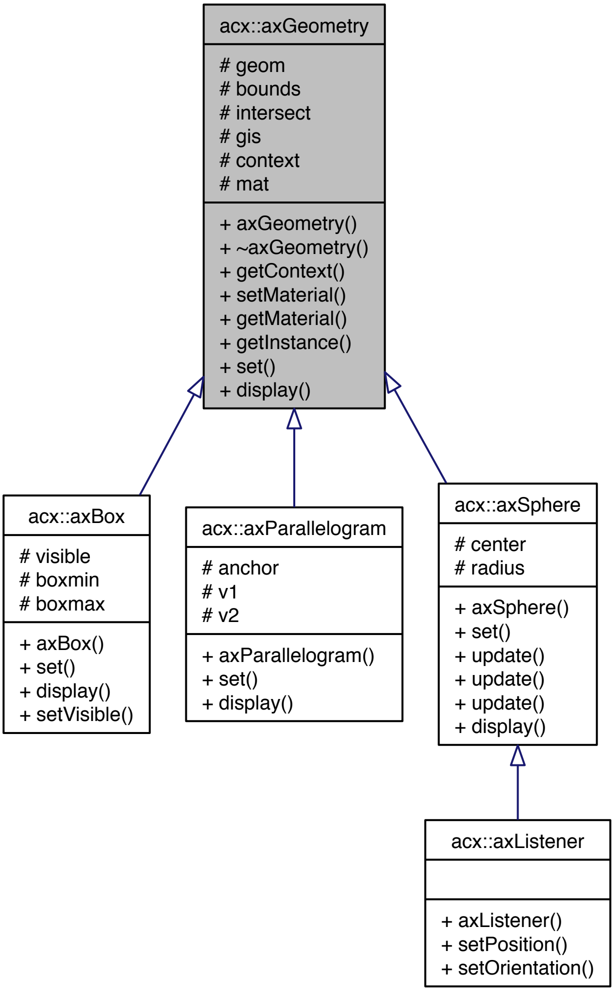


Figure 5.8: *Class diagram related to the definition of the geometries*

entation and occupied volume. According to the study described in [43], the listener is modeled as a sphere. The size of the sphere representing the listener is adapted in order to match the minimum distance between two adjacent rays. In fact, since the generated rays are created with an initial relative angle, the size of the listener must be higher in order to guarantee

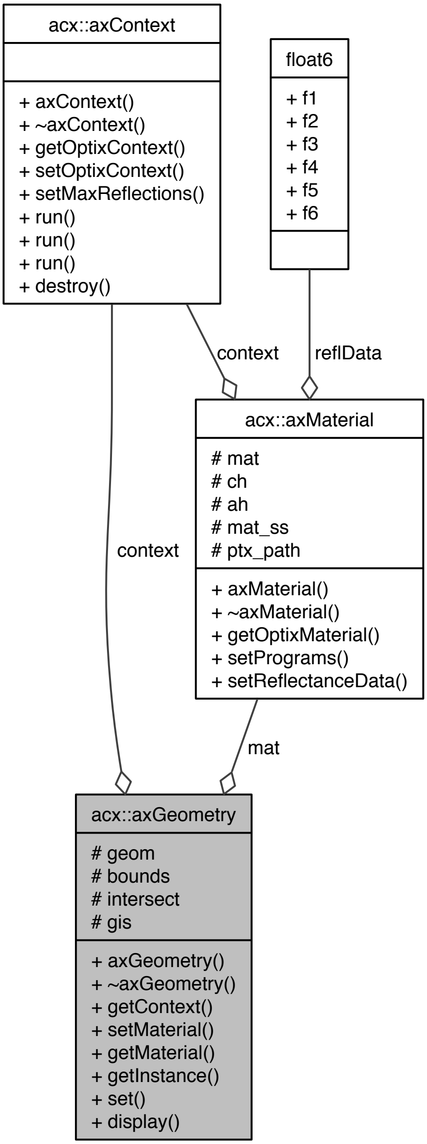


Figure 5.9: *Collaboration diagram related to class* `axGeometry`

the intersection with approaching rays.

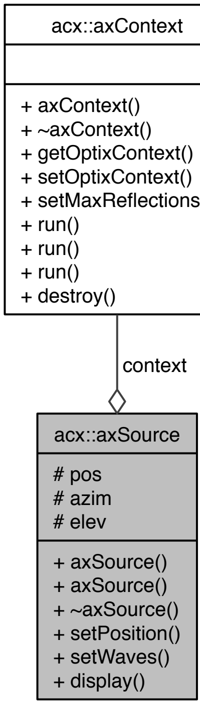


Figure 5.10: *Collaboration diagram related to class* `axSource`

Class `axSimulation` is devoted to the control of the whole simulation process. The collaboration diagram in Fig. 5.12 highlights the relationship between class `axSimulation` and all the principal classes available within the framework. In fact, beyond the abstract entities described in previous paragraphs, class `axSimulation` collaborates with:

- class `SoundR`, which manages the data coming from the sound source, holds and plays the result of the simulation. It is the direct link between sound source data and the audio engine OpenAL.
- class `GLWidget`, through which the simulation framework is integrated with the Graphical User Interface, developed upon the QT library. Class `GLWidget` is the target for the control items available on the GUI window, such as those for the control of source and lis-

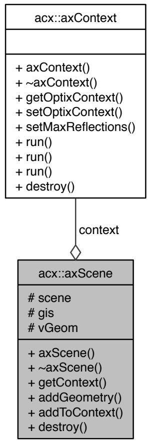


Figure 5.11: *Collaboration diagram related to class* `axScene`

tener position and other important settings to setup before starting a simulation.

- struct `WaveData` represents a single ray fragment, defined by its origin, the direction vector, length and a flag which indicates whether or not the ray fragment intersects the listener. Class `axSimulation` contains a collection of `WaveData` elements, one for each ray generated and for each reflected ray. struct `WaveData` is accessed by the GUI for the visualization.

- struct `FilterData` holds, for each ray generated from the source or reflected after a collision, the coefficient of absorption of the six main frequency ranges, computed incrementally depending on the material encountered by the ray.

As mentioned before, class `axSimulation` holds and manages the whole simulation process, by creating the proper instances of the classes devoted to the definition and control of the sound source, the raytracing module, the filters and the data structure which will hold the results of the simulation.

As summarized by the call graph depicted in Fig. 5.13 related to the function `axSimulation::launchSimulation`, the main phases of the simulation activity concern:

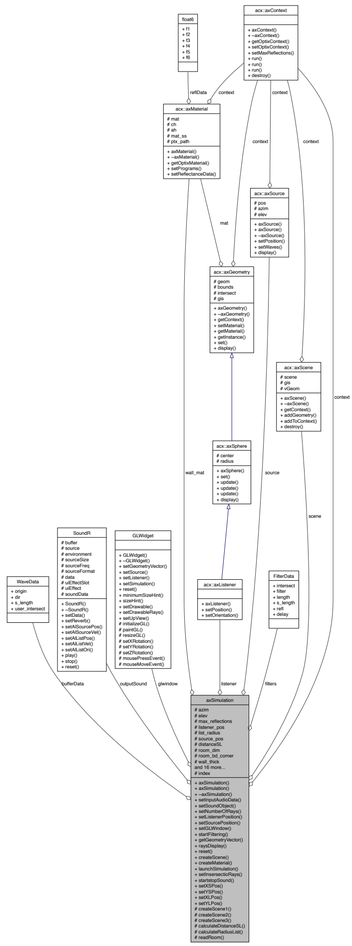


Figure 5.12: *Collaboration diagram related to class* `axSimulation`

- the creation of the geometry of the scene (`axScene::addGeometry`)
- the creation and the configuration of the context relative to the scene (`axScene::addToContext`), which is passed to the specific context created within the OptiX environment in order to perform the ray-tracing (`axContext::getOptixContext`)
- the simulation itself (`axContext::run`)
- the check for intersections between the listener and the generated rays

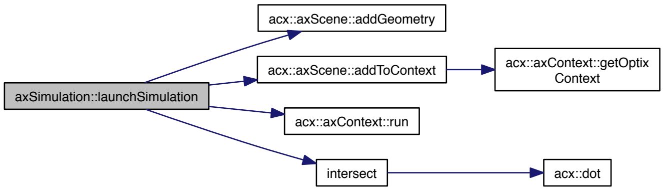


Figure 5.13: *Call graph for function* `axSimulation::launchSimulation`

5.2.2 Graphical User Interface

Figure 5.14 shows the graphic user interface of the Virtual Acoustic Environment. The central windows shows the environment and the position of Listener and Sound Source. The right dock-widget contains all the commands needed to customize the simulation. It is possible to select between different rooms, modify air parameters and choose a material for the selected geometry. Moreover it is possible to activate the visualization of all the traced trays or only the ones that intersect the listener (see Figure 5.15).

