GENERALISED AUDIO SYNTHESIS ALGORITHM FOR SIMULATING FIREARM AND SUBSONIC/SUPERSONIC PROJECTILES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF INFORMATICS INSTITUTE
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

TEKSIN SAKA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
GAME TECHNOLOGIES

DECEMBER 2015

Approval of the thesis:

GENERALISED AUDIO SYNTHESIS ALGORITHM FOR SIMULATING FIREARM AND SUBSONIC/SUPERSONIC PROJECTILES

submitted by **TEKSIN SAKA** in partial fulfillment of the requirements for the degree of **Master of Science in Game Technologies Department, Middle East Technical University** by,

Prof. Dr. Nazife Baykal
Director, Graduate School of **Informatics Institute** ________________

Assoc. Prof. Dr. Hüseyin Hacıhabiboğlu
Head of Department, **Game Technologies** ________________

Assoc. Prof. Dr. Hüseyin Hacıhabiboğlu
Supervisor, **Modelling and Simulation, METU** ________________

Prof. Dr. Nafiz Alemdaroğlu
Co-supervisor, **School of Civil Aviation, Atılım University** ________________

Examining Committee Members:

Prof. Dr. Yasemin Yardımcı
Informatics Institute, METU ________________

Assoc. Prof. Dr. Hüseyin Hacıhabiboğu
Modeling and Simulation Department, METU ________________

Prof. Dr. Nafiz Alemdaroğlu
Co-Supervisor,Aerospace Engineering, METU ________________

Assoc. Prof. Dr. Ahmet Oğuz Akyüz
Computer Engineering Department, METU ________________

Assist. Prof. Dr. Tolga İnan
Electrical and Electronics Engineering, TED University ________________

Date: **02/12/2015**

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name: TEKSIN SAKA

Signature :

ABSTRACT

GENERALISED AUDIO SYNTHESIS ALGORITHM FOR SIMULATING FIREARM AND SUBSONIC/SUPERSONIC PROJECTILES

Saka, Teksin

M.S., Department of Game Technologies

Supervisor : Assoc. Prof. Dr. Hüseyin Hacıhabiboğlu

Co-Supervisor : Prof. Dr. Nafiz Alemdaroğlu

December 2015, 39 pages

Artificial creation of audio signals involves mathematical equations and processing models in order to simulate real samples of audio data. Most frequently used model for audio synthesis is physical modeling synthesis. Successful simulation of the audio source requires a slightly or completely different equation to match physical properties of instrument or source. However physically modeling and simulating sound sources that containing great energy impulses in very short time periods, less than a millisecond, has proven itself to be a challenge. The aim of this thesis is development of a novel generalized base audio synthesis algorithm which could have distinct implementations to synthesise audio signals pertaining to gunshots from several different calibre and types of firearms, shock waves created by passing by of projectiles fired from these weapons, and impacts of these projectiles on certain material types (concrete, metal etc.).

Study of these three distinct subject has been divided in three different processes. For muzzle blast synthesis a combined methodology of Friedlander equation supported by Hopkinson's Scaling Law and the United States Navy Studies of overpressures for estimating peak overpressure and positive phase duration, extracted noise interpolation of two vastly different firearms for weapon characteristics is devised.

For bullet impact sound on different materials an energy conversion based modular approach is utilised. Real waveforms of bullet impact sounds are divided into energy-time components to allow for parametric approach of synthesis.

For sonic booms of passing by projectiles while they are still cruising at supersonic speeds, also referred as cracking sound, are presented as N-profile waveforms supported by maximum pressure and time duration estimates with aerodynamic studies of NASA.

With this novel approach peak overpressures and positive phase durations for muzzle blast and cracking sound have been estimated with greater accuracy and synthesis of impact sounds on different materials has been achieved.

Keywords: Gun sounds, Muzzle blast, Impacts, Sonic boom, Physically based sound synthesis

ÖZ

ATEŞLİ SİLAHLAR VE SUBSONİK/SÜPERSONİK CEPHANELER İÇİN GENELLEŞTİRLİMİŞ SES SENTEZ ALGORİTMASI

Saka, Teksin
Yüksek Lisans, Oyun Teknolojileri Bölümü
Tez Yöneticisi : Doç. Dr. Hüseyin Hacıhabiboğlu
Ortak Tez Yöneticisi : Prof. Dr. Nafiz Alemdaroğlu

Aralık 2015 , 39 sayfa

Ses sinyallerinin yapay olarak üretiminde gerçek ses datalarını simüle edebilmek için matematiksel denklemler ve proses modelleri kullanılır. En çok kullanılan model ise fiziksel modelleme sentezidir. Bir ses kaynağının başarılı şekilde simüle edilebilmesi için enstrüman yada kaynağın fiziksel özelliklerini karşılayan benzer yada tamamen farklı denklemler gerektirir. Fakat çok kısa zaman dilimleri içerisinde, bir milisaniyeden daha kısa, yüksek miktarda enerji impulsları barındıran ses kaynaklarının fiziksel olarak modellenmesi ve simüle edilmesi beklenilenden daha büyük bir zorluk teşkil etmiştir. Tezin ana amacı ise farklı kalibrede pek çok farklı ateşli silaha ait ateşleme, mermilerin geçişi ve bu mermilerini belli özellikteki yüzeylere çarpma seslerinin sentez edilmesi gibi farklı alanlarda kullanılabilecek özgün genelleştirilmiş temel ses sentez algoritması geliştirmektir.

Bu üç farklı konu üç farklı prosese bölünmüştür. Namlu patlama sentezi için tepe basınç değerleri ve pozitif süre zarfı sentezi için Hopkinson Ölçeklendirme Kanunu ve Birleşik Devletler Donanma Çalışmaları ile desteklenen Freidlander denkleminden oluşan birleşik bir metodoloji, silah karakteristikleri için birbirinden çok farklı iki ateşli silahtan elde edilmiş gürültü interpolasyonu geliştirilmiştir.

Farklı malzemelere mermi çarpma sesleri için modüler bir enerji dönüşüm metodu geliştirilmiştir. Senteze parametrik yaklaşımı mümkün kılmak için gerçek mermi çarpma ses dalga formları enerji-zaman bileşenlerine ayrılmıştır.

Çatlama sesi olarak da bilinen, süpersonik hızlarda seyrini sürdüren mermilerin geçerken yaratıkları sonik patlamalar N-profil dalga formları halinde sunulmuş ve maksimum basınç ve zaman süreçleri tahminleri NASA’nın aerodinamik çalışmaları ile desteklenmiştir.

Bu özgün yaklaşım ile namlu patlama ve çatlama sesleri için tepe basınç değerleri ve pozitif zaman süreçleri daha isabetli şekilde belirlenmiş ve farklı materyaller üzerine isabet eden mermi sesleri elde edilebilmiştir.

Anahtar Kelimeler: Silah Sesleri, Namlu Patlaması, Çarpma,Sonik Patlama, Fizik Tabanlı Ses Sentezi.

To friends, family and all my mentors...

ACKNOWLEDGMENTS

I would like to express my gratefulness to Assoc. Professor Hüseyin Hacıhabiboğlu whose guidance in audio and sound made it possible for me to marry physics to sound in digital realm and Prof. Dr. Nafiz Alemdaroğlu whose oversight allowed for a new dimension on the study and future expansion of the work already done.

I want to express my gratitude to my family and Ayberk Sağdıç, both of whom never doubted me

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

SPL	Sound Pressure Level
M	Mach number of the specified object
FMJ	Full Metal Jacket
dB	Decibel

CHAPTER 1

INTRODUCTION

Video gaming today is divided in genre and rich in variety. In these genres action games such as First Person Shooters, Third Person Shooters and other varieties hold an important place. As of 2014 action games among all other genres action and shooter genres across all platforms hold up to %49.9 of total sales [**21**] . Shooter games and most of the action games feature a shooter game play element that allows player to wield different types of firearms to use in battles versus AI opponents or other players. Sounds belonging to these in game weapons are considered as an important game element by themselves by the players. The firing sound , especially, from these weapons when listened carefully can give away a players location, how far it is, what direction weapon is facing, what type of weapon he or she is using and even in some games how many shots are left in reserve to be used long before two opponents can get within visual range of each other . This kind of information when gathered from a safe distance in such a manner gives an undeniable tactical and strategic advantage to other side in planning an attack or defence depending on the current situation.

When considered how important gun sounds are in this specific genre it is only expected that developers of this genre making investments in this specific area. Gun sounds are expected to be authentic, precise and clean by the players and developers alike. Sounds of these weapons are obtained primarily by recording methods on real life shootings in the field instead of synthesizing them in a digital environment. Main reason for this is gun sound elements being hard to recreate physically correct in a digital environments. Sounds like gunshots, explosions, impacts have two common properties that make them hard to predict and formulize thus making them hard to be generated digitally. These are very high impulses (amplitudes) and very short time periods. When combined together in low sampling rates these two properties together make a very hard combination to be generated.
These circumstances pushed developers to use recording methods for their high quality gun sound needs. But this method requires great amount of financial resources, access to expensive and delicate recording and measuring equipment, expert support on very specific fields like ballistics and wave physics and a very flexible time budget. The nature of recording method makes it impossible for developers with much less resources to use it. Many independent game developers or independent film makers instead chose to use much lower quality sound libraries that exist on internet instead giving them a handicap in their work.

Currently there is no deep study for digital gunshot sound generation for media purposes but a deep understanding of gunshot sounds and ballistics can be found for forensic and military purposes. A recent study [**2**] details what a recorded gunshot consists of in detail.

1.1 Scope

The aim of this thesis is development of a novel generalized base audio synthesis algorithm which could have distinct implementations to synthesise audio signals pertaining to gunshots from several different calibre and types of firearms, shock waves created by passing by of projectiles fired from these weapons, and impacts of these projectiles on certain material types. Main contribution of this study is a method that relies on real physical formulas describing impact and explosion effects on atmosphere which is constructed as a modular based approach which then allows parametric real-time digital signal generation. Hence our resulting algorithms is not restricted to game development software and video editing programs and can be implemented in any target software that is required to generate these signals without any restriction.

