NATURAL SOUNDS

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ABSTRACT

Natural sounds, as one of the most important resources of nature, have attracted attention from many researchers. Although, psychological approaches, acoustical approaches and psychoacoustical approaches have been employed on the research of natural sounds, not many analytical investigations have been conducted on specific natural sounds except for the biological natural sounds.

The aim of this study is to present the properties and reveal the generation mechanisms of the selected natural sounds.

This thesis concentrated on studying the characteristics of various specific natural sounds by acoustical approach. Field recording has been mainly adopted for the collection of sound samples. For the selected samples, computational analyses were conducted to investigate the attributes of the sounds. Sound signatures including waveform, frequency spectrum and sonogram were displayed to visualize the analyzed signals. The generation mechanisms were reviewed and discussed to reveal the variables that contribute to the sound characteristics.

Sound samples including cavity wind sound, aeolian sound, wind sound through vegetation, thunder clap, thunder rumble, thunder crack, plunging breaker sound, spilling breaker sound, rock wave sound, boiling mud pot sound, geyser eruption sound, fumaroles eruption sound and different bubble sounds were selected and analyzed to reveal their properties.

TABLE OF CONTENTS

ABSTRACT .... *i*

TABLE OF CONTENTS .... *ii*

LIST OF FIGURES .... *vi*

LIST OF TABLES .... *x*

ACKNOWLEDGEMENT .... *xi*

1 INTRODUCTION *1*

1.1 Natural Sounds **1**

1.1.1 Natural versus man made sounds 1

1.1.2 Natural sound as a whole concept 2

1.1.3 Specific natural sound research 4

1.1.4 Classification of natural sounds 4

1.2 Methods **7**

1.2.1 Theoretical approaches 7

1.2.2 Methods in the thesis 8

1.3 Scope and Structure **13**

1.4 References **15**

2 WIND SOUNDS *17*

2.1 Introduction **17**

2.1.1 Wind sounds 17

2.1.2 Wind formation' ... 18

2.2 Wind Sounds Generation Mechanism ... 21

2.2.1 Helmholtz resonance ... 21

2.2.2 Aeolian tones ... 28

2.3 Analysis of Wind Sounds ... 33

2.3.1 The cave wind sound ... 33

2.3.2 Aeolian sounds ... 36

2.3.3 Wind sounds through vegetation ... 40

2.4 References ... 47

3 THUNDER SOUNDS ... 49

3.1 Introduction ... 49

3.1.1 Overview ... 49

3.1.2 Lightning and thunder ... 49

3.1.3 Shock wave ... 56

3.2 Thunder Sounds Analysis ... 59

3.2.1 Thunder clap ... 59

3.2.2 Thunder rumble ... 61

3.2.3 Thunder cracks ... 63

3.3 References ... 65

4 SEA WAVE SOUND IN THE SURF ZONE ... 67

4.1 Introduction ... 67

4.1.1 Sea wave ... 68

4.1.2 Breakers 70

4.2 Wave Sound Generation Mechanism 76

4.2.1 Wave energy 76

4.2.2 Sound source mechanisms 78

4.3 Wave Sound Analysis 82

4.3.1 Process 82

4.3.2 Results and discussion 82

4.4 References 91

5 GEOTHERMAL SOUNDS 95

5.1 Introduction 95

5.1.1 Geothermal 95

5.1.2 Geothermal sounds 102

5.2 Boiling Experiment 108

5.3 Geothermal Sounds Analysis 113

5.3.1 Boiling mud pot sound 113

5.3.2 Eruption field sounds 116

5.4 References 118

6 BUBBLE ACOUSTICS 121

6.1 Introduction 121

6.1.1 The two types of natural bubbles 122

6.2 Bubble Sound Mechanisms 126

6.3 Bubble Sound Analyses 129

6.3.1 Single bubble sound 129

6.3.2 Release of underwater bubble 135

6.3.3 Rain sounds 138

6.4 References 141

LIST OF FIGURES

Figure 1.1: Waveform, frequency spectrum and spectrogram displays 12
Figure 1.2: Circular chart illustrating the scope and ramifications of acoustics 13
Figure 2.1: Wind hitting an electric wire 18
Figure 2.2: Formation of wind as a result of localized temperature and pressure differences 19
Figure 2.3: Helmholtz resonance 22
Figure 2.4: Idealized Helmholtz resonance 22
Figure 2.5: The waveform of Helmholtz resonance experiment 25
Figure 2.6: The enlargement of the signal waveform 25
Figure 2.7: The sound spectrum of the entire signal 25
Figure 2.8: The sound spectrum of the flask resonance in dying away stage 26
Figure 2.9: Configuration of the experiment 27
Figure 2.10: Cavity pressure level and corresponding frequency versus wind speed U^0. 28
Figure 2.11: Flow around a cylinder 28
Figure 2.12: Schematic drawing of experimental setup 30
Figure 2.13: Mean velocity vector map 30
Figure 2.14: Examples of instantanous vector map 31
Figure 2.15: Time-averaged sound intensity distribution 31
Figure 2.16: Waveform of cave wind sound 34
Figure 2.17: Frequency analysis of cave wind sound 34
Figure 2.18: Waveform, Sonogram and Frequency analysis of the aeolian sound produced by 1mm line 37
Figure 2.19: Waveform, Sonogram and Frequency analysis of the aeolian sound produced by 2mm line 38
Figure 2.20: Waveform, Sonogram and Frequency analysis of the aeolian sound produced by 3mm line 39

Figure 2.21: Waveform, Sonogram and Frequency analysis of wind sound through a pine tree 41
Figure 2.22: Waveform, Sonogram and Frequency analysis of wind sound through aspen tree 43
Figure 2.23: Waveform, Sonogram and Frequency analysis of wind sound through bush 45
Figure 3.1: Building up electrical charges 51
Figure 3.2: Parameters of shock wave 57
Figure 3.3: Waveform of the thunder claps 60
Figure 3.4: Sonogram of the thunder claps 60
Figure 3.5: The sound spectrum analysis of the clap signal 60
Figure 3.6: Waveform of thunder rumble 62
Figure 3.7: Sonogram of thunder rumble signal 62
Figure 3.8: Sound spectrum analysis of the thunder rumble signal 62
Figure 3.9: Waveform of sharp thunder cracks 64
Figure 3.10: Sonogram of sharp thunder cracks 64
Figure 3.11: Spectrum analysis of sharp thunder cracks 64
Figure 4.1: Characteristics of waves formed by different forces 68
Figure 4.2: Idealized ocean wave diagram 69
Figure 4.3: Waves entering shallow water 71
Figure 4.4: Typical spilling breakers at Kapiti Beach New Zealand 73
Figure 4.5: Predominating plunging breakers and occasional spilling breakers in Happy Valley Beach New Zealand 73
Figure 4.6: The type of the breaker depends on the slope of the bottom and the steepness of waves offshore 74
Figure 4.7: Three types of breaker 75
Figure 4.8: Motion of a water particle in a wave 77
Figure 4.9: Logarithmic timeline of bubble plume evolution 80
Figure 4.10: High speed video images of a breaking wave acoustically active phase 81