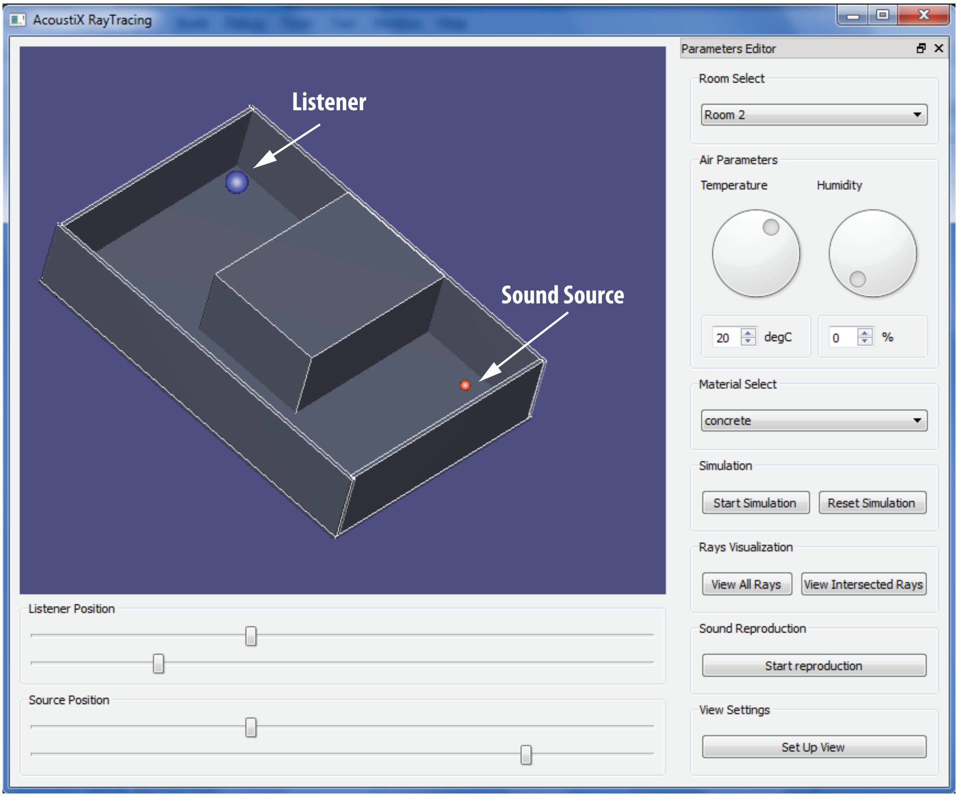
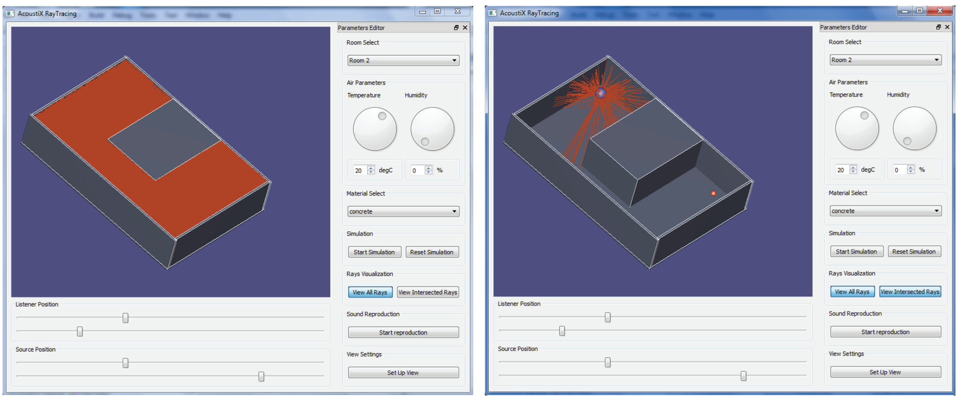


Figure 5.14: *The Virtual Acoustic Environment GUI*



a) b)

Figure 5.15: *Visualization of rays traced in a simulation. a) shows all the rays traced, while b) shows only the rays that intersect the listener*

CHAPTER 6

Validation of the Virtual Acoustic Environment

Once the Virtual Acoustic Environment has been defined and implemented, as described in Chapter 5, it has been necessary to validate the algorithm and investigate the quality of the simulations.

The choice of tests and validation methods has been made taking into account the final use of the Virtual Acoustic Environment, and its role in the overall Virtual Acoustic Method, which has been illustrated in Chapter 2.

The Virtual Acoustic Environment can be described as a tool that is able to simulate how a sound is modified when travelling from a source to a receiver, in a closed environment.

Referring to its context of usage, the Virtual Acoustic Environment can be described as a tool able to reproduce in a realistic way the acoustic feedback perceived by a user while he is using an industrial product within its working environment.

The evaluation of the Virtual Acoustic Environment has been conducted taking into account both the quality of the numerical simulation and the similarity, in terms of acoustic feedback perceived by users, between real sounds and sounds obtained with the use of the environment.

More in detail, two different typologies of tests have been performed:

- a numerical validation. Real sounds. i.e. sounds recorded directly in a real configuration, have been numerically compared with simulated sounds, i.e. sounds obtained with the Virtual Acoustic Environment. The test has been conducted by analyzing the sounds in the frequency domain, and by comparing the levels (in dB) of the different frequencies between real and simulated sounds.

- a validation of the perceptual equivalence between real and simulated sounds. The test has been conducted by asking subjects to evaluate a characteristic of the sounds, by using a unidimensional category scaling (described in Section 2.3.2).

6.1 Sound Dataset for tests setup

Since both numerical and perceptual tests are based on a comparison between sounds recorded in real conditions e sound simulated with the Virtual Acoustic Environment, it has been considered convenient to define a unique dataset of sounds that has been used for both typologies of tests.

As explained in Section 3.3.2 the Virtual Acoustic Environment has been designed to simulate the sonic response of a product within its working environment. Consequently, the sound generated by an industrial product has been chosen for the definition of the dataset of sounds. The dataset has been created by using the sound generated by a hairdryer.

The sounds have been recorded, using the same model of hairdryer, in three different rooms, each room differing in material and size. Moreover, for each room two different configurations have been obtained by changing the relative positions between the sound source and the listener. The 6 recorded sound obtained have been reproduced by simulation, obtaining a final dataset including 12 sounds, and three experimental conditions (3 room configurations X 2 relative positions X 2 real/non real)

In the following list the dimensions of the rooms and walls material are given:

- Room 1 is 5.45 m large, 4,5 m long, and 2.85 m high. Walls material is mainly plasterboard, with two doors made in faced chipboard.

- Room 2 is 4.5 m large, 2,2 m long, and 2.55 m high. Walls material is mainly made of ceramic tiles, with three doors made in faced chipboard.

- Room 3 is 4.5 m large, 4,5 m long and 2.65 m high. Walls are covered with carpet, and the only one door is made in faced chipboard.

Figures 6.1, 6.2 and 6.3 show the position of the sound source and the listener in the three rooms.

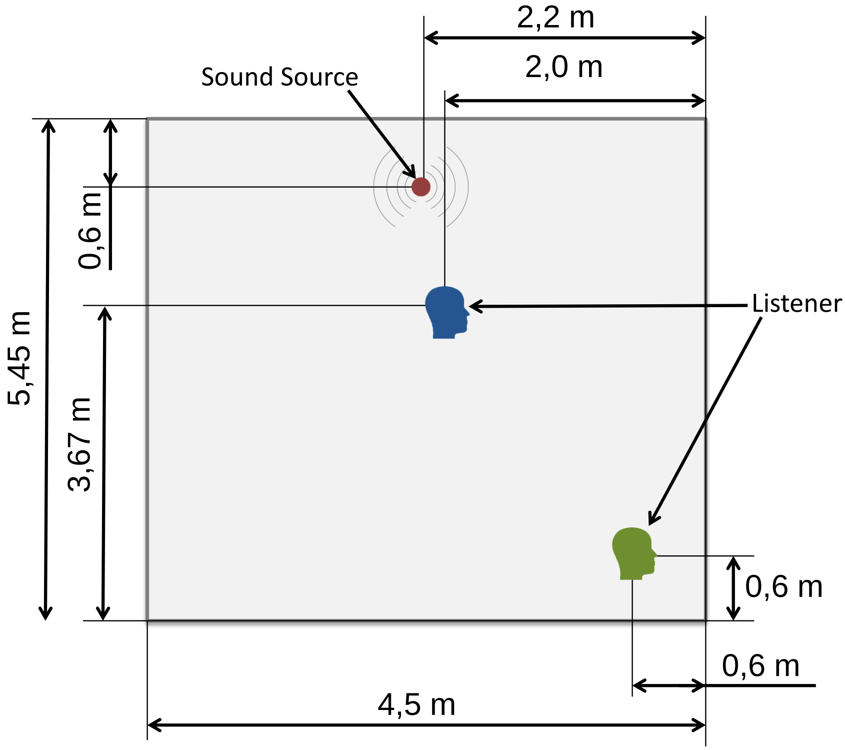


Figure 6.1: *Position of listener and sound source in room 1. The blue head represents the configuration 1, the green head represents the configuration 2*

Table 6.1 shows a summary of the six configurations.