Study of these three distinct subjects has been divided in three different processes. Muzzle blast, cracking sound of the bullet and impact sound of these bullets resulting from collision with other materials at very high speeds.

1.2 Outline

The thesis consists of these following chapters:

- Chapter 2 introduces an overview of related past work including forensics, aerodynamics, digital signal generation and wave physics.
- Chapter 3 explains the muzzle blast partition of the study, detailing into peak pressure, positive time duration estimates and waveform construction methods.
- Chapter 4 explains impact sounds partition, describing pre existing waveform inspections, ballistic calculations on different calibre of ammunitions, thin plate vibration studies and final waveform generation methods.
- Chapter 5 explains cracking sound partition describing aerodynamic principles behind the shock wave theory, presenting difficulty of precise recordings and thus generation and estimation method for cracking sound and also a simplified sonic boom solution for this problem.

- Chapter 6 presents experimental data and compares the findings of this study and a short discussion on results.
- Chapter 7 presents a summary of our contributions and possible future work to expand upon the algorithms and methods described here as a conclusion. . . .

CHAPTER 2

BACKGROUND AND RELATED WORK

As explained before, although there are separate detailed research in fields of plate vibrations by impacts, estimations of sonic booms created by objects travelling at supersonic speeds and shockwaves resulting from explosions caused by explosives there is currently no deep research in generating gunshot sounds which cover these three distinct fields all together. Thus in the search of related past academic and experimental work each different phase has to be taken one by one case.

The only type of research focusing on gunshot sound as a whole process, basically academic works focusing on muzzle blast and cracking sound as a whole, can be found on forensics research. One specific study [**2**] manages to give detailed insight and experimental results regarding these two phases.

2.1 Muzzle Blast

Muzzle blasts are shockwaves caused by discharging of the rapidly expanding hot gases through muzzle which is caused by ignition of ammunition's propellant. Ideal explosions in air create shockwaves characterized by an almost instantaneous rise in pressure, followed by an exponential decay from the peak value to a partial vacuum, and then back to the ambient air pressure level [**2**] Signature of a muzzle blast is highly dependent on physical characteristics of the weapon such as length of the barrel, muzzle brake type and shape, porting as well as ammunition type and characteristics being propellant composition, bullet diameter, aerodynamic characteristics (drag coefficient) of the bullet.

Muzzle blasts are usually impulsive, loud and very short sounds. Especially around near distance of the shooter. A muzzle blast sound only lasts only a few milliseconds, and it's peak sound pressure level (SPL) can very well reach and exceed 150 dB regarding 20 μPa in near shooter vicinity [**16**].

An important point is that a muzzle blast is an explosion driven by a chemical reaction of explosive material which is pointed towards a single direction via barrel tube. This allows us to take muzzle blasts as explosions in the air. Thus signature of a muzzle blast can be defined and predicted as ideal explosions. Ideal explosions in air have a clear physical description in terms of pressure changes they create as a shockwave which is an instant rise with exponential decay following it to a vacuum state and then back to normal air pressure [**2**] .

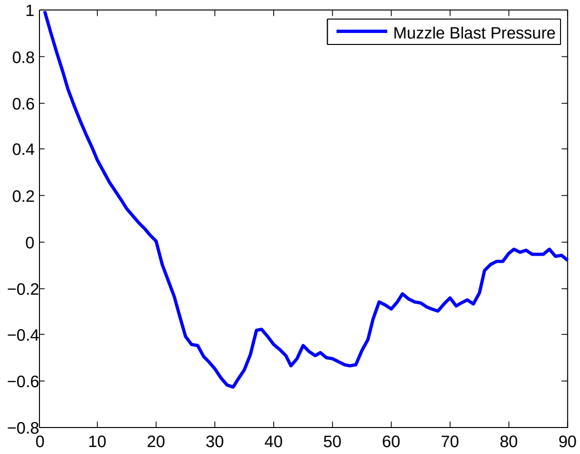

Figure 2.1: A muzzle blast signature with only muzzle blast and it's ground reflection [**17**]

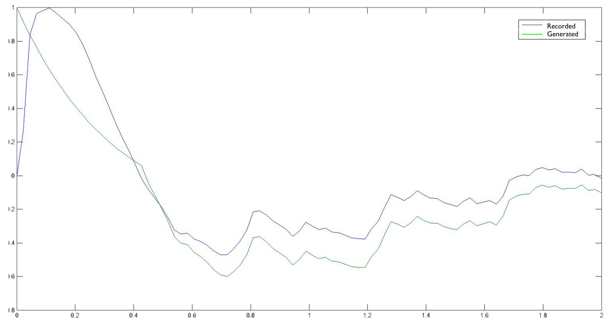

Figure 2.2: Waveform comparison of synthesized and recorded AK-47 rifles

Muzzle blasts from small to mid calibre weapons such as pistols, handguns to assault rifles and light machine guns, when measured by properly calibrated equipments, present a distinct "pressure signature" in time domain. In Figure 2.1 mentioned peak pressure, exponential decay and return to ambient pressure can be clearly seen. The only difference would be a reflection of original muzzle blast signal from ground is also overlaid on the original signal.

As mentioned before muzzle blasts can be considered ideal explosion in air and thus can be represented and formulated as one. During the century there have been many experiments and studies on explosions, their predictability and their physical characteristics, whether be nuclear or not. A well known military experiment has managed to characterise known physical properties of a large scale gas explosion. The experiment is called "Operation Distant Plain" [**5**] In fact a series of total six experiments Distant Plains' aim was to find solutions to some specific problems militaries encountered about nuclear weapons. A great volume of stoichiometric propane or methane with oxygen mixtures was detonated and blast waves were carefully measured.

Most common and base equation describing pressure changes in ambient air caused by explosions is Friedlander Equation. Given estimated base peak pressure, positive time duration and decay rate Friedlander Equation can form the base of many different

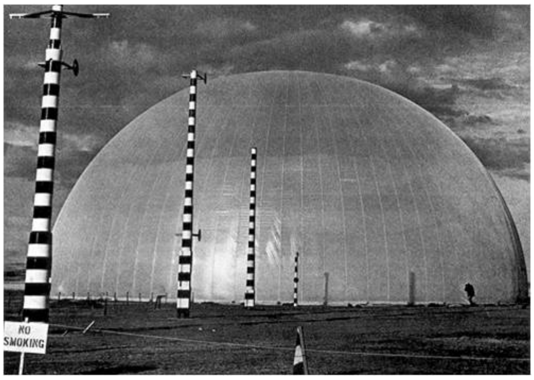

Figure 2.3: Tanks that hold gas mixtures for detonation during Operation Distant Plain, 1966 - Image adopted from [**5**]

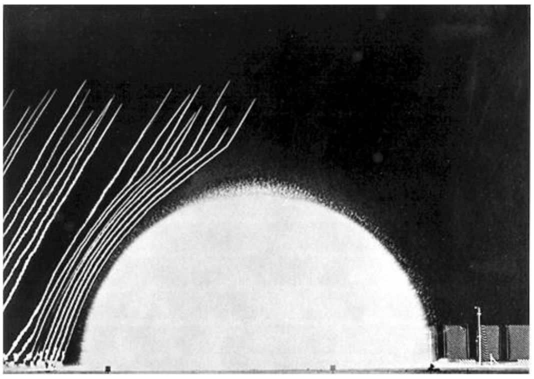

Figure 2.4: Contrast photography and smoke tracers for measurement of gas explosions - Image adopted from [**5**]

explosion related studies.

$$p(t) = P_0 + P_s(1 - \frac{t}{T_0})e^{\frac{-bt}{T_0}} \tag{2.1}$$

where;

P_0 is ambient pressure

P_s is peak pressure

T_0 is positive phase duration

b is decay rate

It could be considered as a basis for explosion pressure values estimate studies. Below is a signal of pressure values generated for peak pressure 200 Pa, positive phase duration 0.5 and decay rate 1.

It should be kept in mind that SPL levels drop drastically depending on azimuth and elevation of the listener. Detailed experiments with many different calibre and types of firearms has been conducted by many different study groups and confirmed this result [**18**] , [**2**]. Parametric and detailed approach on the matter has been conducted

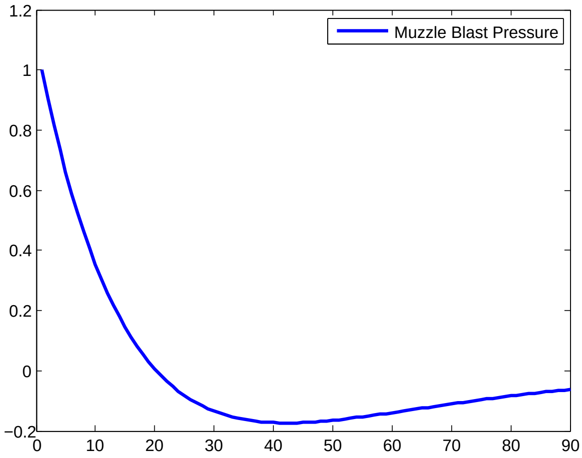

Figure 2.5: A generated pressure/time graph with Friedlander Equation - Image adopted from [**2**]

upon the matter by military research centers for concern of noise control and hearing loss. Formulated approach study can be found in the work of [**22**] et al [**14**]

$$L(\theta) = \frac{D_0 cos\gamma_0(1+cos\theta)}{2} + L_n \quad (2.2)$$

where;

$L(\theta)$ is dB level measured at azimuth θ degrees.