Figure 4.11 Waves at Happy Valley Beach New Zealand 83
Figure 4.12: Sonogram of sea wave sound 85
Figure 4.13: Signature of plunging surf sound 85
Figure 4.14: Signature of spilling surf sound 85
Figure 4.15: Spectrum analysis of the entire process (1), the plunging breaker (2) and the spilling breaker (3) 86
Figure 4.16: Waveform, spectrum analysis and sonogram of the sound generated by a sea wave clapping on the rock 89
Figure 4.17: Enlargement of the impact signal 90
Figure 4.18: Enlargement of the splashing signal 90
Figure 5.1: Illustration of a geothermal reservoir 96
Figure 5.2: Photograph of geyser 97
Figure 5.3: A fumarole's sound being measured by sound level metre 99
Figure 5.4: Photograph of a mud pot 99
Figure 5.5: The Ring of Fire 100
Figure 5.6: Geothermal field in New Zealand 101
Figure 5.7: Water vaporization 102
Figure 5.8: Schematic diagram of the flow issuing from a circular nozzle in still air 104
Figure 5.9: Relative over-all pressure in the near field of a model air jet as a function of the axial distance 106
Figure 5.10: Comparisons of noise and frequencies as a function of exit velocity for a model jet 106
Figure 5.11: Sound level waveform of the boiling process 108
Figure 5.12: Spectrum analysis of five selected points 110
Figure 5.13: Waveform and sonogram of mud bubble collapse 114
Figure 5.14: Whole process spectrum analysis of mud bubble collapse sound 114
Figure 5.15: Spectrum analysis of mud bubble collapse sound at 0.6 second 114
Figure 5.16: Waveform of water bubble collapse sound 115
Figure 5.17: Spectrum analysis of water bubble collapse sound 115
Figure 5.18: Waveform of geyser eruption sound 116

Figure 5.19: Spectrum analysis of geyser eruption sound 116
Figure 5.20: Waveform of steam vent sound 117
Figure 5.21: Spectrum analysis of steam vent sound 117
Figure 6.1: The evolution progression of a drop bubble 123
Figure 6.2: Waveform of single drops into water 129
Figure 6.3: The enlargement of the tenth drop of water signal 130
Figure 6.4: The enlargement of the fifth drop of water signal 130
Figure 6.5 Sonogram of single drops into water 130
Figure 6.6: The enlarged sonogram of the fifth drop 131
Figure 6.7: The enlarged sonogram of the tenth drop 131
Figure 6.8: Frequency analysis covered the entire process 133
Figure 6.9: Frequency analyses of the two adjacent signals by the fifth drop 133
Figure 6.10: Waveform of one quick releasing underwater bubble 135
Figure 6.11: Sonogram of one quick releasing underwater bubble 135
Figure 6.12: Frequency analysis of the releasing bubble sound along time history 137

LIST OF TABLES

Table 1.1: Natural sound classification 6

Table 2.1: Classification of thunder sounds 56

Table 6.1: Liquid density 124

Table 6.2: Raindrop bubble acoustics 137

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1 INTRODUCTION

1.1 Natural Sounds

Technically, Harris (1998) defined sound as a physical disturbance in a medium (i.e., in a gas, liquid, or solid) that is capable of being detected by human ears.[1] The frequency of human hearable sound ranges from 20 hertz to 20k hertz. However, for other creatures in nature, it can be expanded to a much greater extent. An elephant may hear a loud infrasonic sound with a frequency of 5 hertz; similarly, very high pitched ultrasonic sound can be heard by bats, but not human beings, and if the sound is loud enough, it could cause damage or pain even though not being heard.[2] Thus, more acceptably, sound is generated as long as when a body moves back and forth rapidly enough to send a causing wave through the medium in which it is vibrating. Since the earth is never still, it is full of sounds, both man made sounds and natural sounds.

1.1.1 Natural sounds versus man made sounds

Man-made sounds are the sounds that related to people or peoples' activities. Man caused sounds are not just the sounds that people themselves produce, such as talking, but also the many varied sounds that attend the presence of people such as automobiles, aircrafts, radios, and pets. Human beings communicate with each other and explore the world by giving off and receiving sound signals. A baby's crying tells mum it is now hungry; a police siren tells the pedestrians the policemen are on their duty; a short-long whistle tells the audiences the soccer game is over. In the process of exploiting petroleum reservoirs, seismic survey has been widely used by receiving and analyzing the reflective properties of sound waves to various rock strata.[3]

Natural sounds, on the other hand, are the sounds that absent the intrusion of sounds caused by human beings and human technology. These natural sounds include the sounds produced by wild animals, the sounds associated with the natural phenomena such as wind blowing, water running, earthquake, thunder clapping, rain falling and wave surfing, etc. Many animals rely on sounds for communication, navigation or detection of predators and prey. An utterance from a wild baby bird expresses the need of food to its mother; the loudness of a thunder indicates the magnitude of the coming rain; the intensity of the waterfall sound shows how much potential energy it contains.

Ways that natural sounds express themselves are of great diversity. Taking animals as examples: they use a multitude of different mechanisms to produce sounds. Mammals use two thin folds in the larynx (vocal chords) to produce sounds. Small muscles control the tension on the vocal chords and thus the timing and pitch of the sounds. The cavities in the throat, mouth, and nose sometimes resonate and thus modify the nature of the sounds issuing from the animal's mouth. Birds produce their songs by means of a special organ (the syrinx) that consists of two (or in some species four) thin membranes in the wall of the bronchi or low trachea. Frogs have a larynx with vocal chords, although the structures are not homologous with those of mammals. Crickets scrape a series of bumps (a comb) on one wing against a thickened ridge (a file) on the other. [4, 5]

1.1.2 Natural sound as a whole concept

Natural sounds usually do not come alone. Bernie depicted that in undisturbed natural environments, natural sounds are very much like instruments in an orchestra.[6] On land, in particular, this delicate acoustic fabric is almost as well defined as the notes on a page of music. [6] Abundant previous research take natural sounds as an integral concept, which means that the various natural sounds existing in a certain area are all considered as contributors to the soundscape. For instance, when talking about the forest soundscape, it means the combination of the natural sounds that are produced by wind through the trees, leaves falling from the branches, rushing water nearby, voice of the animals and so on.

The following definitions were widely used when treat natural sound as a whole concept.[7] They are:

Natural ambient sound

Natural ambient sound includes the intermittent sounds of wind, water, and animals.

Natural soundscape

A natural soundscape is an area characterized by certain ambient acoustical and sound level qualities, excluding the intrusion of sounds caused by human beings or human technology.

Natural quiet

Natural quiet is defined as natural ambient sound plus the self-noise generated by visitors in non-mechanized activities.

One of the most important resources of the natural world is its voice or in other words, the natural soundscape.[6] Research show that the unthreatening natural environments can have significant stress-reducing effects for many people. However, it is not sure if these effects are due to hearing the sounds of nature or to a combination of hearing and seeing nature. A variety of natural sounds are nowadays used in sound therapy industries and natural sound therapy is found to be extremely beneficial in almost all stress related problems.[8] It can be helpful for:

- Easier, more effective sleep.
- Regaining vitality and a sense of well being.
- Obliteration of tiredness.
- Deep relaxation, relief from anxiety and consequent healing of stress-related disorders such as high blood pressure, hypertension, digestive problems.