Table 6.1: *Configurations used for the definition of the dataset of sounds*

Configuration	Room	Distance Source/Listener (cm)
1	1	120
2	1	454
3	2	120
4	2	380
5	3	149
6	3	410

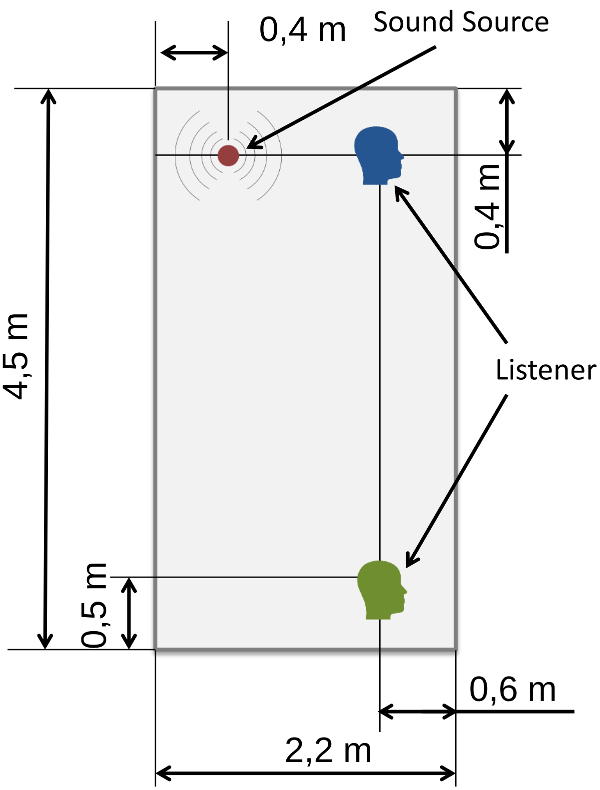


Figure 6.2: *Position of listener and sound source in room 2. The blue head represents the configuration 3, the green head represents the configuration 4*

Real sounds have been obtained by directly recording a working hairdryer in three real rooms with the configurations listed above.

The professional hardware listed below has been used for the recordings:

- Rode NTG-3 Precision RF-Biased Shotgun Microphone (Figure 6.4(a))
- ZOOM H4 Handy Digital Recorder (Figure 6.4(b))

To obtain the simulated sounds, the Virtual Acoustic Environment has been used to define three virtual configurations corresponding to the real ones. Three virtual rooms, with the same dimensions and wall material characteristic of the three real rooms described above, have been created.

The sound source has been obtained by recording the sound coming from the hairdryer in a soundproof room, in order to reduce the influence of the environment, e.g. sound reflections and reverberation. In this way it has been possible to record only the direct sound.

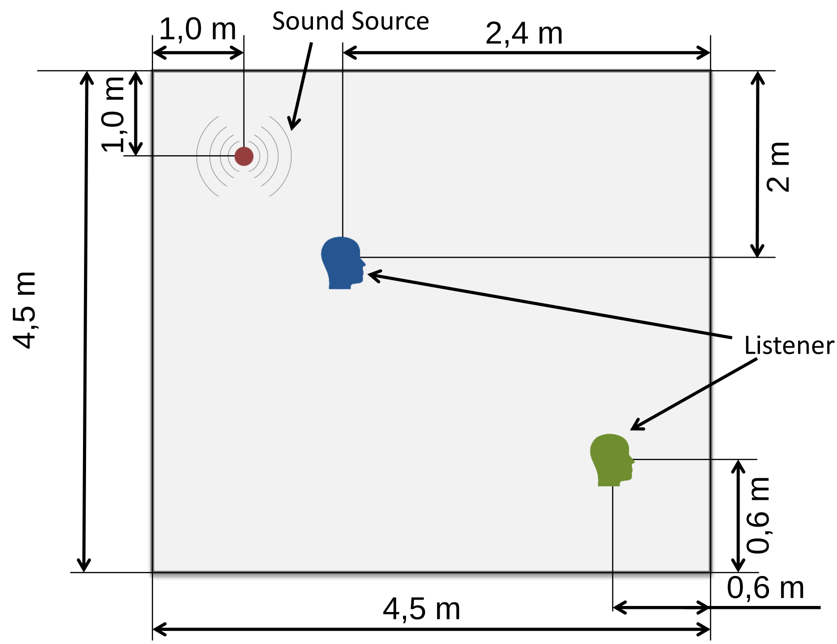


Figure 6.3: *Position of listener and sound source in room 3. The blue head represents the configuration 5, the green head represents the configuration 6*

For what concerns the walls material, due to the impossibility of experimentally obtaining the absorption curves of the real walls, tabulated absorption coefficients for similar materials have been used.

Before to present the tests and the results, some considerations about the creation of the dataset are given. In particular, the choice of the industrial product used for the tests, i.e. the hairdryer, and the choices related to the definition of the 6 configurations are analyzed.

The number of configurations has been chosen by considering the test of the perceptual equivalence, where users are asked to ear the different sounds and evaluate them. Since for a proper statistical analysis of the results, users had to evaluate all the different configurations (both real and virtual ones) at least 4 times, it has not been possible to use more than 6 configurations, in order to avoid an excessive heaviness of the test.

It has been chosen to use only one kind of sound source, i.e. one industrial product, and to vary the environment, in terms of material of the walls, dimension of the rooms and relative position between sound source and listener. This choice comes from the purpose of the tests, which aim at investigating the quality of the sound propagation algorithm. This can be

(a) Rode NTG-3 Precision RF-Biased Shotgun Microphone

(b) ZOOM H4 Handy Digital Recorder

Figure 6.4: *Hardware used to record real sounds in the 6 different configurations*

better analyzed by varying the characteristics of the propagation environment of the sound.

For what concerns the definition of the sound source used in the tests, the hairdryer has been chosen mainly for two reasons:

- Ease of setup. The dimensions and the weight of a hairdryer facilitate the movement of the product and the positioning for the recording of the real sounds.

- Wide frequency range of the generated sound, if compared with the sound coming from other household appliances. The sounds coming from household appliances, e.g. the sound generated by the compressor of a fridge or by the motor of a washing machine, usually involves only a specific range of frequencies. The sound coming from a hairdryer, due to the combination of different phenomena that contribute to create the global sound, e.g. the sounds generated by the motor and by the fan, the sound produced by the movement of the air going out from the nozzle, has a wide frequency spectrum. Figure 6.5 shows the frequency spectrum, in one-third octave bands scale. It is possible to notice that the sound cover almost all the frequency bands.

The average sound power level is 61 dB, the maximum value of 74 dB corresponds to a frequency range between 1122 and 1413 Hz and the minimum value of 51 dB corresponds to a frequency range between 112 and 141 Hz.

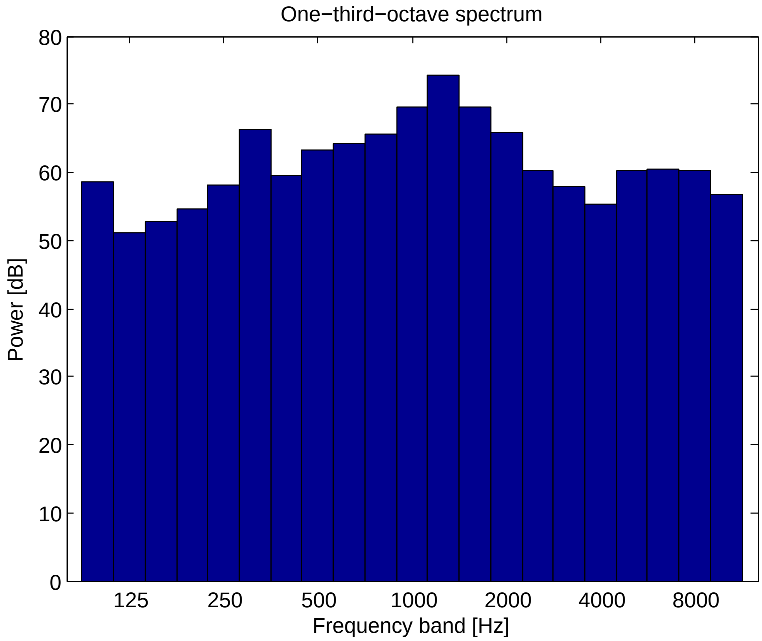


Figure 6.5: *Frequency spectrum, in one-third octave bands scale, of the sound generated by a hairdryer*

6.2 Numerical Validation

As introduced in Section 7, a numerical analysis has been conducted for the evaluation of the accuracy of sound simulations performed with the Virtual Acoustic Environment.