D_0 is difference of peak pressure in dB between front side and back side of the gun direction (usually 14 dB)

γ_0 is gun elevation in degrees

L_n is sound level behind the gun at an arbitrary distance

Another important point for determining the distance effect for muzzle blast SPL is the energy dispersion of sound wave and it's effect on positive phase duration of waveform. As showed in the aforementioned study positive phase duration increases up to a certain distance [**2**] This also raises the question of predicting the positive time duration for the given firearm. In answering this question a well known rule regarding the physical effect of explosives as a ratio of cube root of their energies called Hopkinson's Scaling Law can be used. Hopkinson's Law states that two different explosions with two different energy levels can be compared in terms of their impulses, positive time durations and their perceived distances as cube

$$(\frac{E_2}{E_1})^{\frac{1}{3}} = \frac{R_2}{R_1} = \frac{T_2}{T_1} = \frac{I_2}{I_1} \quad (2.3)$$

where;

E is energy of the explosion, or muzzle blast energy in this case

R is distance from the explosion

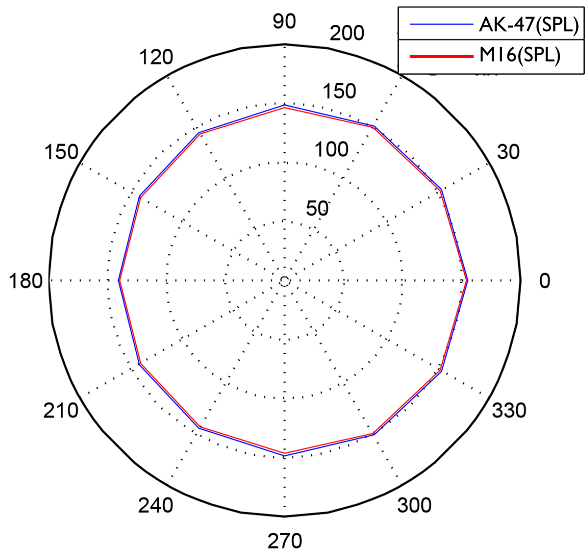

Figure 2.6: AK-47 and M16 Muzzle Blast Pressure values in 20 μSPL depending on azimuth angles

T is positive phase duration

I is impulse in psi/ms

Hopkinson's Scaling Law is derived from Square Cube Law which states that when an object increases in size it's volume increases greater than it's surface area. Thus while surface area is proportional to the square root of the multiplier the volume is proportional to cube root of multiplier. Real life gunshot sound recordings usually include at least one echo of original signal that overlays over original one with some time delay. The time of the delay depends on distance to shooter, or muzzle of the gun and amplitude of it depends on ground material sound is reflected from. A parametric solution for time of delay has been described by Back, Hirotaka 2011 et al.

$$t_{doa} = \frac{2h_1h_2}{v_0r_0} \qquad (2.4)$$

where;

t_{doa} is time difference in arrival

h_1 is height of the source

h_2 is height of the listener

v_0 is speed of sound in medium

r_0 is projected distance along surface between source and listener

Described method above is stated as accurate to $\%6$ for $r_0 > 2(h_1 + h_2)$ [**2**].The shooter's height is presumed to be 1.8 meters and gun height is considered to be 1.5 meters.

Above formula gives as delay of arrival time but as long as we do not consider what kind of environment the weapon is fired wAcoustic reflection of materials is a well studied subject and there are lists available to public that specify the absorption rate of specific materials depending on incoming sound's frequency.

Table 2.1: Sound absorption coefficients for various materials at different frequencies (Acoustical Surfaces Inc)

Materials	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz
Brick - Unglazed	0.03	0.03	0.03	0.04	0.05	0.07
Brick - Unglazed, Painted	0.01	0.01	0.02	0.01	0.02	0.03
Concrete Block - Light, Porous	0.36	0.44	0.31	0.29	0.39	0.25
Concrete Block - Dense, Painted	0.10	0.05	0.06	0.07	0.09	0.08

It must be taken into account that even firearms that use same type of ammunition when their gunshot sounds are recorded at exactly same distance and azimuth within the exactly same environment give different values. This is the result of two different factors. First one is overall firearm characteristics. These are mainly defined by the role that specific firearm is supposed to fill. This role defines main characteristics such as barrel length, muzzle brake types. Two firearms even though using exactly same ammunition which is a real world case since both firearm manufacturers and customers seek interoperability and access to already existing ammunition standards for ease of logistics and lower operating costs, can have different barrel lengths and porting to allow for different roles. A suitable comparison would be Accuracy International Arctic Warfare and M60. Both use 7.62x51 NATO ammunition; first is a sniper rifle whereas the latter is a machine gun.
The second factor is what is called "Internal Ballistics". It depends largely on construction of inner workings of loading and firing mechanisms, rifling on the barrel, materials used on the gun. All these elements manifests themselves as subtle and frequent changes in final measurements which we can also call body formant or simply firearm specific characteristic of the sound. A most basic example would be an automatic assault rifle with larger inner part movement margins for higher tolerance on the field would expected to have more distinct, or higher amplitude noise, in it acoustic signal than a rifle that has strict and very narrow margins for internal movements for allowing lower recoil to allow precise shots

2.2 Impact Sound

Generating various sound effects digitally with real time algorithms during real time process according to player actions and interactions with game elements or environments instead of using pre-recorded and processed sound files with suitable extensions such as .ogg or .wav is a constant topic for researchers in digital audio field. Though types of sounds that needs to exist in a digital game can be high in count researchers usually focus on most common types such as impacts, explosions and likewise destruction sounds. One such example is a proposed and integrated method for generating continuous contact sounds with modal frequencies of the object depending on geometric shape of the object pre-calculated and stored as a "sound texture" for use in a custom developed dynamics simulator [**22**])

Impact sound of a projectile fired from a firearm to any material differs greatly from many other impact sounds frequently observed in nature, and usual digital synthesizing methods used for creating impact sound for games and other digital media based on frequency modulation may not yield accurate results for this case. Most common scenario for measuring physical properties of ammunitions and their effects is firing them with different configurations such as single shot, burst shot with 3 consecutive shots and full automatic mode to dense materials that are encountered everyday life so that overall effect of the given ammunition can be measured close to real life scenarios. Appropriate examples would be thick ply wood stacks or wooden materials that simulates doors, improvised barriers, fences and denser but thinner metal plates simulating guard doors, security structures and vehicle covers. Since video games and movies of all spectrum of financial budget, when using a real militaristic background for design, try to emulate real life examples for presenting realistic and believable experiences to their players approaching the study in this peculiar way should yield accurate results. When viewed with this mindset it should be safe to assume using very high speed - low mass projectiles' impact on variable material density plates as a starting point for digital synthesis should be a highly accurate approach. Ammunitions are usually made from denser materials for increasing mass and covered with physically resistant materials to allow penetration into tougher, resistant materials among many other operational benefits. For example a common ammunition type is Full Metal Jacket (FMJ). This type of ammunition has a lead core allowing higher mass for greater kinetic energy capacity during flight and a steel alloy cover, fully encircling the lead core. Lead although denser and heavier in any given same volume has a lower heat and physical resistance properties. When used as is as ammunition, it tends to melt from heat caused by the ignition of propellant and leaving residue in the barrel because of rifling. This causes very low aerodynamic properties of projectile and very high maintenance and very low barrel life for firearm.

Considering this circumstance it is safe to assume the projectile to be a dense metal in it's nature. Meaning it will not change it's shape to absorb the kinetic energy and thus the sound we are going to synthesize can be simulated as point impacts that causes vibrations on a thin metallic plate. Vibrations of point impacts and loads and natural frequencies of these vibrations on plates with arbitrary thickness and support numbers is a well researched well understood subject. Bhat presents a mathematical model for simulating natural frequencies in his work et al [**3**] . Their work details modal frequencies depending on number of supports the arbitrary plate has and presents a

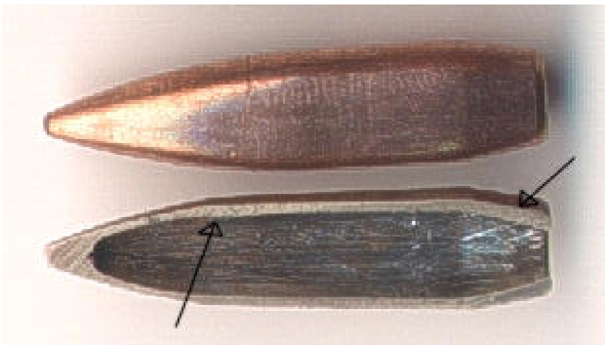

Figure 2.7: Cut of view of a Full Metal Jacket Ammunition - Image adopted from [**9**]

solution of using orthogonal polynomial for extracting the frequency for each modal number. Another research with more suitable integration into this study presents a compact solution for finding out a plates natural frequencies which is much more suitable for real time applications such as game engines [**21**]

$$\omega_{mn} = \pi^2 (\frac{m^2}{a^2} + \frac{n^2}{b^2}) \sqrt{\frac{D}{\rho h}} \tag{2.5}$$

where;

ω is natural frequency

m, n are modal numbers

a, b are width and length of the plate

$D = \frac{Eh^3}{12(1-\vartheta^2)}$

E = Elasticity modulus

h = Thickness

ϑ Poisson Ratio

ρ Density

2.3 Cracking Sound

Most of the modern firearms possess a property called "Supersonic Muzzle Velocity". Muzzle Velocity is a term used for speed of the projectile at the exact point in time when it leaves the gun barrel completely. A supersonic muzzle blast indicates a projectile velocity well over Mach 1, or speed of sound in ambient air at current conditions, at departure of muzzle of the gun. Generally in ideal conditions speed of sound is considered 343.2 m/s. In fact when investigated carefully it becomes obvious that many rifles and submachine guns when using standard munitions and in non-modified configurations possess muzzle velocity much higher than indicated speed of sound .
Objects travelling at supersonic speeds cause a phenomena called "Sonic Boom" .

Sonic booms are shock waves caused by sound waves folding onto each other and forming a single front also called a "Mach Cone" . A distinct feature of this cone of shockwave when recorded or measured it presents a clear signature waveform that can be used to identify the recording belonging to a shockwave. This waveform is called "N-Wave" .