1.1.3 Specific natural sound research

Every natural sound has its unique characteristics. Studies have shown the importance and applications of specific natural sound analysis. By measuring oceanic and land rain and by listening to it, it is theoretically possible to forecast weather and climate. "This is because the formation of a raindrop in the air is accompanied by latent heat release. This heat release is one of the primary sources of energy driving atmospheric circulation." [9] Recognizing individual farm animals and their conditions by analyzing the sounds they make, is a possible way to improve animal welfare, animal health and farm efficiency. For example: A project of analysis of mosquito wing beat sound led to the identification of the species of mosquitoes that caused disabling diseases to a traveling army, and this also led to the design of the mosquito sound trap.[10]

1.1.4 Classification of natural sounds

Natural sounds are countless and ways of classifying these natural sounds are various.

The most natural way is to categorize the natural sound based on the generation mechanism. However, it is often difficult to draw a distinct line between the mechanisms of every natural sound. For instance, the generation mechanism of the raindrop sound onto a water surface depends on the drop size. Different sizes of raindrops produce dramatically different sounds as they hit water, which is primarily because that some sizes of drops generate bubbles while others do not. Animals also employ a multitude of mechanisms to produce their unique sounds. The vocal organs that they use are very different from each other. On the other hand, some apparently different sounds originate from similar mechanisms. For instance, the wave sound in the surf zone, the stream water sound and the waterfall sound all involve with bubbles. All these factors make an accurate classification method by generation mechanism impracticable.

Natural sounds can also be classified by the object that makes the sounds. Wind sounds, water sounds and animal sounds are three possible sub-categories. While many natural sounds are in fact due to the interaction of more than one object. There are rock sounds, there are water sounds, and there are sounds made by water crashing over rocks or pouring over rocks, or by rock splashing into water. Wind sounds can be generated by wind passing through trees or wind blowing across a cavity.

However, for the convenience of organizing the natural sounds, this thesis combined the aforementioned two classifying methods and the categories of natural sounds are listed in Table 1.1.

Table 1.1: Natural sounds classification

Natural Sounds	Animal Sounds	Insects Sounds	
		Bird Sounds	
		Mammal sounds	
	Weather Sounds	Rain sounds	Rain on the ground ·Rain on the water
		Wind sounds	·Wind blowing across cavity ·Wind through vegetation ·Wind through thin cylinder
		Thunder sounds	·Thunder clap ·Thunder ramble ·Thunder crack
	Water related Sounds	Sea wave sounds	·Plunging breaker wave sound ·Surging breaker wave sound ·Rock wave sound
		River and stream sounds	River sounds Stream sounds Waterfall sounds
		Boiling sound	·Boiling water sound
	Physical phenomenal sounds	Geothermal sounds	·Boiling mud sound ·Steam eruption sound ·Geyser eruption sound
		Fire sounds	
		Singing sand sound	

The sounds followed by · have been sampled, analyzed and discussed in this thesis.

1.2 Methods

Previous studies about natural sounds were conducted under two different circumstances. One was to assess the effects of natural sounds on human beings or animals; the other was to scientifically analyze and identify the properties of natural sounds. For both conditions, a number of approaches were adopted.

1.2.1 Theoretical Approaches

1) Psychological approach

The psychological research approach is to investigate people's evaluations to sounds. This approach is often used nowadays to evaluate the human intrusions on natural sounds. Anderson, et al (1983) argued that the basic assumption of this approach is that people differ in how they perceive their environment, and that this difference affects the way people judge the desirability of sounds.[11] The psychological approach treats actual sounds as only one factor affecting noise evaluations and another key factor is the expectations that people have for noise in various settings.[12] A social survey is the main method for the psychological research approach to investigate people's reactions to sounds.

2) Acoustical approach

The second approach is based on sound metrics. These metrics are independent of human perceptions.[12] The metrics of the sound here are the properties of sound that are measured directly by equipment or indicated by indirectly methods such as computational processes. In contrast to the psychological approach, the acoustical method does not use a survey to measure people's reaction to sound. Instead, sound recording and analyzing instruments are employed to indicate the characteristics of the sound.

3) Psychoacoustical approach

This approach combines elements of both the psychological and acoustical methods. In other words, psychoacoustical studies consider both human reactions to the sound and the independently measured sound metrics.

1.2.2 Methods in the Thesis

The acoustical approach is adopted in this thesis to study the characteristics of selected natural sounds, such as wave sounds, wind sounds and geothermal sounds.

1.2.2.1 The Process

Although the generation mechanisms of natural sound are various, the routines of decoding these ciphers are relatively common. Recording, measuring and analyzing the relevant sound signals are necessary for all the selected sound samples.

1) Recording

Field recording is the first step in studying natural sounds. It is the main source of sound signal samples in this thesis. Recording method, equipment and the condition of equipment affect the accuracy and quality of the recording results. Hence, certain techniques are required under different conditions.

<u>Recording equipment</u>

The equipment used in the field was a CR: 831A Sound Level Meter with MK: 224 pre-polarized Free-field ½" Condenser microphone capsule on it. The sound level meter provides an AC output socket that could be connected to SONY MZ-R700 MiniDisc through a ZL: 802 2m to 3.5mm Stereo Jack output cable.

2) Other sources of natural sounds

Some sound signals used in this thesis were obtained from CD-ROM retrieved from Massey University and Wellington City Libraries. A few signals were obtained from the World Wide Web. The original resources are shown in each case.

3) Analysis

Analyzing can be done after choosing the satisfying sound signal samples from the recorded sound archives. Firstly, the sound samples were transferred into a computer and converted into appropriate wave forms such as .rm, .wav, .mp3 or .au according to application circumstances. Secondly, for different natural sounds, different sound parameters were used according to the analyzing requirement. For instance, for the waterfall sound, the absolute value of sound levels are crucial to indicate the potential energy, while for the animal vocalization, the temporal and spectral pattern of the signals, not the absolute value is more important. Finally, the appropriate diagram is displayed, and the in-depth analysis done.

4) Display

Animals and human beings respond to both the temporal and spectral structure of sounds. A sound signal can be described by some important sound attributes including temporal properties such as duration, repetition, and sequencing of sound elements, as well as spectral properties such as frequency, bandwidth, harmonic structure, and noisiness. Temporal properties can be measured from the amplitude-time waveform, which specifies acoustic pressure as a function of time, and the amplitude envelope, which specifies time-averaged acoustic intensity as a function of time. Spectral properties can be derived from the power spectrum, which specifies energy distribution as a function of frequency, and the frequency-time spectrogram, which specifies energy distribution as a function of both frequency and time.[13]

Under different circumstances, the following displays were used in this thesis to visualize the characteristics of selected sound signal samples.