The analysis has been performed by comparing the simulated sounds with the corresponding real ones. The comparison has been conducted in the frequency domain. Specifically, the level of sound power for the different frequency bands is compared. In order to properly compare the frequency spectrum of two sounds, it has been necessary to apply a frequency-band filter. More in detail, the sounds have been compared using the one-third octave band scale. Despite it is not the most accurate band scale - also 1/12th octave band filters can be used - the one-third octave band results to be the most suitable scale to represent the human perception of the sound.

Kurt Veggeberg [82] describes the effectiveness of the one-third octave band filter in the following way:

> *"Although some acoustics engineers argue that the ear is better, most believe the one-third octave spectrum paints a picture closest to human-ear perception"*

Appendix A reports the frequency limit for octave and 1/3 octave bands.

Once applied the one-third octave band filter, the pairs of sounds - real and virtual - for each configuration have been compared.

The following figures show the comparison between the frequency spectrum of real and virtual sounds in the 6 configurations.

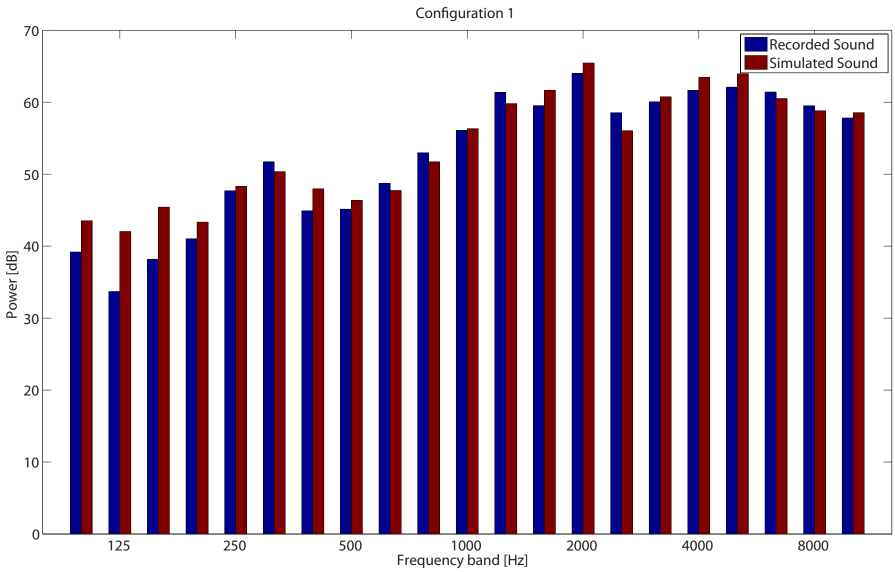


Figure 6.6: *Frequency spectrum comparison between real and virtual sounds - Configuration 1*

The first two configurations refer to the room 1 (Figure 6.1), which is $\sim 70m^3$ big. The walls are made of plasterboard and they are 10 cm thick.

In configuration 1 (Figure 6.6), where listener and sound source are 1.2 m away, the maximum level of sound power is 64 dB for the real sound, and it occurs for the band of frequencies between 1778 and 2239 Hz. The simulated sound shows a maximum level of 65.5 dB in the same range of frequencies.

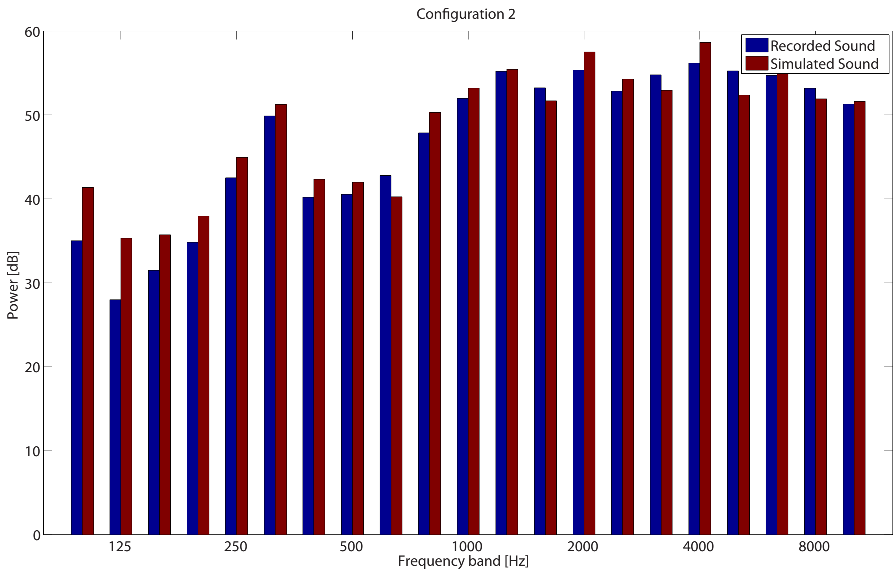


Figure 6.7: *Frequency spectrum comparison between real and virtual sounds - Configuration 2*

In configuration 2 (Figure 6.7), where the distance between listener and sound source is 4.5 m, the sound intensity turns out to be reduced. In the real sound, a maximum value of 56dB occurs in the 1/3 octave band whose central frequency is 4000 Hz. For the same range of frequencies the simulated sounds has a sound intensity of 58 dB.

Configurations 3 and 4 refer to room 2 (Figure 6.2). It is $\sim 25m^3$ big and the lateral walls are made of ceramic tiles.

The maximum value of sound power obtained from the real sound of configuration 3 (Figure 6.8), where listener and sound source are 1.2 m away, is 72 dB in the 1/3 octave band of 2000 Hz. The virtual sound has a value of 74 dB for the same frequency band.

In configuration 4 (Figure 6.9) the distance between the sound source and the listener is 3.8 m. For both real and virtual sounds the maximum value of sound power level occurs in the frequency band of 2000 Hz and it is 71 dB for the real sound and 73 dB for the virtual one.

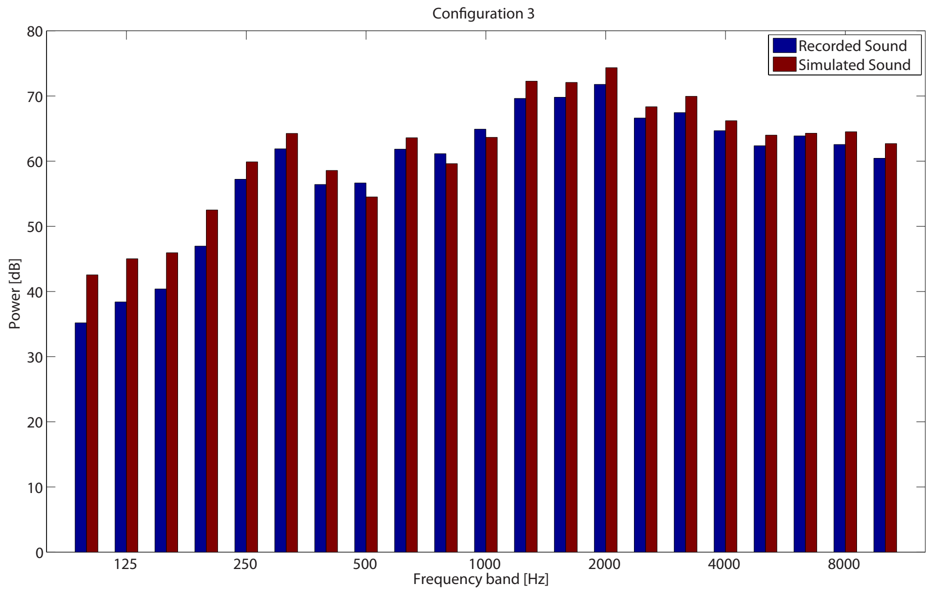


Figure 6.8: *Frequency spectrum comparison between real and virtual sounds - Configuration 3*