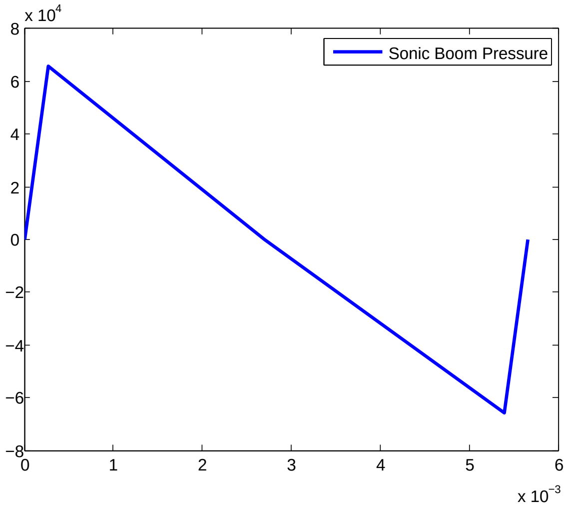

Figure 2.8: N- Wave Profile of A Shock Wave

The two defining characteristics of this waveform are it's duration and it's two obvious almost symmetric positive and negative peak values. A shockwave belonging to a firearm ammunition, cracking sound, lasts much shorter than one millisecond and has two separate maximum and minimum values. Shockwaves in general, even for much larger sized objects like aircraft, possess these two distinct points. These two points represent the front and back ends of the object.

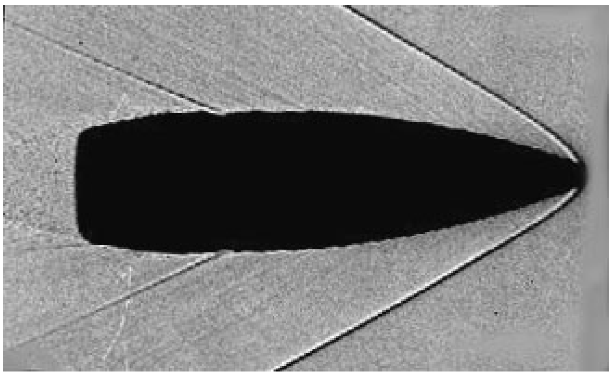

Figure 2.9: A shadowgraph photograph of .308 Winchester round travelling in air, clearly depicting shockwave - Image adopted from [**12**]

As projectiles fired from firearms travel through air, their speed decreases due to air friction but in close ranges around 50 meters the projectile is still supersonic and like all objects travelling at supersonic speeds it also causes a sonic boom. But due to dimensions of the projectile being much smaller than an aircraft or rocket propelled munition the amplitude of the sonic boom or shock wave is also very low. It is often described as a "miniature shockwave" . It is commonly called as cracking sound because of similarity.

Although estimating the angle of shock cone is relatively a simple geometric calculation [**14**] to be able to precisely calculate a sonic boom's amplitude requires applying fluid mechanic principles and Navier - Stoke Equations with appropriate boundary conditions. These equations are usually process heavy and used in simulations and not in real time applications due to calculations required for solving momentum/ mass equations taking longer processor time.

There have been recent research for generating aerodynamic sounds real time [**7**] In their work if the dimensions and the shape of the object is known then a pre-calculated sound texture can be extracted and used to generate the sound mentioned object would make while moving in a fluid medium (air) . Although very useful for constant size objects like swords when varying size and diameters of firearm ammunition is considered a requirement for a simpler method becomes self explanatory.

Another research from NASA however presents a simplified solution with pre-determined and simplified equations batches allowing for prediction of amplitude of sonic booms on aircraft travelling at supersonic speeds of various shapes and aerodynamic properties [**4**] His study includes a three step calculation method for estimation of bow shock overpressure and duration. A visual implementation of Muzzle Blast and Impact sound waveform generations.

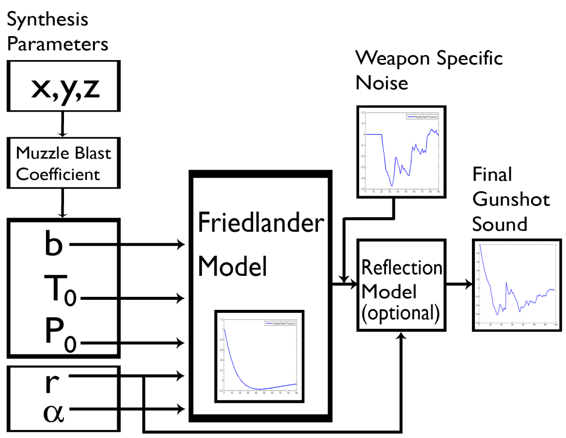

Figure 2.10: Muzzle blast waveform generation visual representation

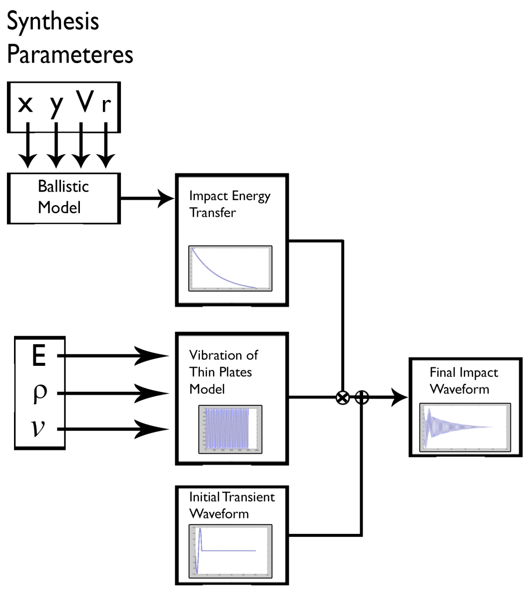

Figure 2.11: Impact waveform generation visual representation

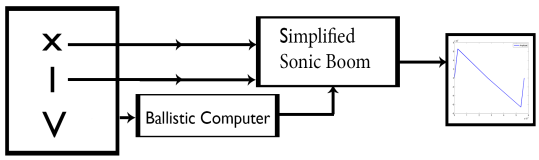

Figure 2.12: Cracking sound waveform generation visual representation

CHAPTER 3

PROPOSED METHOD

Recording real life range shootings for procuring gunshot sounds is expensive, time consuming, requiring high level of expertise on different specific areas and generating algorithms to synthesise accurate firearms sounds real-time to bypass this process requires knowledge ballistic, aerodynamic, material and general firearm related principles for high quality and believable sounds and simplifications for fast enough generation for quick iteration and on the go, real-time processes if needed. As explained in Introduction chapter the problem of generating gunshot sound consists of three distinct parts. These are :

- Muzzle blast
- Impact sound
- Cracking sound

3.1 Muzzle Blast

Muzzle blast can be summarized as a directed explosion with specific SPL level, positive time period and noise, related to structure of the firearm and reflection of the same waveform overlaying on some base sound. Proposed method includes a novel ratio based close estimation method for SPL in dB. Positive time duration in milliseconds is estimated through Hopkinson's Scaling Law. Decay rates are picked from real life experiment measures with consideration showed for type of firearm. With these three values known a Friedlander Equation can be solved for increasing time values, t, and base of the waveform can be established.

Amplitude of a muzzle blast depends on total energy available to generate that sound. That energy is sourced from ignition of propellant in ammunition case. Rapidly expanding gases form the basis of the muzzle blast sound. But not all of that energy transforms into a muzzle blast completely. It must be kept in mind that main task of the propellant is to propel the projectile through the barrel, supply enough power to reloading mechanism of the firearm, and allow projectile to use the rifling of the barrel for self stabilisation in air flight.

For that reason we must determine the energy available to us for representing muzzle blast energy. First step would be figuring out what is the total energy available.

It is a known fact that higher calibre firearms has "louder" ,as depicted by their shooters, muzzle blasts than their lower calibre counterparts. Thus it is safe to assume that total amount of energy is the total amount of propellant available to us, that is the amount in casing of the munition.

Firearm munition casings are cylindrical shaped, empty, thin metal cases. They are filled with modern propellants for maximum energy discharge speed and safe operation. Thus the total amount of energy available to us is the amount stored in that cylindrical volume.

Another important fact about the net energy available to us is that energy is required to push the projectile along the barrel and propel it out at very high speeds. So the longer the barrel is the higher total energy is required to propel it to same kinetic energy levels. Thus the longer the barrel is the less energy there will be available to us for turning into a muzzle blast. The well known construction of silencer and common knowledge of among the same calibre firearms the one with the longer barrel is "more silent" confirms this assumption.

So we are left with two relationships regarding to muzzle blast energy:

- It is proportional to total propellant mass
- It is reversely proportional to barrel length

If we assume x to be bullet diameter, y to be case length and z to be barrel length all in the same units (millimeter) than we can very simply characterise a firearm about it's muzzle blast energy with a relative relationship to other ones with a single coefficient, regarding it's selected physical properties having the most impact on it's muzzle blast energy. Let's assume that coefficient to be "Peak Pressure Coefficient" and regarded as C_p.In this case:

$$C_p = \frac{xy}{z} \tag{2.6}$$

At this point for ease of introduction proposes another similar two concepts regarding to different machinery should be introduced, being wing loading and ground pressure.

When fighter aircraft are compared against each other in terms of maneuverability and some other important flight characteristics wing loading is an important concept that is compared. Wing loading is described as loaded weight of the aircraft divided by it's wing area. The lower wing loading is the more of the lift can be devoted to turning and other tasks. Thus when two aircraft are compared in terms of turning capability the one with the lower wing loading offers better maneuverability.