1. ***Waveform***: a graph of amplitude over time. (See graph 1 in Figure 1.1)

A waveform is analogous to an oscillogram obtained from an oscilloscope. It is the simplest, most direct translation of sound into a picture. Each of the other two graphs is calculated from the waveform, not acquired independently from a recording.

Information that can be obtained from waveform:

- Duration of a signal
- Repetition rate of the signal
- Changes in amplitude over time

2. ***Frequency spectrum***: a graph of amplitude by frequency. (See graph 2 in Figure 1.1)

It describes how much energy is contained in each frequency band of a signal, averaged over a specified time interval. In the following analyses, unless otherwise stated, the signal analyzed is that at greatest amplitude.

Information that can be obtained from frequency spectrum:

- Frequency composition of a signal
- Dominant frequency of noise signals
- Carrier frequencies, harmonics, and beat frequencies

3. ***Spectrogram*** *or* ***sonogram***: a graph of frequency by time. (See graph 3 in Figure 1.1)

Information that can be obtained from spectrograms:

- Temporal changes in frequency
- Subtle differences in signals not apparent from other graphs
- The deepness of the color in the frequency-time spectrogram indicates the energy distribution. The bar chart alongside the spectrogram below, shows the relationship between the deepness of the color and the intensity of the sound, (Graph 4 in Figure 1.1) and applies to all the following figures.

On the abscissa of the graphs, the term "hms" refers to the time in seconds.

On the ordinate of the graphs representing amplitude, the scale in deciBels is the level down from the maximum amplitude recorded.

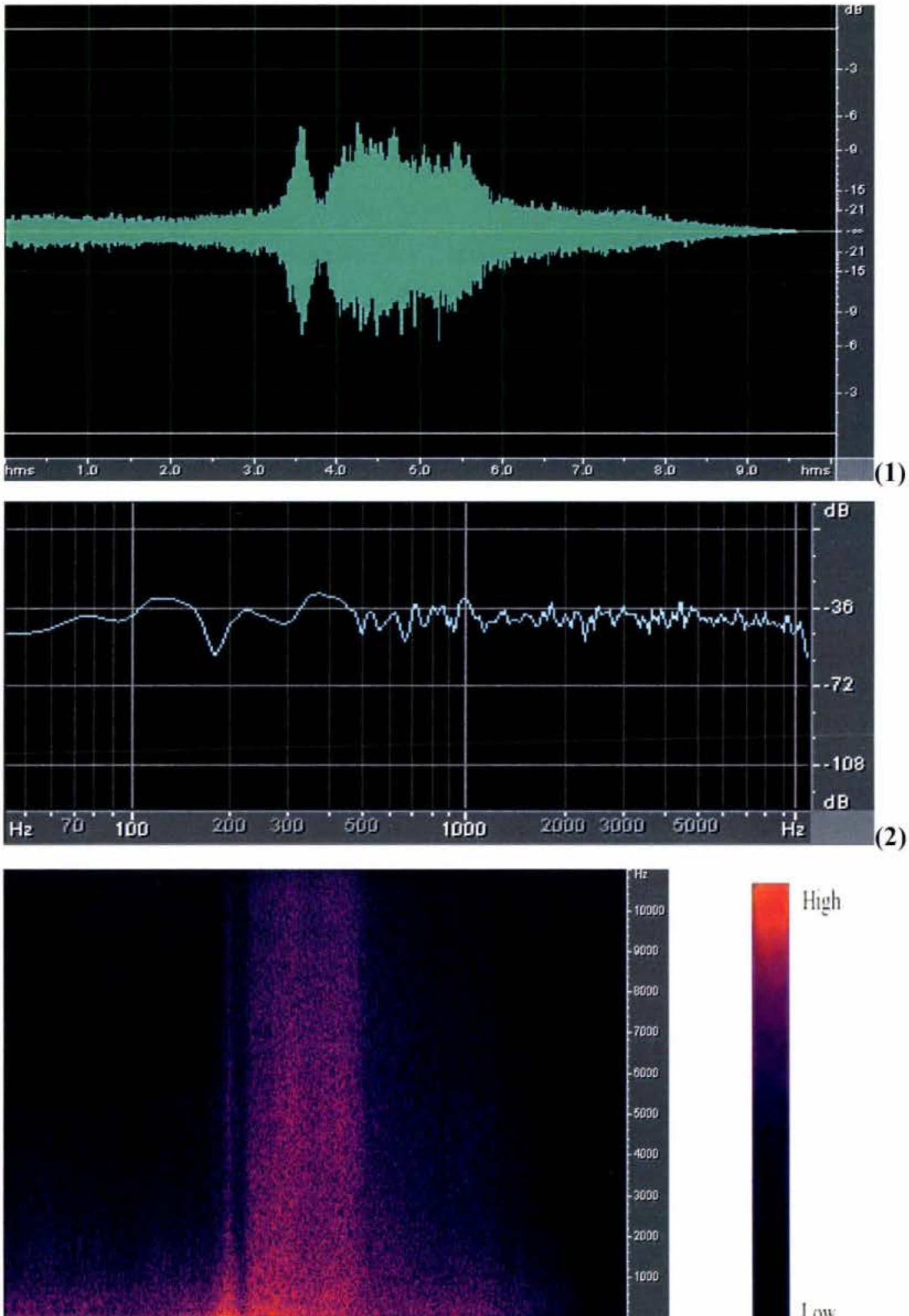

Figure 1.1: Waveform, frequency spectrum and spectrogram displays

1.3 Scope and Structure

The circular chart shown in Figure 1.2 illustrates the scope and ramification of acoustics. Acoustics is an area interrelated with earth sciences, engineering, arts and life sciences, while natural sound is mainly related to oceanography, physics of earth and atmosphere, physiology and so on. It is impossible to enumerate all kinds of natural sounds; therefore some representative natural sounds are selected in this thesis according to the classification in Table 1.1.