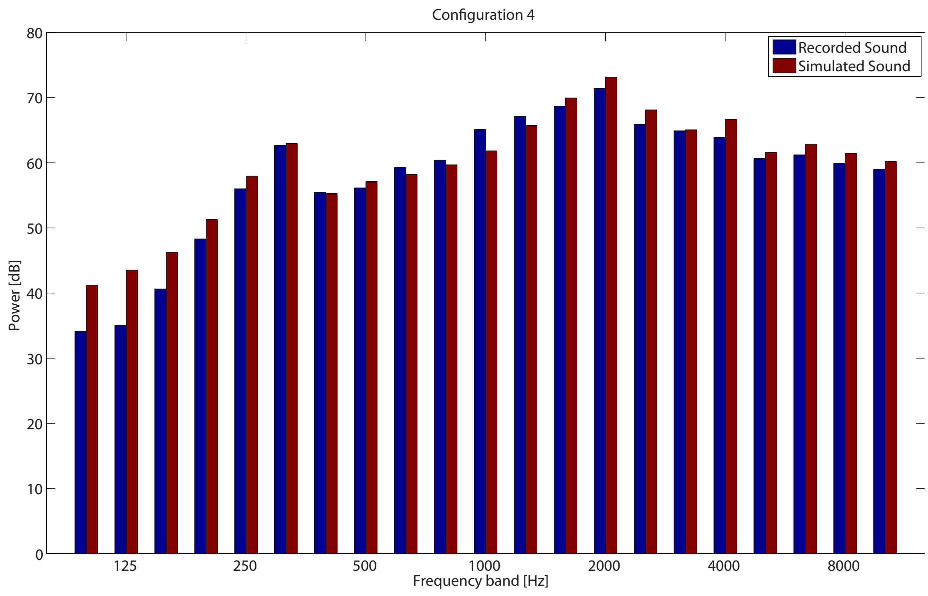


Figure 6.9: *Frequency spectrum comparison between real and virtual sounds - Configuration 4*

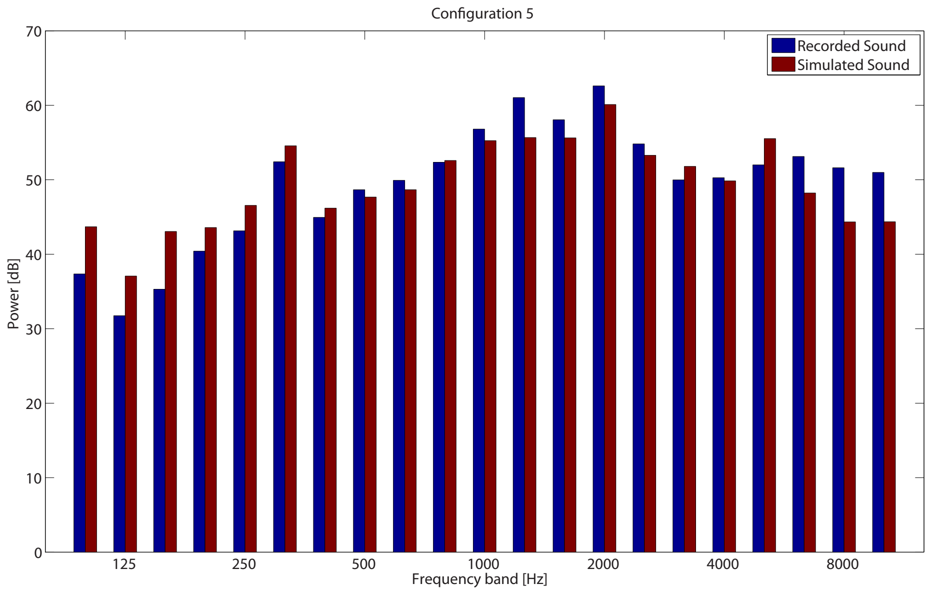


Figure 6.10: *Frequency spectrum comparison between real and virtual sounds - Configuration 5*

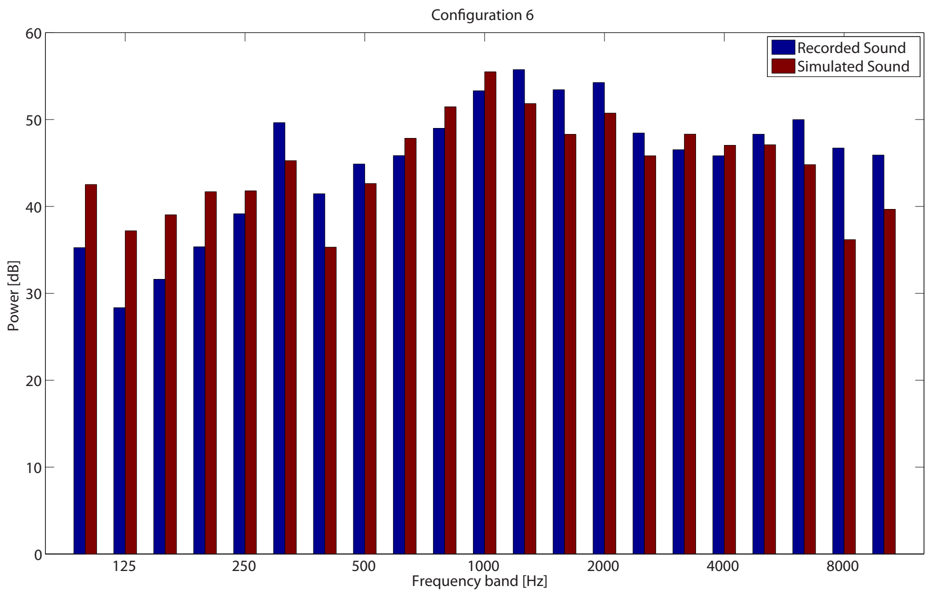


Figure 6.11: *Frequency spectrum comparison between real and virtual sounds - Configuration 6*

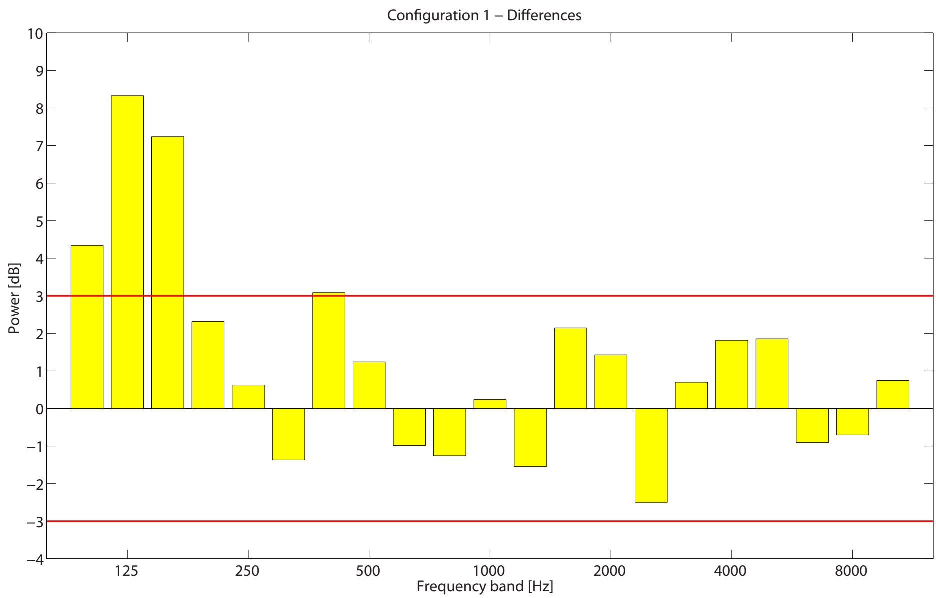


Figure 6.12: *Sound power differences between real and virtual sounds - Configuration 1*

The two last configurations refer to room 3 (Figure 6.2), which is $\sim 54m^3$ big. In this room walls are covered with carpet.

The distance between the sound source and the listener is 1.5 m in configuration 5 e 4.1 m in configuration 6.

In configuration 5 (Figure 6.10) the maximum values are 62 dB for the real sound and 60 dB for the virtual one, and both occur in the frequency band of 2000 Hz.

In configuration 6 (Figure 6.11) the maximum value is 55 dB for the real sound in the frequency band of 1250 Hz, and 55 dB for the virtual sound in the frequency band of 1000 Hz.

In order to evaluate the effectiveness of the sound propagation algorithm of the Virtual Acoustic Environment, the differences, in terms of sound power level, between real and virtual sounds, for all the frequency bands, have been analyzed.