The other concept is ground pressure, a very similar to concept to wing loading. Ground vehicles with heavy duty expectance in urban and jungle areas are usually designed and equipped with more than 4 wheels or sometimes even tracks. One of the main reasons behind this is to reduce ground pressure. Ground pressure is loaded vehicle weight divided to total contact surface of wheels or tracks. The greater ground pressure is the more likely the vehicle will get stuck on soft ground, damage roads and bridges seriously and have more frequent breakdowns. Thus vehicles with such duty expectancies are designed to have more wheels or to have tracks instead in order to increase total contact area with surface, reducing ground pressure.

It should be strictly kept in mind though, for accurate and exact comparison of two similar physical entity; i.e. machinery; many different ratios are needed and the best comparison result can be achieved via all parameters considered including environmental values that are independent from the entity itself. But for most practical uses and as a base "specification requirement" for one aspect usually one ratio is described and prioritized before all others

With this in mind we should expect a firearm with higher C_p to have higher SPL at the same distance since C_p is a concept that we described to tell us the energy available to convert into a muzzle blast. Now we need to select a base firearm with relative simple mechanical workings, common acceptance around the globe and using a calibre of munition similar or same as other most modern same class firearms.

For this study M-14 has been selected as a base SPL level. It precedes M-16 and other designs derived from it and uses 7.62x51 NATO munition which itself is a standard across world. The base design is older thus feature a special porting. It is also chosen as the base SPL level in [**12**] Thus providing a perfect base example of a basic firearm. If inspected it can be clearly seen that in his work Luz had the same approach to firearms, making calculations on the simplification ground that a firearm is a cylindrical pipe with projectile travelling through it [**12**]

The base SPL provided for this study are taken from (Free Hearing Test) [**8**] . Now we can compare other firearms C_p with this base one and find out their own SPL.

Table 3.1: Different firearms, their properties and calculated coefficients (C_p)

Rifles	Calibre	Case Length	Barrel Length	C_p
M16	5.56	45	508	0.5
M4	5.56	45	370	0.67
M14	7.62	51	559	0.63
.308 Winchester	7.62	51	609.6	0.63
Handguns				
M9	9	19	125	1.37
Sig Sauer P226	9	19	112	1.52
M 1911	11.43	23	127	2.07
Smith Wesson Model 13	9	33	76.2	3.4
Baretta M1934	9	17	94	1.62
Light Machine Guns				
M60	7.62	51	560	0.7
M249	5.56	45	465	0.53
Machine Guns				
M16	12.7	99	1143	1.1

Please notice that difference class of firearm possess different values for C_p. For example pistols have a much higher C_p values than rifles. Thus it becomes possible to use this coefficient to make a distinction between firearm types. Which lets us use Equation 2.3 to determine the positive phase duration. Again the base positive phase duration is a median value taken from [**2**]. And changes according to calculated C_p from entered values.

$$(\frac{E_2}{E_1})^{\frac{1}{3}} = \frac{R_2}{R_1} = \frac{T_2}{T_1} = \frac{I_2}{I_1} \quad (2.3)$$

Noise belonging to specific firearm supposed to be shooting is taken as an interpolation between two different noise sets belonging to two different firearms from two different blocks of the world that formed the design basis of great percentage of firearms produced worldwide, allowing for an accurate interpolation between composite-metal, complex-simple type of firearm noise description.

On the mechanical and metal end of the spectrum AK-47 again was selected for aforementioned properties. On the composite and complex end M16 was selected due to same reasons as being a baseline design for many other later rifle designs and using aluminium and composite materials instead of sheet metal or steel.

It should be noted that the sound samples required for noise extraction was procured from [**6**] . Since they provided uncompressed .wav formats and were kind enough to provide microphone positioning these samples were deemed appropriate.

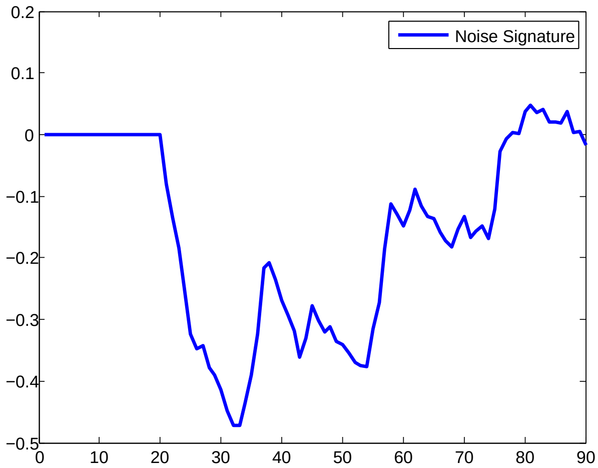

Figure 3.1: Extracted noise from a real AK-47 shooting, 3 meter distance

Interpolation between two noise banks is made on a scale over 100. Depending on how advanced or simple the gun physical composition is an appropriate value can be applied. Also 90 samples or equivalent 2 ms for 44100 sampling rate has been selected for total time duration for t value.

The decay rate , b, is selected as 0.47 for rifles and 0.29 for handguns. Vales are taken from [**2**]

The azimuth dependent SPL reduction is calculated via Equation 2.2. with azimuth in degrees.

$$L(\theta) = \frac{D_0 cos\gamma_0 (1+cos\theta)}{2} + L_n \quad (2.2)$$

Figure 3.2: Extracted noise from a real AR15 shooting, 3 meter distance

For ground reflection time delay of arrival time is calculated with Equation 2.4 [**2**]. The shooting environment is selected as an open area environment with light concrete with porous footing (surface) to emulate a real life shooting scenario. With absorption rate and delay of arrival known the ground reflection can be accurately constructed and added to main waveform finally building the muzzle blast waveform. The final waveform is saved to a .wav extension file, an extension that is selected for the reason of being common in game development environment. Latest waveform values are normalized between -1 and 1 to prevent clipping.

3.2 Impact Sound

As mentioned in Chapter 2; although vibration on plates under point loads and sudden releases is a well known and formulated subject, vibrations combining these conditions with kinetic energy transfers require a more reliable approach.

For impact sounds a real life waveform sample of an M60 machine gun shooting on a thin metallic plate object has been chosen and the waveform has been broken up to it's basic waveforms components, one for accommodating the kinetic energy transfer from projectile to plate and another for specific material's natural frequency response to that effect.

The example is taken from [**13**]. It should be kept in mind that the main source of concern is not extracting exact values but having an idea of waveform shapes and durations.

The viewed waveform can be broken into 2 main waveform multiplications with an extra waveform simulating first non- parameterised sine part. These parts are natural frequency response and kinetic energy to amplitude parts.

First part would be natural frequency which we will assume a sine wave in the same frequency of the natural frequency response of the object with the same duration value

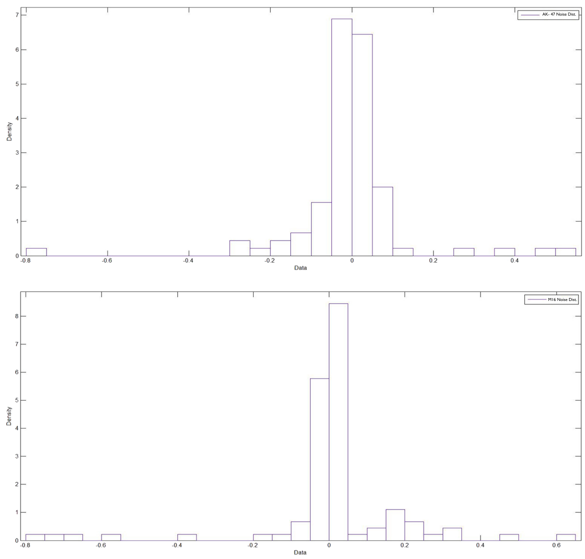

Figure 3.3: noise from distribution of AK-47 (above) and AR15 (Below)

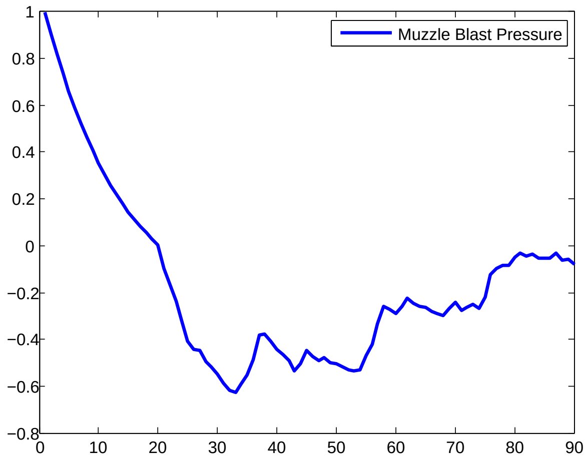

Figure 3.4: Final waveform of an AR-15, 24 meters, 0 azimuth

that is 57 milliseconds we got inspected from our real life shooting record and with amplitude of A. To have this frequency we will use the Equation 2.5 [**21**]

$$\omega_{mn} = \pi^2 \left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right)\sqrt{\frac{D}{\rho h}} \tag{2.5}$$

We can assume the plate has the same dimensions as one mentioned in original work [**21**] et al that is 0.2 and 0.1 meters but since we want a variable dimension arbitrary plate with any random material composition the values of dimensions and material properties such as Poisson ratios or density can easily be changed to achieve desired result.