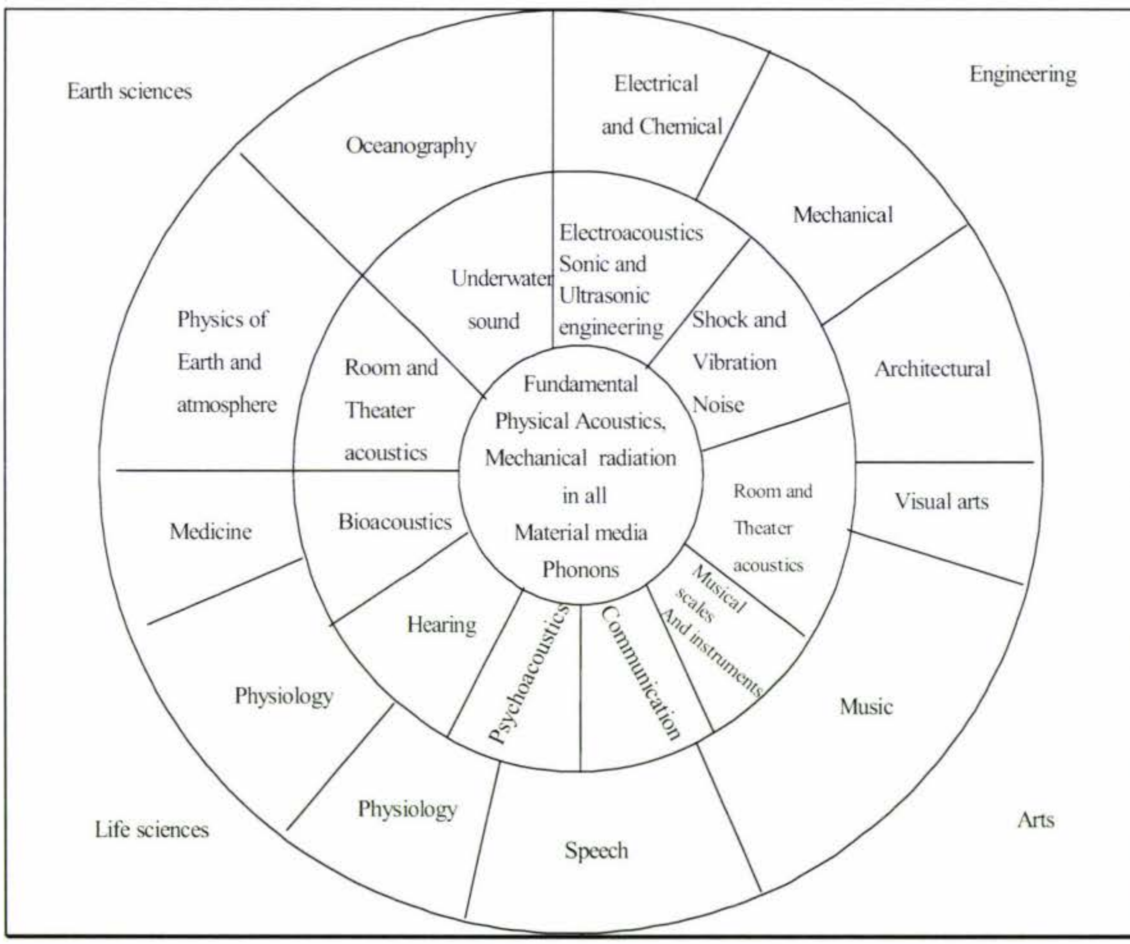

Figure 1.2: Circular chart illustrating the scope and ramifications of acoustics [14]

Chapter two introduces wind caused sounds mainly by two mechanisms,Helmholtz resonance and aeolian pitch, and discusses the parameters that have effects on the wind caused sounds. Cave wind sound, vegetation wind sounds and different diameter line wind sounds were taken as samples and analyzed to reveal the characteristics of wind sounds.

Chapter three focuses on the shock wave, which is the mechanism of thunder sound. Samples of three kinds of most frequently heard thunder - thunder clap, thunder ramble and thunder cracks - were taken and analyzed to be compared and contrasted.

Chapter four introduces three types of breaking waves that most exist and discusses the generation mechanisms of the wave sounds in the surf zone. Spilling and plunging breakers were analyzed and compared. Beach wave sound and rock wave sound were also analyzed and compared for seeking the differences.

Chapter five introduces geothermal activities and the sound occurring in geothermal areas. Different sound generation mechanisms, such as boiling, jet and cavitations are mentioned. Mud boiling sound, steam eruption sound and geyser eruption sound were analyzed to depict the characteristics of geothermal sounds.

Chapter six introduces bubble sounds in depth and some bubble related sounds are analyzed.

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2 WIND SOUNDS

2.1 Introduction

2.1.1 Wind Sound

When wind blows, it passes through or over various obstructions. In the process of passing these obstructions, a disturbance is created in the air that leads to the generation of pressure variations. These variations lead to longitudinal waves, which, if in the audible frequency range, would be heard.

Wind usually cannot make any sound itself, but it can be heard very frequently both in our daily life and in nature. Woodwind instruments are the most common applications of wind sound. For example, blowing onto a sharp edge causing air enclosed in a tube to vibrate produces the sound of a flute.

In nature, there are several ways in which wind makes itself heard.

1. Trees and other vegetation provide a natural outdoor instrument. As branches and leaves shake, they cause vibrations in the surrounding air. The faster the object moves, the higher will be the pitch that is heard. The willow has been likened to a flute, the pine to a violin. In this thesis, the wind sound through pine trees, aspen trees and bush were recorded, analyzed and discussed. As a matter of fact, this kind of sound produced by wind consists of two parts. One is the sound generated by the vibrating air as a result of shaking branches and leaves. The other is the impact sound of branches and leaves, which makes the distinctness between them opaque.

2. A low pitch results when large open objects resonate, which is like air blowing across a jug. These effects sometimes make whistling, whirring, or moaning sounds that consist of many frequencies. When wind (a jet of air) blows across the opening, a

difference in pressure is created between inside and outside (Wind lowers pressure by pushing air out of the way). This difference in air pressure makes the empty space resonate. This resonance is occurring because outside wind moves in and out of the space. As some air comes into the enclosure, it is pushed back out by the higher pressure inside. This repeating event causes a standing wave. The resonance creates sounds. The analysis of the cave wind sound in this thesis indicated the characteristics of this kind of wind sounds.

3. High pitch sound arises when narrow objects cause changing eddy current of air. Figure 2.1 illustrates the sound generation process. Once it hits the object, the wind splits apart and forms swirls of air behind the object and the swirls of air makes the generation of pressure variation, which produces sound. Three samples of wind sound through different size lines were selected, recorded and analyzed in this thesis to investigate the properties of this kind of sounds.

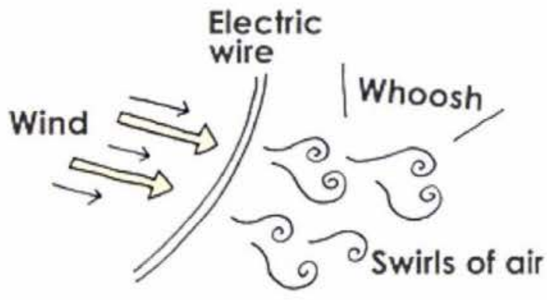


Figure 2.1: Wind hitting an electric wire [1]

2.1.2 Wind Formation [2, 3]

Wind may happen in several different forms. It can be a burst coming out of a thunderstorm's downdraft. It can be a light southerly breeze in the summer. Wind comes in all of its various forms due to many different imbalances in the atmosphere.