The sound power of real sounds has been used as nominal value. Then, the range of variation of the sound power of virtual sounds, compared with the nominal value, has been investigated.

Since doubling the sound power increases the sound power level by 3 dB, the range between -3 dB and 3 dB has been used as the *range of tolerance* of the analysis. If the sound power level of the virtual sound, for a

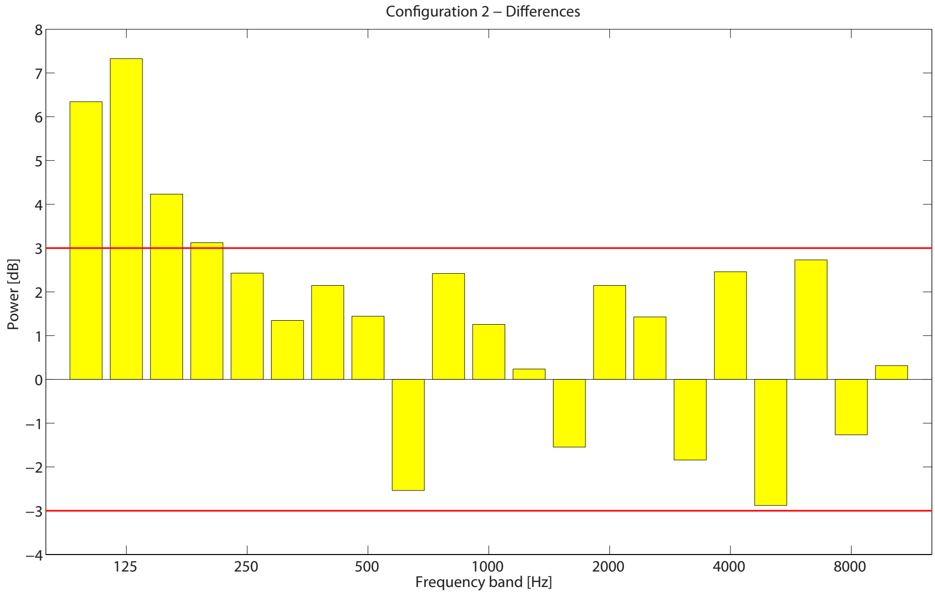


Figure 6.13: *Sound power differences between real and virtual sounds - Configuration 2*

specific frequency band, varies by more than 3dB from its nominal value, than the simulation cannot be considered as reliable.

Figures 6.12 and 6.13 show the variation of the sound power level respectively for configuration 1 and 2. The boundary limits of -3 dB and 3 dB are displayed with red lines. It is possible to notice that both simulations produced reliable results for middle and high frequency bands. On the other hand low and mid-low frequencies - i.e. frequency bands from 100 Hz to 160 Hz - present significant differences (7-8 dB).

Results of configurations 3 and 4, illustrated in Figures 6.14 and 6.15, show a behaviour quite similar to the previously-described configurations. Also in this case the simulations result to be accurate for middle and high frequency bands, but low frequencies differ between real and virtual sounds.

Different results have been obtained for the last two configurations, as shown in Figures 6.16 and 6.17. The simulations performed in the third room appear to be quite different when compared with real sounds recorded in the same room. In this case, the differences are noticeable also for middle and high frequencies. The difference between real and virtual sound is higher in configuration 6, where the distance between sound source and listener is bigger.

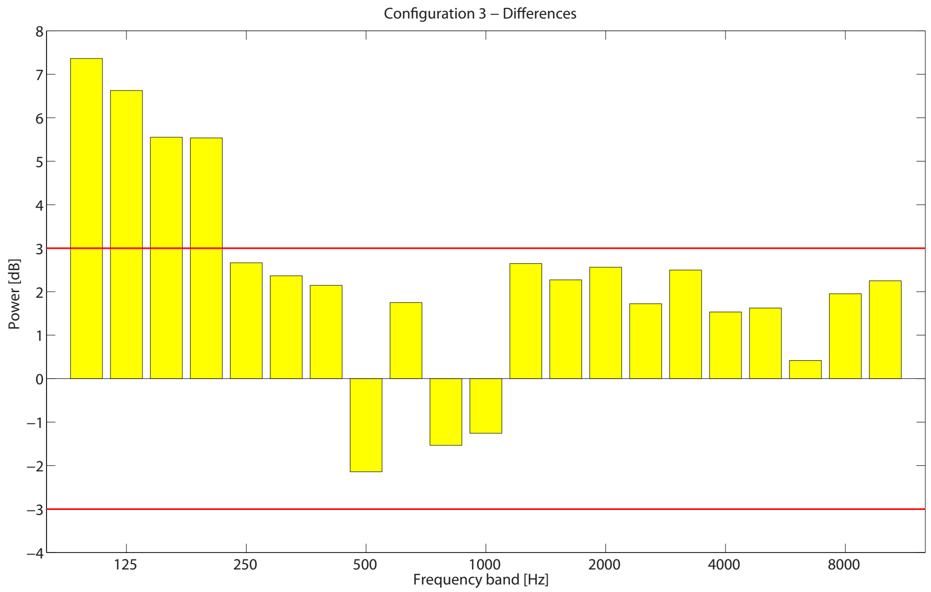


Figure 6.14: *Sound power differences between real and virtual sounds - Configuration 3*

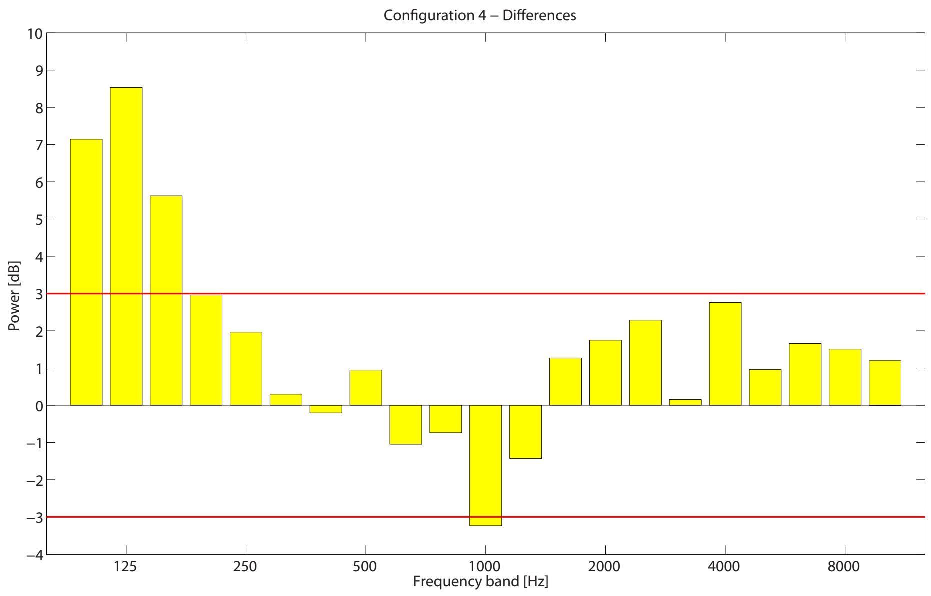


Figure 6.15: *Sound power differences between real and virtual sounds - Configuration 4*

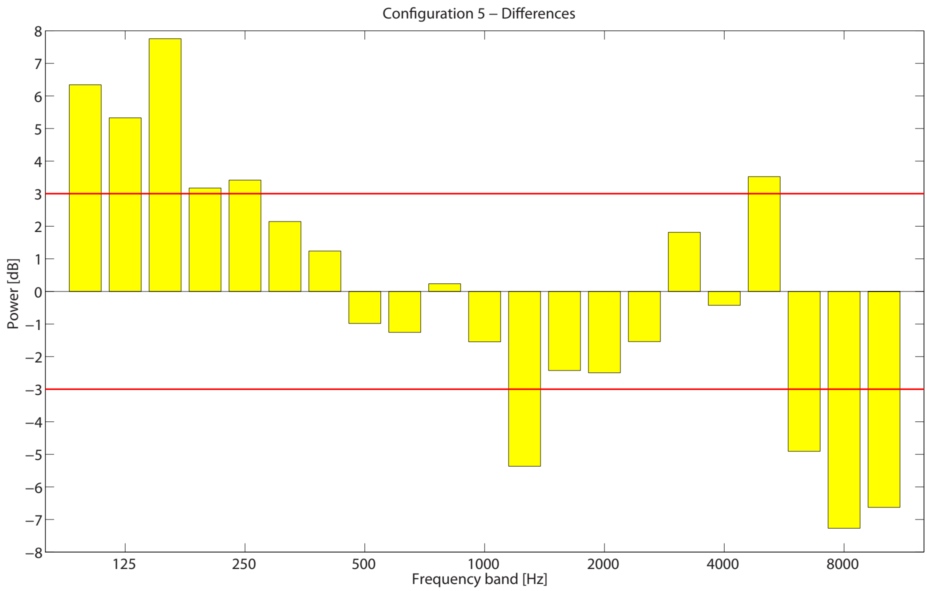


Figure 6.16: *Sound power differences between real and virtual sounds - Configuration 5*