To find amplitude of our signal, A, we need to equal it to kinetic energy of the projectile at the moment of impact. These two graphs would look similar as time/amplitude and time/energy graphs that exponentially decreasing making a base graph of an ex-

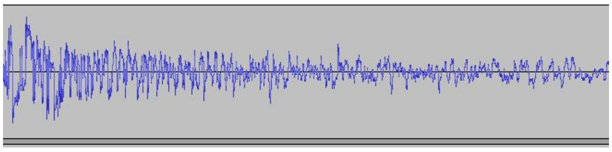

Figure 3.5: Waveform inspection of impact sound of (M60 Bullet Recording [**15**]

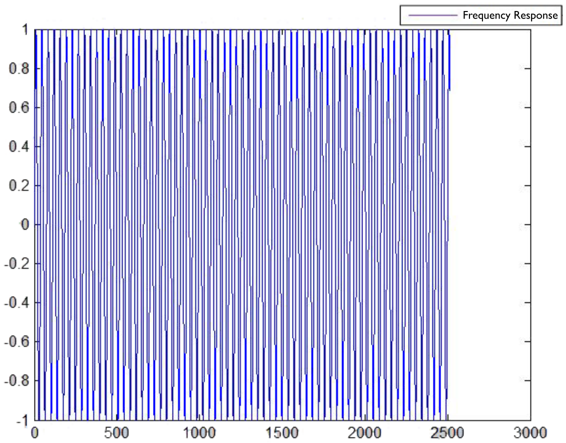

Figure 3.6: Waveform for natural frequency response of the material and amplitude

ponential function. Since the area under must equal to kinetic energy drop at point of impact we can establish the equality where A is amplitude, or maximum value of our signal and t is time duration again being 57 milliseconds.

$$\frac{1}{2}mV^2 = Ae^{-t} \tag{2.6}$$

We need to find the speed and mass of our projectile. Determining the speed of a firearm projectile is a very complicated task and is heavily dependent on past ballistic experimental results. At this point we can use an already available ballistic computer online to determine the speed of our projectile (JBM Ballistics)[**21**] Or it can even be downloaded as code files and be compiled into any project for fast process times. In this study a lower precision substitute method is used [**18**] . This method is based upon work of McCoy [**17**].

Now mass of the projectile needs to be determined. Users enter calibre and case length but not mass of the core. This can be solved by assuming the projectile we use is a standard ballistic model G series. In this study it will be assumed a G1 type projectile.

In terms of clarification, ballistic models needed to be explained further. Ballistic models are utilized for estimating of real life results of real projectiles' performance in terms of range, air resistance and accuracy depending of pre-defined and tested "virtual" projectiles. These virtual projectiles possesses defined shapes and "ratios" of the dimensions of these shapes so that they can used for larger are smaller sized projectiles of the same class.

Although there have been many different ballistic models tried through history of the firearm for modern ballistics; fire controls, mobile ballistic computers; mostly

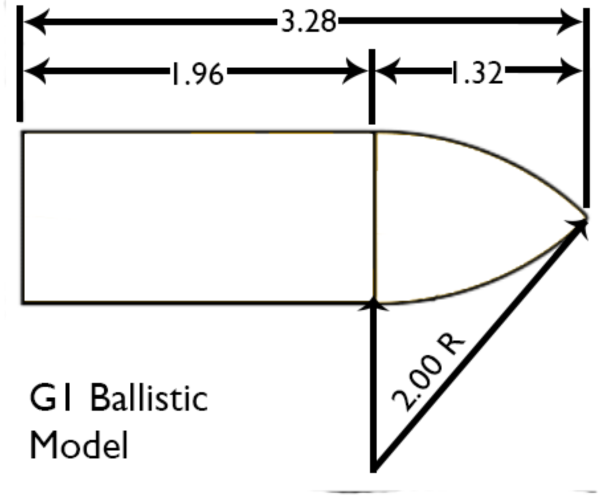

Figure 3.7: A standard G1 projectile - Image adopted from (Kestrel Meters)

accepted model is the "G" model. G model is ordered from one to seven; or from G1 to G7, G7 being a modern low-drag long-barreled rifle/gun round and G1 one being a blunt-bottom pistol or handgun round. This allows easy classification and utilization of the models for practical purposes, one being hand-held ballistic computers for hunting/shooting.

One reason that many fire solution computers and ballistic computers are unable to do real time calculations of fired projectiles is that these projectiles do not posses a thrust and they are simply thrown forward with rapid expansion of propellant ignition gasses. Thus they have a base muzzle velocity or base energy pool that is depleted because of aerodynamic drag over distance. This is best calculated via empirical data rather than aerodynamic drag formulas.

Advantage of using standard projectiles is that they have standard ratios between their dimensions allowing us to calculate their volumes with already existing information. We can also assume that this is a simple FMJ projectile that has mostly lead core. Thus as we know the density of the lead and projectile volume itself we can easily find the mass of our bullet and finally determine amplitude, A.

Our other waveform is in fact a very simple, exponentially decaying signal from 1 to 0 in the same time duration, 57 milliseconds. It's only purpose is to shape the waveform into our idealized model.

The last part is the sine wave that lasts 6 milliseconds

These waveforms when combined present us the final waveform of bullet impact sound of a specific material plate.

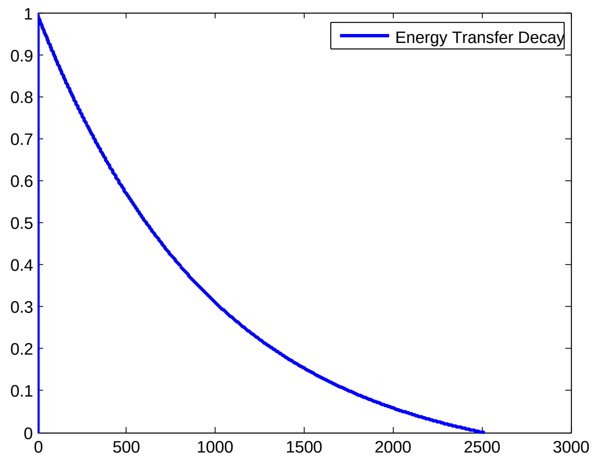

Figure 3.8: Waveform for kinetic energy transfer

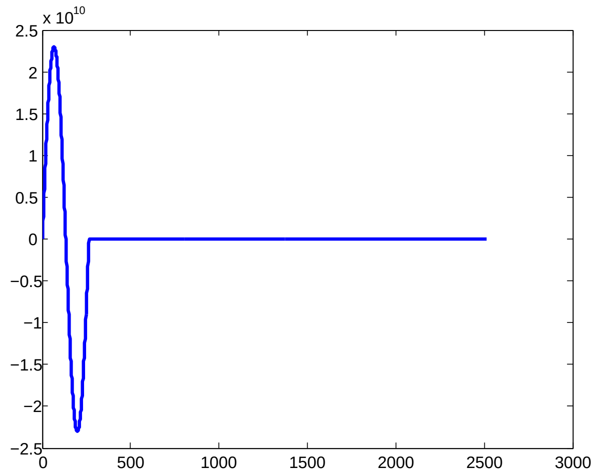

Figure 3.9: Initial transient waveform

3.3 Cracking Sound

Cracking sound or miniature sonic boom of the supersonic projectile's bypassing sound as explained, is in fact an N-wave profile with very short time period and very high amplitudes. Shock waves resulting from supersonic travels can only be estimated accurately and physically by solving a Navier- Stokes equation series which has well defined boundary conditions and accurately placed assumptions regarding to mass, and local speed changes, making it extremely hard to calculate during run time or acceptable speeds for fast iteration required in design and production phases.

Thus for fast estimations cracking sound solution is presented as a simplistic N-wave profile generation. But for future expansion and detailing on the matter of sonic boom generation a possible solution of sonic boom estimation is suggested. Such an estimation is presented in [**4**] et al. In his work a series of formulas and assistance for programming with handheld calculators is presented. A three step approach is used for sonic boom amplitude and time duration estimations

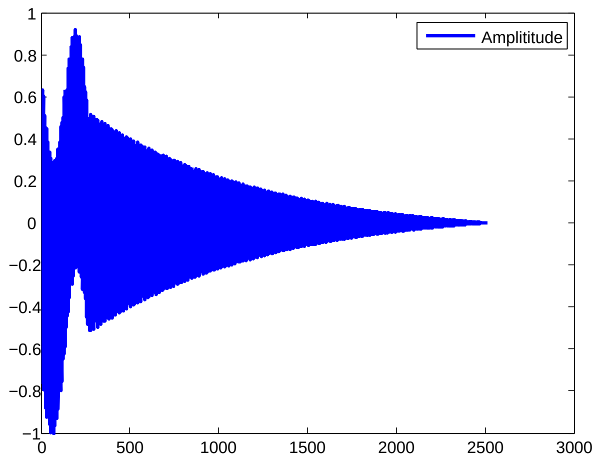

Figure 3.10: Final impact sound waveform

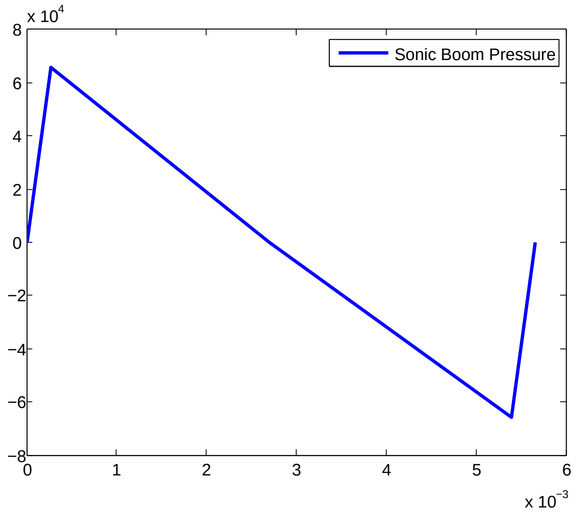

Figure 3.11: A simplified N-Wave shock profile

- Determining aircraft shape factor K_S

If given aircraft's shape factor is calculated and presented by the charts supported by [**4**] then mentioned exact values must be taken. If not given as suggested curve fitting on present data and below calculations must be held.

$$K_S = 0.685\frac{\sqrt{A_{e,max}}}{l^{\frac{3}{4}}l_e^{\frac{1}{4}}} \tag{2.7}$$

- Determining propagation parameters M_e, h_e and atmospheric factors K_P, K_T

$$M_e = \frac{1}{sin(\gamma + cot^(-1)\sqrt{M^2-1})} \tag{2.8}$$

$$d_x = K_d(\frac{h}{\sqrt{M_e^2-1}}) \tag{2.9}$$

$$h_e = hcos\gamma + d_x sin\gamma \tag{2.10}$$

- Final calculation of bow sock over pressure ΔP_{max} and signature time duration Δt

$$\Delta P_{max} = K_P K_R \sqrt{P_v P_g}(M^2 - 1)^{\frac{1}{8}} h_e^{-\frac{3}{4}} l^{\frac{3}{4}} K_S \tag{2.11}$$

$$\Delta t = K_t \frac{3.42}{a_v} \frac{M}{(M^2-1)^{\frac{3}{8}}} h_e^{\frac{1}{4}} l^{\frac{3}{4}} K_S \tag{2.12}$$

where;

K_P is pressure amplification factor

K_R is reflection factor which is assumed to be 2.0

K_d is ray path distance factor

K_t is signature duration factor

K_S is aircraft shape factor

$A_{e,max}$ is maximum effective area in m^2

h_e is effective aircraft altitude in km

l is aircraft fuselage length

l_e is effective aircraft length which coincides with $A_(e, max)$

a_v is speed of sound at aircraft altitude

M is Mach number

h is altitude of aircraft

P_v is atmospheric pressure at aircraft altitude in Pa

P_g is atmospheric pressure at ground level in Pa

γ is flight path angle

d is distance between aircraft ground track position at the time of sonic boom generation in km

d_x is component of d in aircraft ground track

It must be kept in mind that the given values are for relatively very large geometrical shapes of aircraft and thus new effective areas, lengths must be pre calculated and compiled into process-easy data blocks that would be fed into required real time applications.