In a thunderstorm triggered by a cold front, the winds involved are caused directly by heat and moisture imbalances. Heat ahead of the cold front causes moist air to rise from the surface of the earth. As the air rises, eventually the environment will cool to a point where the moisture in the rising air equals the moisture capacity that the environment can sustain. This is the point where condensation takes place. As the condensation continues, a cloud will form. As more heated air containing ample moisture rises, the cloud builds to a thunderstorm cell. The rising air makes an updraft building the cloud to the point of temperature inversion. As the air reaches the top of the thunderstorm, all moisture is condensed out and the rising air cools beyond the surrounding environment's temperature. At this point the rising air begins to sink. Much of this cool air begins to sink so there is a downdraft in the mature thunderstorm. The downdraft is typically at the front of the storm pushing ahead of the thunderstorm to cause a gust front. On the backside of the storm, the updraft pulls in the air behind the storm up and into the cloud. This updraft is where one can commonly find a tornado drop out of. These updrafts and downdrafts can be quite severe considering that a mature thunderstorm can form in as little as 15 minutes. The same sort of process is true for convective thunderstorms.[4]

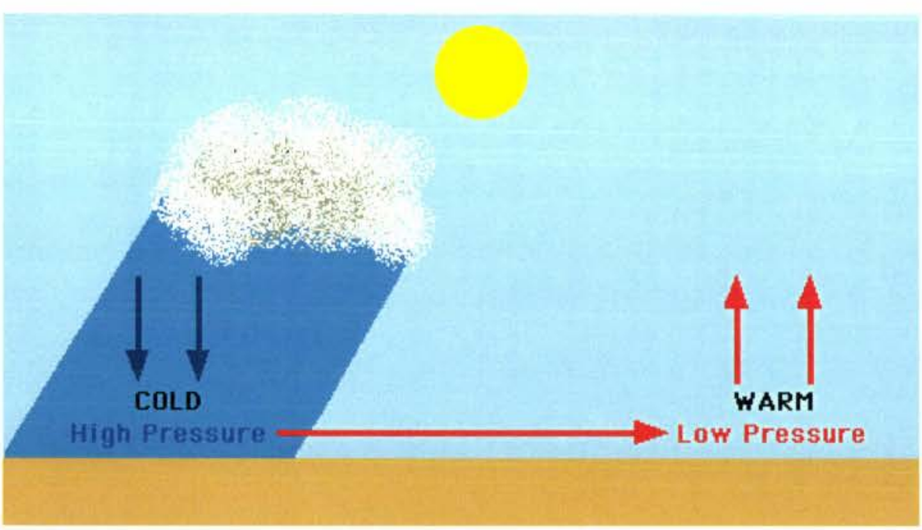


Figure 2.2: Formation of wind as a result of localized temperature and pressure differences [3]

A more subtle way that heat can influence the formation of wind is through localized temperature differences. This usually occurs simultaneously with pressure differences.

When underneath a dome of high pressure, the wind blows towards a location of lower pressure. As heat becomes a factor where a given high-pressure location is colder than a given low-pressure location, the wind will intensify to counteract the two imbalances.

As the earth is affected by varying heat energy from the sun, the state of the air is different in different regions. Warm air expands and rises up while cold air condenses and sinks, hence resulting the flow of air and forms wind. [3] The process is illustrated in Figure 2.2.

2.2 Wind Sounds Generation Mechanism

Cavity resonance sound and aeolian sound are the most frequently heard sounds generated by wind. They exist in both high speed and low speed situations. The noises due to aeronautics at high speed, such as airfoil slat, landing gear and openings, etc. are some of the major noise sources in aeroacoustics. For ground transportation at low Mach number, the automobile industry is concerned with the noises produced by the door gaps, the side mirror and the aerial. All these noises may be categorized as airframe noises that are generated by the interaction between the vortex streets in the turbulent wake or between the vortices and the solid body edges.[5]

Most theory deals with high-speed flow (supersonic, transonic or high subsonic flow) where the noise is generated by the fluid resonant oscillation mode. This will not take place in the study of wind where, due to the low speed or the low Mach number of the airflow, cavity resonance and turbulence from obstructions (aeolian sound) are the main mechanisms.

2.2.1 Helmholtz Resonance

Helmholtz Resonator

When wind blows across a cave opening, resonance occurs. Helmholtz (1954) conducted the research demonstrating the theory. [6] The scene can be idealized to a Helmholtz resonator or Helmholtz oscillator shown in the following Figure 2.3.

A Helmholtz resonator is a container of gas (usually air) with an open hole. A volume of air in and near the open hole vibrates because of the 'springiness' of the air inside.

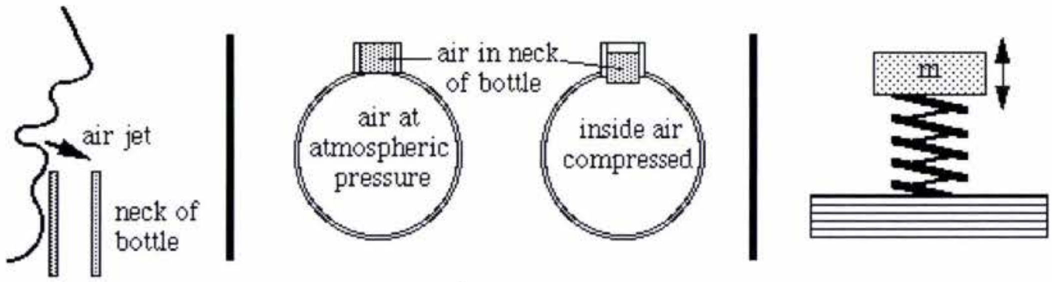


Figure 2.3: Helmholtz resonance [6]

When air jet blows across the neck of the bottle, the air in the bottle is compressed. Its pressure increases and it tends to expand back to its original volume. For the lump of air at the neck of the bottle, the air jet forces it a little way down the neck, thereby compressing the air inside. That pressure then drives the lump of air out, but when it gets to its original position; its momentum takes it on outside the body a small distance. This rarifies the air inside the body, which then sucks the lump of air back in. It can thus vibrate like a mass on a spring. The air jet is capable of deflecting alternately into the bottle and outside, and that provides the power to keep the oscillation going.

Resonance Frequency

The resonance frequency of the sound can be derived when the Helmholtz resonator is idealized to a bottle shown in Figure 2.4.

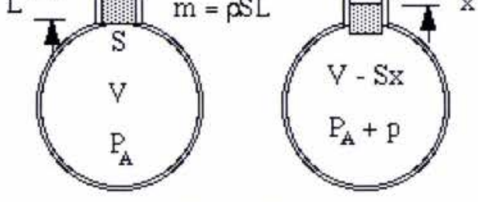


Figure 2.4: Idealized Helmholtz resonance [7]

For a typical bottle, the sound produced has a wavelength of few metres, so assumption that the wavelength of the sound produced is much longer than the dimensions of the resonator can be made. This assumption enables one to neglect the pressure variations inside the volume of the container, which means that the pressure oscillation will have the same phase everywhere inside the container.

Let the air in the neck have an effective length L and cross sectional area S, its mass is then SL times the density of air ρ. If the air in the neck of the bottle descends a small distance X into the bottle, it compresses the air in the container so that the air that previously occupied volume V now has volume V-SX. Consequently, the pressure of that air rises from atmospheric pressure P_A to a higher value $P_A + p$.

The vibrations that give rise to sound also cause the temperature of the air change, which gives a larger change in pressure. Technically they are adiabatic, meaning that heat has no time to move, and the resulting equation involves a constant γ, the ratio of specific heats. As a result, the pressure change p produced by a small volume change ΔV is

$$\frac{p}{P_A} = -\gamma \frac{\Delta V}{V} = -\gamma \frac{SX}{V}$$

The mass m is moved by the difference in pressure between the top and bottom of the neck. The force is pS.