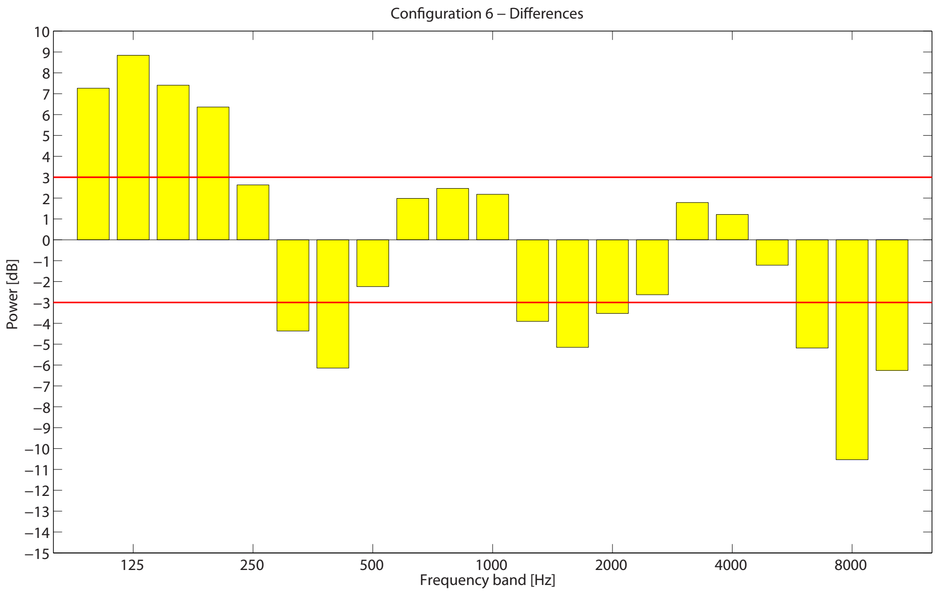


Figure 6.17: *Sound power differences between real and virtual sounds - Configuration 6*

6.2.1 Considerations about the results

The numerical analysis showed that the sound propagation algorithm of the Virtual Acoustic Environment has been able to reproduce, with a good level of accuracy, the propagation of sound waves in two of the three environments chosen for the test.

The test setup has been studied to specifically evaluate two characteristics of the sound propagation algorithm:

- ability to correctly simulate the variation of the sound power level, as function of the variation of the distance between sound source and listener;
- ability to correctly simulate the propagation of the sound in closed environments with different characteristics - dimensions and walls material.

On the basis of the results analysis, it is possible to assert that the sound propagation algorithm is able to simulate the variation of the sound power level with a high level of accuracy. This characteristic can be evaluated by comparing the values of the sound power level in the configurations that refer to the same room - i.e. comparison between configuration 1 and 2, between 3 and 4 and between 5 and 6. In fact, for those pairs of configurations the environment is the same, and only the relative position between sound source and listener changes.

In all the three rooms the attenuation between the configuration where the sound source and the listener are closer and the one where they are more distant is comparable in real and simulated sounds.

For what concerns the simulation of sound propagation in the environment, and consequently of the attenuation caused by the reflections and the absorption of the walls, it is possible to notice that the sound propagation algorithm is very accurate for middle and high frequencies.

The loss of accuracy in low frequencies is a known problem for geometrical methods for sound propagation, and in particular for the ray-tracing method.

On the basis of the results obtained it is reasonable to consider that an additional method should be implemented for the simulation of the propagation of low frequencies.

A final consideration must be made about the results of configurations 5 and 6. In this case, the results are quite inaccurate also for middle and high frequencies. In this case the wrong results can be justified with the lack of correct information about the walls material. In fact, the walls of room 3 are covered by a small layer of carpet followed by a wall made in plasterboard. It is probable that the combination of those two layers contributes to create a more complex absorption curve that cannot be found in tabulated data.

6.3 Validation of the perceptual equivalence

The perceptual equivalence test has been performed to investigate if the Virtual Acoustic Environment is able to reproduce the acoustic feedback perceived by people during the use of an industrial product. Therefore, an assessment test has been conducted, and a specific characteristic - the level of annoyance - has been evaluated for the different sounds. Afterwards, a statistical analysis on the obtained results has been performed.

The test has been performed with the same dataset of sounds previously described in the numerical test.

6.3.1 Test Conditions

20 subjects aged between 21 and 42 years (27.65 ± 5.07) participated at the listening test. The test consisted in listening a set of sounds and evaluating, for each sound, the perceived level of annoyance.

A pair of headphones - AKG K240 Studio - were used for the test. It has been decided to use this kind of headphones because of their flat frequency response. In this way any kind of equalization of the sounds has been avoided.

All the stimuli were repeated 4 times and organized in a random order. Consequently, subjects were asked to evaluate a total of 48 sounds (12 sounds x 4 repetitions).

Subjects had to answer to the following question: *"How annoying do you judge this sound if you imagine to perceive it while staying in a room?"*. The evaluation was conducted by using a unidimensional category scaling with a seven-point scale (see Figure 6.18), where 1 corresponds to 'not annoying at all' and 7 corresponds to 'very annoying'.

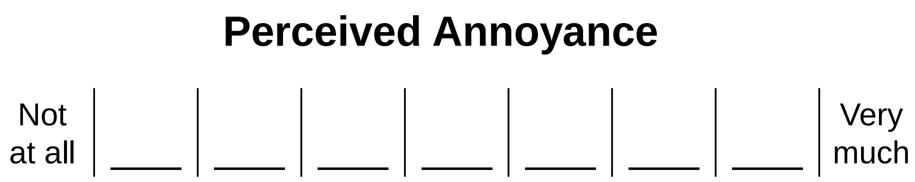


Figure 6.18: *7-point scale with verbal endpoints*

6.3.2 Statistical Analysis

The statistical analysis has been performed on a total of 960 observations - 20 subjects x 12 sounds x 4 repetitions.

The data have been fitted with a linear regression model [41], since it results to be a suitable model for the analysis of data obtained from listening tests [23].

The model has been defined by using the evaluation of the annoyance as the dependent variable, which depends on the following predictors:

- room
- configuration in room
- variable real/virtual

The purpose of the analysis is to evaluate which of those parameters influence the dependent variable. Therefore the analysis shows whether the level of annoyance, in the different observations, depends on the room, the distance between the sound source and the listener (that is represented by the parameter *configuration in room*). Moreover, it is analyzed if the parameter real/virtual - that indicates if the sound is recorded or simulated, for a specific configuration - is significant or not. This last variable is the most important for the purpose of the analysis. In fact, if the results show that the parameter real/virtual is not significant, it means that this parameter does not influence the level of annoyance and as a consequence that, statistically, the annoyance perceived by subjects when listening real and virtual sounds of a specific configuration, is the same.

Table 6.2 illustrate a summary of the correlations between the variables room, configuration in room and real/virtual.

The variables *configuration in room* and *real/virtual* are dichotomous variable. The variable *configuration in room* is 0 when the sound source and the listener are close and 1 when they are distant, and the variable *real/virtual* is 0 for real sounds and 1 for virtual sounds. The variable *room* can assume three values - 1, 2 and 3 - since three rooms have been used for the setup of the tests.

Coherence analysis within subject

Before to apply the linear regression model to the data, it has been necessary to evaluate the coherence within subject, in order to assess the reliability of the data obtained from each subject. To explain the concept of *coherence* of subjects, an example is given.

Table 6.2: *Correlation between the explanatory variables of the linear regression*

Sound	Room	Configuration	Real/Virtual
1	1	0	0
2	1	1	0
3	2	0	0
4	2	1	0
5	3	0	0
6	3	1	0
7	1	0	1
8	1	1	1
9	2	0	1
10	2	1	1
11	3	0	1
12	3	1	1

Each subject evaluated four times all the 12 sounds. A coherent subject should evaluate the same sound with the same, or at least similar, level of annoyance (e.g. 1, 2, 2, 3), while an incoherent subject should evaluate the same sound with values very different from each other (e.g. 1,6,7,2).