To modify the formula according to a firearm munition sized projectile the coefficients must be taken from provided tables in [**4**] and measurements such as effective maximum area, length and height must be considered for conditions of a firearm near ground level.

When tables provided are checked below it can be seen that factors of K_P, K_t, K_d are dependent on altitude and velocity and can be approximately taken as 1 for near ground level. K_R is the reflection factor and is taken as 2. P_v and P_g, atmospheric pressure at altitude and ground level for a firearm projectile travelling just above the ground (1.5 meters) can be thought as equal to each other and ground level atmospheric pressure of 101 kPa. Effective projectile altitude, h_e, is projected in kilometers and dependent on γ the flight path angle. Since we presume the projectile to be parallel to ground that gives 0 for flight path angle and in Equation 2.10 h_e effectively equals to h which is 1.5 meters above the ground and is 0.0015 km.

Since we are using G1 ballistic model for our projectile it becomes clear that $A_{e,max}$ is the bottom of the projectile in x direction which has the greatest cross section area perpendicular to the flow. This also makes l_e equal to l, or total length of the projectile.

The shape factor K_S thus can be easily calculated when $A_{e,max}$ equals to bottom area of projectile which is a circle. Thus if x is considered to be bullet diameter;

$$K_S = 0.685\frac{\sqrt{\pi(\frac{x}{2})^2}}{l} \quad (2.13)$$

And as following;

$$\Delta P_{max} = 2(101)(M^2-1)^{\frac{1}{8}}0.0015^{-\frac{3}{4}}l^{\frac{3}{4}}K_S \quad (2.14)$$

$$\Delta t = \frac{3.42}{344}\frac{M}{(M^2-1)^{\frac{3}{8}}}0.0015^{\frac{1}{4}}l^{\frac{3}{4}}K_S \quad (2.15)$$

CHAPTER 4

RESULTS

This chapter details the results of the implementations of proposed methods mentioned in Chapter 3. The results are gathered under each regarding subject and results are listed specific requirements of that subject.

4.1 Muzzle Blast

Muzzle blast sound sample are synthesized from some key values that are predicted via a novel method and substituted in Equation 2.1, Equation 2.2 and Equation 2.3. Thus these values must be estimated values compared to real life counterparts.

Below is a table comparing estimated SPL levels of this study to values taken from (Free Hearing Test)[**8**] on rifle and handgun basis. The types of ammunition for comparison are chosen by their commonality in use of general firearms

Table 4.1: Real and estimated SPL levels of firearms

Rifles Rounds	Real Life SPL	Estimated SPL
.223 55gr in 18" Barrel	155.5 dB	154.9 dB
30-30 in 20" Barrel	156 dB	157.8 dB
.308 in 24" Barrel	156.2dB	156.2 dB
Handgun Rounds		
9x19 mm	159.8 dB	157.3 dB
Sig Sauer P226	157 dB	159.9 dB

Positive phase duration T_0 real values are taken from [**2**] in their estimations. They are compared with results acquired from Equation 2.3. The types of ammunition for comparison are chosen by their commonality in use of general firearms

Also synthesized and recorded sound files of the same firearm have been compared in their waveforms and their correlations has been calculated in 4 different firearms; two modern full automatic assault rifles (AK-47 and AR-15), a Second World War infantry rifle (SKS) and a modern pistol (PPQ Walther) The correlation coefficient is calculated as;

Table 4.2: Different firearms, their properties and calculated coefficients

Rifles Rounds	Real Positive Phase Duration	Estimated Positive Phase Duration
5.56x45 mm (M16)	0.42 ms	0.43 ms
30-0.6 in 564 mm Barrel	0.57 ms	0.52 ms
Handgun Rounds		
9x19 mm (P226)	0.24 ms	0.21 ms
9x29.5 mm (Model 60)	0.32 ms	0.31 ms

$\rho = \frac{cov(X,Y)}{\sigma_X \sigma_Y}$

ρ is a value between +1 and -1. A value closer to +1 indicates a perfect linear relationship while a value close to 0 means they are unrelated as mentioned in [**2**].

Table 4.3: Different firearms' correlation coefficients with their synthesized counterparts

Rifles Rounds	Correlation Coefficients
M16	0.9038
AK-47	0.8954
SKS	0.7286
PPQ Walther	0.6624

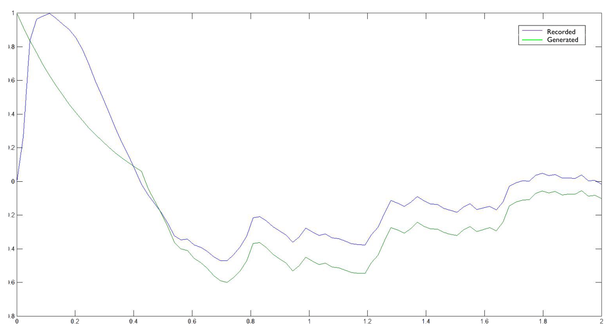

Figure 4.1: Waveform comparison of synthesized and recorded AK-47 rifles

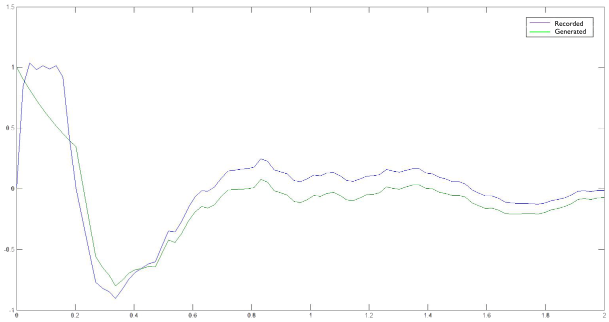

Figure 4.2: Waveform comparison of synthesized and recorded M16 rifles

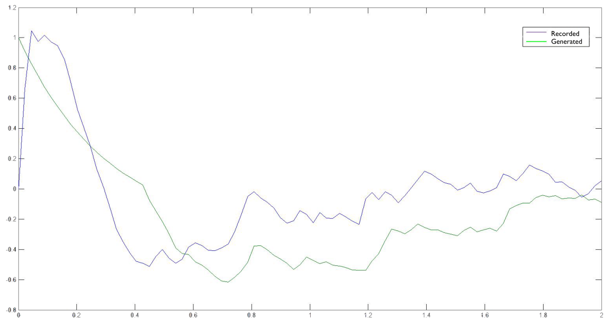

Figure 4.3: Waveform comparison of synthesized and recorded SKS rifles

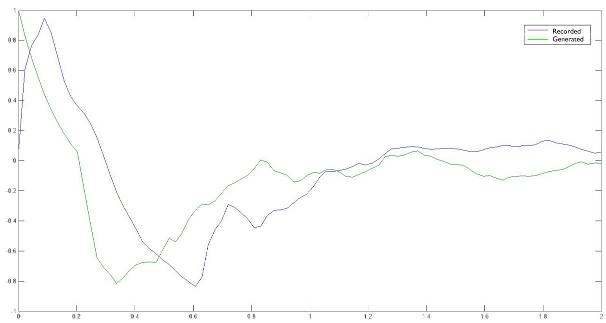

Figure 4.4: Waveform comparison of synthesized and recorded PPQ Walther andguns

Also an ABX type listening test has been conducted with listening subjects. ABX test being a double blind and true-or-false single choice tests in which test takers must make their choices between two different sound files played to them (A and B) and then listen a third sound file (X) and must decide which sound file it exactly is, whether A or B. The test conditions and measuring are described below.

- Test has been conducted with randomly selected test group, people beyond 18 and with a background of divert fields and interests.
- A high quality ASUS Orion Pro pro-gamer type headset has been used as a listening device.
- The test site has been carefully monitored for reducing outside noises.

- A total number 6 subjects has taken the test.
- Test included sound files of 6 pairs of different firearm types (two assault rifles, two pistols of different models, a bolt action rifle and a sniper rifle), each being one recorded and one generated.
- For each pair subjects have been given 15 repetitions. Within these repetitions subjects were free to listen the sound files as many times as possible. But their choices were final.
- The assumption is made on a binomial distribution basis. If the result of a test file can not achieve a confidence level beyond % 95 or their p-values are less than 0.05 than null hypothesis that sound files are discernable is invalid and there is no discernable differences between them.

Below is the table describing the test results. As can be seen for across all firearms classes neither % 95 confidence value nor 0.05 p-values is reached and for pistols (PPQ Walther and M1911) it became even harder for test subjects to discern the recorded and generated audio.