According to Newton's law for acceleration a:

$F = ma$

Or $\quad \frac{d^2 X}{dt^2} = \frac{F}{m}$

Substituting for F and m gives:

$$\frac{d^2 X}{dt^2} = \frac{pS}{\rho SL} = -\frac{\gamma S P_A}{\rho VL} X$$

So the restoring force is proportional to the displacement. This is the condition for Simple Harmonic Motion, and it has a frequency which is 1/2 times the square root of the constant of proportionality, so

$$f = \frac{1}{2\pi}\sqrt{\frac{\gamma S P_A}{\rho V L}}$$

Since the speed c of sound in air is determined by the density, the pressure and ratio of specific heats, the formula can be written as:

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{VL}}$$

Natural Resonance Frequency Experiment

A simple experiment was conducted by blowing air flow across the opening of a flask and measuring the respective data. The flask in the experiment has a volume of 500ml, neck length about 8cm, neck inner diametre about 3cm. A microphone set up near the flask records the sound, which is shown in the oscillogram below.

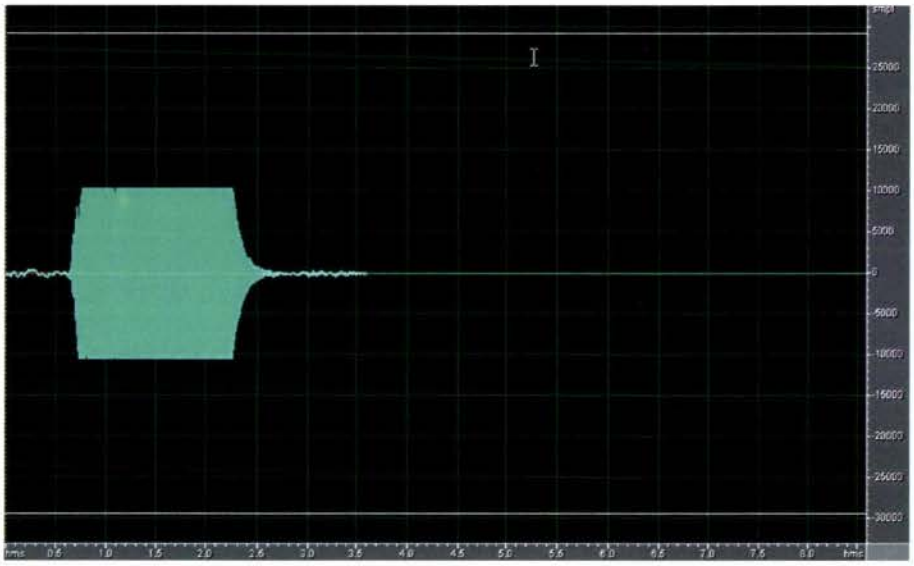


Figure 2.5: The waveform of Helmholtz resonance experiment

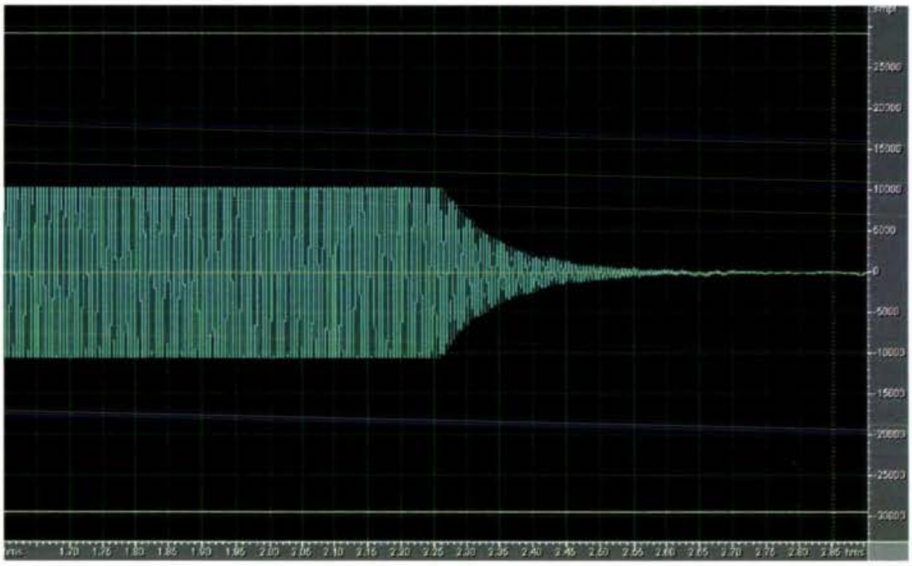


Figure 2.6: The enlargement of the signal waveform

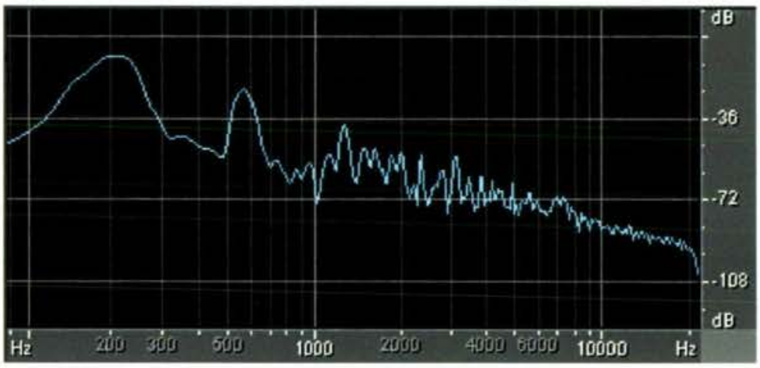


Figure 2.7: The sound spectrum of the entire signal

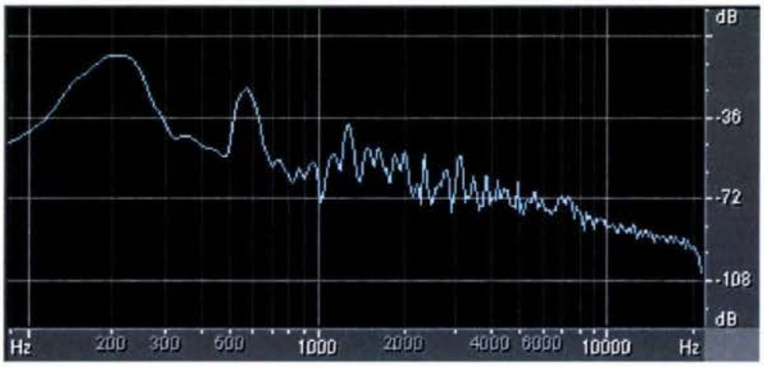


Figure 2.8: The sound spectrum of the flask resonance in dying away stage

From the above figures, we can see that the oscillation is established when air jet blows across the opening of the flask. At the end of the process, when the blow stops at time point of 2.27 second, the oscillation gradually dies away as it loses energy by means of heat and sound radiation. The following sound spectrum presented in Figure 2.7 shows that a single resonant frequency (Helmholtz resonance) dominates during the entire period, and it becomes weaker but still dominates during the die away period(See Figure 2.8). The dominant Helmholtz resonant frequency in this experiment is about 210 HZ, which is very close to the calculated frequency.