The subjectâĂŹs judgments were considered non-coherent if the standard deviation computed among the four given judgment exceeded the value of 1.7. This limit represents the standard deviation of a subject that evaluated the same sound with values that differ more than the mean of the scale. For a 7-point scale, whose main value is 4, a standard deviation equal or bigger than 1.7 means that the subject evaluated the same sound, for example, with 1 and 5.

240 standard deviations (20 subjects x 12 sounds) have been calculated and compared with the limit value. No one of the 20 subjects resulted incoherent. The maximum value of standard deviation found with this analysis is 1.54.

Results and considerations

The above-described linear regression model has been applied to the 960 observations. P-values calculated with the model are used to evaluate whether an explanatory variable results to be significant or not in explaining the variance of the dependent variable. A P-value < 0.05 indicates that the corresponding variable is significant.

P-values obtained with the linear regression model are reported in Table 6.3.

Table 6.3: *P-values obtained with the linear regression model applied to all the observations.*

Variable	Room 1	Room 2	Room 3	Configuration	Real/Virtual
P-value	5.6988e-16	5.2753e-19	3.9154e-08	6.7584e-11	4.1891e-03

All the variables resulted significant. This means that the perceived annoyance differs from a room to another. Besides, it is also depending on the relative position between the sound source and the listener.

The P-value = 0.0042, related to the variable *real/virtual* indicated that the perceived annoyance is different between real and virtual sound for the same configuration.

Grounding on the results obtained with the numerical validation, it has been decided to perform further analyses. Specifically, since the numerical results showed that the simulations in the third room were quite different from the real recorded sound, it has been decided to re-apply the linear regression model only to the data related to the first two rooms. In this case the variable *room* was a dichotomous variable that varies between 0 and 1, as well.

Therefore the model has been applied to 640 observations (20 subjects x 2 rooms x 2 configurations in room x 4 repetitions). P-values obtained are reported in Table 6.4.

Table 6.4: *P-values obtained with the linear regression model applied to the observations related with rooms 1 and 2.*

Variable	Room	Configuration	Real/Virtual
P-value	6.2041e-16	3.6914e-02	2.0373e-01

In this case the P-value = 0.203, related to the variable *Real/Virtual* indicates that this variable is not significant, and therefore it does not influences the choice of the subject for the evaluation of the perceived annoyance.

The validation of the perceptual equivalence confirmed the results obtained with the numerical validation. Both tests highlighted that the Virtual Acoustic Environment has been able to simulate, with an adequate level of accuracy - in terms of sound power level for the different frequencies and in terms of perceived sound quality - the sonic response of a product in two of the three environments used for the validations.

As explained in Section 6.2.1, the lack of accuracy in the simulations related to the third room is probably caused by the use of a wrong absorption curve for the walls material.

Anyway, a different propagation algorithm is needed for the simulation of the low frequencies propagation, since the actual software resulted inadequate.

CHAPTER 7

Conclusions and future works

The research work described in the present thesis concerns the acoustic evaluation of industrial products. More in detail, the implementation and the use of Virtual Acoustic Prototypes as support to the Product Design Process has been studied.

The principal aim of this research was the development of a methodology aiming at integrating the use of the Virtual Acoustic Prototypes within the traditional Product Design Process.

First of all it has been necessary to analyze the role of sounds coming from industrial products. The concept of *sound quality*, opportunely extended to industrial products that generate sounds during operation, has been investigated.

The deepened analysis of the *industrial sounds* has led to a classification of the common sounds that usually are produced when an industrial product is in function. Three main categories have been identified: working sounds, interaction sounds and communication sounds.

While communication sounds are usually expressly designed to provide information to users, working and interaction sounds come from the use and the interaction with the product, and the *quality* of those typologies of sounds is influenced by other design choices (choice of components, materials and so on).

In the present research work it has been decided to focus on the analysis and the simulation of working sounds. Interaction sounds have not been taken into account.

The evaluation of the sound quality of industrial products resulted to be a rather complex problem, since characteristics as pleasantness, annoyance and so on, are qualitative attributes of a sound and they are also strictly subjective. Therefore it is not possible to define a limit between pleasant and unpleasant sounds, between *sound* and *noise*.

In order to understand how to correctly analyze the quality of the sounds generated by products, several tools, which are commonly used for the evaluation of industrial sounds, have been studied. For each of them, strengths and weaknesses have been highlighted.

On the basis of the analysis of the role of sound in the context of Product Design, and of the analysis of the methods and tools for the evaluation of the sound quality of industrial products, the Virtual Acoustic Method has been defined. The main objective, when defining this method, has been to identify of a guideline for using Virtual Prototypes of products to perform acoustic validations during the Design Process.

An interactive environment, called Virtual Acoustic Environment, has been designed and implemented to develop the Virtual Acoustic Prototypes of Industrial Products. The design of the Environment, in terms of sound simulation techniques and algorithms, has been carried out after a deepened study of the literature in the field of Virtual Acoustics. This study has been conducted by analyzing benefits and limitation of the most common techniques used for the simulation of sound fields. The ray-tracing algorithm resulted to be the most suitable method for the simulation of sound propagation.

Once the implementation of the Virtual Acoustic Environment has been completed, two testing sessions have been carried out to validate the Environment.

A numerical validation, where sounds recorded in real configurations have been numerically compared with sounds simulated within the Virtual Environment, has been performed to analyze the level of accuracy of the numerical simulation.

A validation of the perceptual equivalence between real and simulated sounds, conducted by asking subjects to evaluate a characteristic of the sounds, has been performed to assess if the Virtual Acoustic Environment is able to reproduce the acoustic feedback perceived by people when they use an industrial product.

The analysis of the results obtained with the numerical test evidenced that the sound propagation algorithm produced accurate simulations for middle and high frequencies, but a loss of accuracy occurred in low frequencies.

The results obtained with the perceptual test showed that the acoustic feedback quantified by evaluating the level of annoyance perceived by users in the real configurations and in the simulated ones, is comparable.

On the basis of the results obtained with the two testing sessions, it is possible to assert that the Virtual Acoustic Environment is able to reproduce sounds that are comparable with the real sounds, which can be audible in real situations.

Therefore, it is possible to hypothesize the use of the Virtual Acoustic Environment in the industrial context: it could be used for performing the acoustic validation during the development phase, thus reducing even more the need of physical prototypes.

7.1 Future developments

The future developments of the research described in this thesis are related to:

- the improvement of the Virtual Acoustic Environment
- the application of the Virtual Acoustic Method in the industrial context

For what concerns the Virtual Acoustic Environment, test results showed that the simulation of sound propagation is less accurate for low frequencies. Therefore it becomes necessary to integrate the current algorithm with a new method, more suitable to simulate the propagation of low frequencies.

Another improvement is related to the integration and the he use of the other senses - i.e. vision and touch - in the Virtual Environment. The current design of the Virtual Environment involves the only sense of hearing, since the visualization environment consists of a GUI used to edit the parameters of the acoustic simulation.

The integration of visual and haptic informations will lead to the definition of a multi-modal environment that, with the combination of more than one sense, will contribute to increase the interaction and the sense of immersion of users in the Virtual Envionment [39].

In the definition of the Virtual Acoustic Method, specific tools have been identified for the different phases. Despite all the tools have been validated and the different phases have been deeply analyzed, the overall method has not been validated. Therefore it is necessary to perform some testing sessions on one or more case studies, before applying it in the industrial context.

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APPENDIX *A*

Frequency Limits for Octave Bands

Appendix A. Frequency Limits for Octave Bands

Frequency (Hz)					
Octave Bands			1/3 Octave Bands		
Lower Band Limit	Center Frequency	Upper Band Limit	Lower Band Limit	Center Frequency	Upper Band Limit
11	16	22	14.1 17.8 22.4	16 20 25	17.8 22.4 28.2
22	31.5	44	28.2 35.5 44.7	31.5 40 50	35.5 44.7 56.2
44	63	88	56.2 70.8 89.1	63 80 100	70.8 89.1 112
88	125	177	112 141 178	125 160 200	141 178 224
177	250	355	224 282 355	250 315 400	282 355 447
355	500	710	447 562 708	500 630 800	562 708 891
710	1000	1420	891 1122 1413	1000 1250 1600	1122 1413 1778
1420	2000	2840	1778 2239 2818	2000 2500 3150	2239 2818 3548
2840	4000	5680	3548 4467 5623	4000 5000 6300	4467 5623 7079
5680	8000	11360	7079 8913 11220	8000 10000 12500	8913 11220 14130
11360	16000	22720	14130 17780	16000 20000	17780 22390