For sniper and older era bolt-action rifle (SKS and Savage) although distribution of data was different similar percent correct was achieved this is mostly due to very similar actuation method of the firing mechanism and very similar ammunition used on both rifles (7.62 x 39 and 7.6 2x 35).

For assault rifle class (AK-47 and M16) we see a discrepancy of percent correct. Just like sniper and bolt-action rifle mentioned above completely different firing mechanisims(Ljungman system vs Gas Blowback mechanism) and munitions used (5.56 x 45 vs 7.62 x 39) was the root cause of this. It is also worth mentioning that both firearms are completely built from different materials and have very different body geometries that also should have contributed to that result.

Table 4.4: Test results of ABX listening test

Firearms	Percent Correct	Confidence Level	p-value
AK-47	% 76	11 (< % 95)	$p < 0.05$
M16	% 66	10 (< % 95)	$p < 0.05$
PPQ Walther	% 53	8 (< % 95)	$p < 0.05$
M1911	% 54	8 (< % 95)	$p < 0.05$
SKS	% 72	10 (< % 95)	$p < 0.05$
Savage Model 10	% 72	10 (< % 95)	$p < 0.05$

4.2 Cracking Sound

Firearm projectiles travelling at supersonic speeds construct a miniature sonic boom which has a signature of N-wave. These waveforms when recorded properly with care given to recording microphone's dynamic range are extremely short in duration, almost representing an impulse. Most of what is heard are reflections from environmental surfaces. The peak overpressure values of small projectiles are much lower than of aircraft's and usually lower than muzzle blast peak values.

For constructing an N-wave two values need to be known, peak overpressure value and time duration. Both of these values can be approximately obtained by Equation 2.13, Equation 2.14 and Equation 2.15.

For example peak overpressure and signature time duration for a 7.62x51 mm munition travelling at 790 m/s which has a total length of 25 mm core length has been calculated. The values are converted from meters to kilometers and from millimeters to meters to preserve unit nature of the equation.

For 7.62x51 mm NATO munition with 25 mm core length at 790 m/s velocity (2.3 Mach number at 344 m/s speed of sound) 1.5 meters above the ground;

$K_S = 0.685\frac{\sqrt{\pi(\frac{x}{2})^2}}{l})0.185$

$\Delta P_{max} = 2(101)(M^2 - 1)^{\frac{1}{8}}0.0015^{-\frac{3}{4}}l^{\frac{3}{4}}K_S = 353Pa$

$\Delta t = \frac{3.42}{344}\frac{M}{(M^2-1)^{\frac{3}{8}}}0.0015^{\frac{1}{4}}l^{\frac{3}{4}}K_S = 0.003ms$

Since no direct clear data is available for comparison between munitions regarding to their cracking sound properties this data can be compared to example data in [**4**] of SR-71 reconnaissance jet, travelling at Mach 1.99 at 14.48 km altitude for coherence sake. For SR-71 at 14.48 km at Mach 1.99;

$K_S = 0.087$

$\Delta P_{max} = 74Pa$

$\Delta t = 0.17seconds$

As can be seen the longer length of the SR-71 (25 meters for effective length) give a much longer signature duration while lower Mach number and altitude causes lower peak overpressure. The firearm projectile although offering much higher peak overpressure that are closer to muzzle blast values (around 1000 Pa) much shorter signature duration as expected.

CHAPTER 5

CONCLUSION AND FUTURE WORK

The aim of this study is to develop a novel generalized base audio synthesis algorithm that is light enough to be implemented in runtime or fast iteration applications and also which could have distinct implementations to synthesise audio signals pertaining to gunshots from several different calibre and types of firearms, shock waves created by passing by of projectiles fired from these weapons, and impacts of these projectiles on various material types. We have described the related past studies and research made on the matter and also explained the state of the art at production of gunshot sounds and their methods. We have also detailed the disadvantages of this methods being too effort intensive, requiring high expert level knowledge on many different areas and simply being unavailable to independent developers. We showed our proposed method in detail and showed the results we have achieved. Our contribution includes two novel methods for synthesising muzzle blast sounds and impact sound of materials and an modification of an existing algorithm planned for a different purpose into real time and different scoped purposes with a parametric approach that allows many different implementations on many different digital platforms and can be utilised for different digital media purposes.

5.1 Future Work

For each different part of the study we highly recommend;

- • For cracking sound, constructing a very light weight Navier- Stokes energy conservation equation with correct boundary conditions in a simplified form for allowing fast processing speed in real time applications or furthering the study presented here with improving coefficients of equations 2.13, 2.14 and 2.15 allowing for much higher accuracy.
- • For muzzle blast, supporting the algorithm further via additional firearm characteristic noise libraries extracted from appropriate sources then parameterisation of these characteristics with geometric shape, construction material and inner workings thus fully representing the common firearm spectrum.
- • For muzzle blast, supporting the algorithm further via additional firearm characteristic noise libraries extracted from appropriate sources then parameterisa-

tion of these characteristics with geometric shape, construction material and inner workings thus fully representing the common firearm spectrum.

REFERENCES

[1] *Acoustical Surfaces Inc. [Online]* http://www.acousticalsurfaces.com/acoustic_IOI/101_13.htm.

[2] Beck, Steven D. , Hirotaka, Nakasone. Kenneth, W. Marr *Variations In Recorded Acustic Gunshot Waveforms Generated By Small Firearms.*,2011.

[3] Bhat, R. B. *NATURAL FREQUENCIES OF RECTANGULAR PLATES*,Journal of Sound and Vibration,2011.

[4] Carlson, H. W. *Simplified Sonic-Boom Prediction*,1978.

[5] Dewey, M. C., Dewey, J. M. *THE PHYSICAL PROPERTIES OF THE BLAST WAVE PRODUCED BY A STOICHIOMETRIC PROPANE/OXYGEN EXPLOSION*,Bourges,France,2012.

[6] Djordjevic, Z. *The Free Firearm Sound Library. [Online]* http://theaudiospotlight.com/free-firearm-sound-library/.

[7] Dobashi, Y., Yamamoto, T., Nishita, T. *Real-time Rendering of Aerodynamic Sound Using Sound Textures Based on Computational Fluid Dynamics.*,2014.

[8] *Free Hearing Test. [Online]* http://www.freehearingtest.com/hia_gunfirenoise.shtml.

[9] *Become A Sniper. [Online]* http://becomeasniper.com/wp-content/uploads/2013/08/Fmj-Bullet.jpg,2015

[10] *JBM Ballistics. [Online]* http://www.jbmballistics.com/ballistics/calculators/calculators.shtml

[11] *NASA. [Online]* http://history.nasa.gov/SP-60/ch-5.htmll

[12] *Aerospace Web. [Online]* http://www.aerospaceweb.org/question/aerodynamics/q0074.shtml

[13] *Kestrel Meters. [Online]* http://kestrelmeters.com/pages/g1-g7-ballistic-coefficients-what-s-the-difference

[14] Luz, G. A. *DATA BASE FOR ASSESSING THE ANNOYANCE OF THE NOISE OF SMALL ARMS*,Aberdeen: UNITED STATES ARMY ENVIRONMENTAL HYGIENE AGENCY.

[15] *M60 Bullet Recording [Online]* https://www.youtube.com/watch?v=uBlZh5vsnjw,2012, June 27

[16] Maher, R. C. *Acoustical Characterization of Gunshots.*,SAFE,2007

[17] Maher, R. C. *Modeling and Signal Processing of Acoustic Gunshot Recordings.*,IEEE Signal Processing Society 12th DSP Workshop. Jackson Lake, SAFE,2006

[18] MAHER, R. C., SHAW, S. R. *DIRECTIONAL ASPECTS OF FORENSIC GUNSHOT RECORDINGS.*,AES 39th International Conference. Hillerød, Denmark,2010

[19] McCoy, R. *Modern Exterior Ballistics.*

[20] Nicholas, T. *M60 Bullet Recording [Online]* `http://www.jeremytackett.com/ntackett/ballistics.html`

[21] ESA *Essential Facts About The Computer And Video Game Industry.*, NPD,2014

[22] Pater, L. L. *Gun Blast For Field Overpressure.*,Dahlgren: Naval Surface Weapons Center,1981

[23] Pouladkhan, A. R., Emadi, J., Safamehr, M., Habibolahiyan, H. *The Vibration of Thin Plates by using Modal Analysis*,World Academy of Science, Engineering and Technology,2011

[24] van den Doel, K., Kry, P. G., Pai, D. K. *Physically-based Sound Effects for Interactive Simulation and Animation*,SIGGRAPH, 2001

APPENDIX A

PERMIT FROM UEAM

UYGULAMALI ETİK ARAŞTIRMA MERKEZİ
APPLIED ETHICS RESEARCH CENTER

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

DUMLUPINAR BULVARI 06800
ÇANKAYA ANKARA/TURKEY
T: +90 312 210 22 91
F: +90 312 210 79 59
ueam@metu.edu.tr
www.ueam.metu.edu.tr

Sayı: 28620816/350

28 EYLÜL 2015

Gönderilen: Doç.Dr. Hüseyin HACIHABİBOĞLU

Modelleme ve Simülasyon EABD

Enformatik Enstitüsü

Gönderen: Prof. Dr. Canan SÜMER

İnsan Araştırmaları Komisyonu Başkanı

İlgi: Etik Onayı

Danışmanlığını yapmış olduğunuz Game Technologies/Informatics Institute Bölümü Yüksek Lisans öğrencisi Teksin SAKA'nın "ABX Dinleme Testi" isimli araştırması İnsan Araştırmaları Komisyonu tarafından uygun görülerek gerekli onay 11.08.2015 -31.09.2016 tarihleri arasında geçerli olmak üzere verilmiştir.

Bilgilerinize saygılarımla sunarım.

Prof. Dr. Canan SÜMER

Uygulamalı Etik Araştırma Merkezi

İnsan Araştırmaları Komisyonu Başkanı