In practice, the Helmholtz resonance is widely used. It is important for enhancing the tone of guitars, violins, and other string instruments. They are the absorbing frequencies of cavity type "bass trap" in studios. Tunable Helmholtz resonator cavities are used in bass-reflex type loudspeakers to enhance acoustic power and bass response.[8]

Helmholtz resonance also has been considered in some architecture designs. It is found that the measurement techniques using Helmholtz resonance is applicable under micro- gravity conditions.[7]

Flow Velocity

The natural resonance frequency of a cavity is mainly dependent on its dimension and the edge characteristics. However, the wind velocity across the opening determines whether or not the resonant sound can be excited. An experiment by Amandolèse, Hémon and Regardin dealt with this problem.[9]

Figure 2.9 illustrates the experiment setup. The model of the cavity has been mounted in a rectangular wind tunnel which generates very low noise airflow. The pressure P_V in the cavity is measured by a microphone. The resonance frequency of this cavity was measured without wind by using an acoustic source providing a white noise in the test section. The response of the cavity gave a natural frequency of 263 Hz which is in relatively good agreement with the expected value using the classical theory of the Helmholtz resonator.

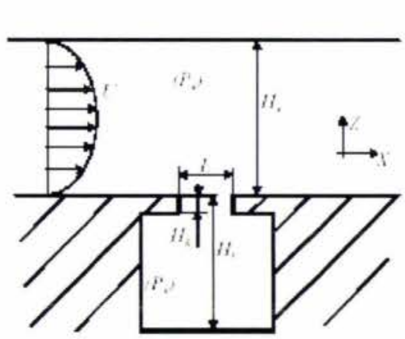


Figure 2.9: Configuration of the experiment

The measurement of the cavity pressure level and corresponding sound frequency was present in Figure2.10 as the first curve. The horizontal dashed line on the frequency curve is the frequency, which corresponds to the natural frequency of the cavity. By observing the measurement, we can see that at a certain velocity, a peak cavity pressure level appears. The results reveal that at velocity of about 16 m/s, the resonance sound is excited and the corresponding frequency is close to the natural resonant frequency of the cavity 263 Hz.

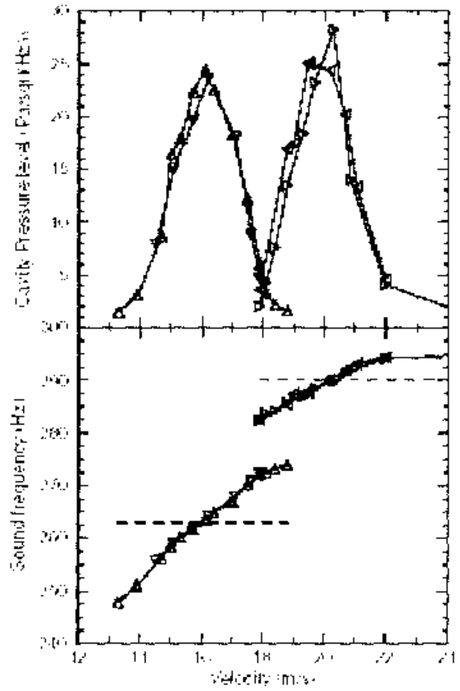


Figure 2.10: Cavity pressure level and corresponding frequency versus wind speed [9]

2.2.2 Aeolian Tones

Aeolian sound is another kind of sound that generated by wind blowing around thin objects. This is often heard when a stream of air passes through transmission power lines. In nature, it can be heard when wind blows around a relatively thin cylinder. Figure 2.11 shows a model of fluid flow around a cylindrical line.

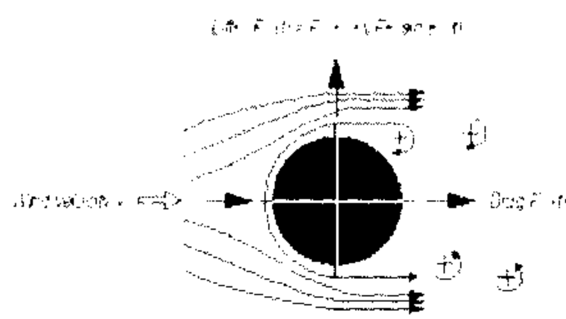


Figure 2.11: Flow around a cylinder [10]

When an airflow passes over a cylinder, a boundary layer, which is significantly affected by viscosity, exists on the surface of the cylinder. The fluid flow is separated from the surface of cylinder in a region, where pressure increases within the boundary layer, and a low pressure region is created just behind the cylinder, thus creating eddies downstream. [9]

Sound pressure waves are generated primarily by vortex shedding from the cylinder surface into its wake. When a vortex is shed from one side of the cylinder, a negative pressure pulse is generated from that side whereas a positive pressure pulse is generated from the other side. The two anti-direction pulses are illustrated in Figure 2.11 by signal "+" with opposite directions. Alterate vortex shedding from the upper and lower side of the cylinder produces negative and positive pulses alternately and thus produces sound pressure waves on both sides.[9]

The separation of fluid flow induces lift FL and drag FD on the cylinder. The aeolian sound generated from the cylinder is pressure noise related to FL.

The boundary layer flow on the surface is classified into laminar flow and turbulent flow depending on the surface roughness and flow velocity. And these two types of flow have opposite qualitative properties to each other. The laminar boundary layer flow on a smooth surface with less surface roughness has a wide range of pressure fluctuation at which separation of flow occurs, and the generated aeolian sound level increases on the other hand. When turbulence is enhanced by a rough surface, the point of flow separation moves rearward of the cylinder, and the region of varying separation point becomes narrow, so the aeolian noise level decreases.[10]

The turbulence distribution, especially in the boundary layer, is the determinative factor of the aeolian sound distribution and intensity. Sato and Kimura (2001) obtained the realtionship between turbulence structure and origin of sound through their combined measuring technique. They measured the sound characteristics and flow field characteristics in the experiment. [11]

The schematic drawing of experimental setup is shown in Figure 2.12.

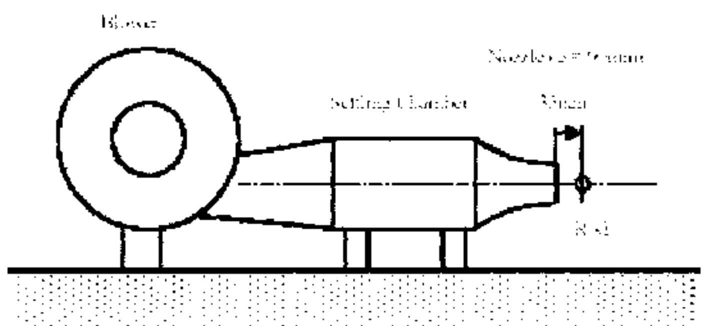


Figure 2.12: Schematic drawing of experimental setup

Airflow was made by a small wind tunnel with a 60mm diameter circular nozzle. The measurements were applied to the two types of circular rod, one 2mm in diameter and the other 6mm in diameter.

Mean velocity vector maps are shown in Figure 2.13

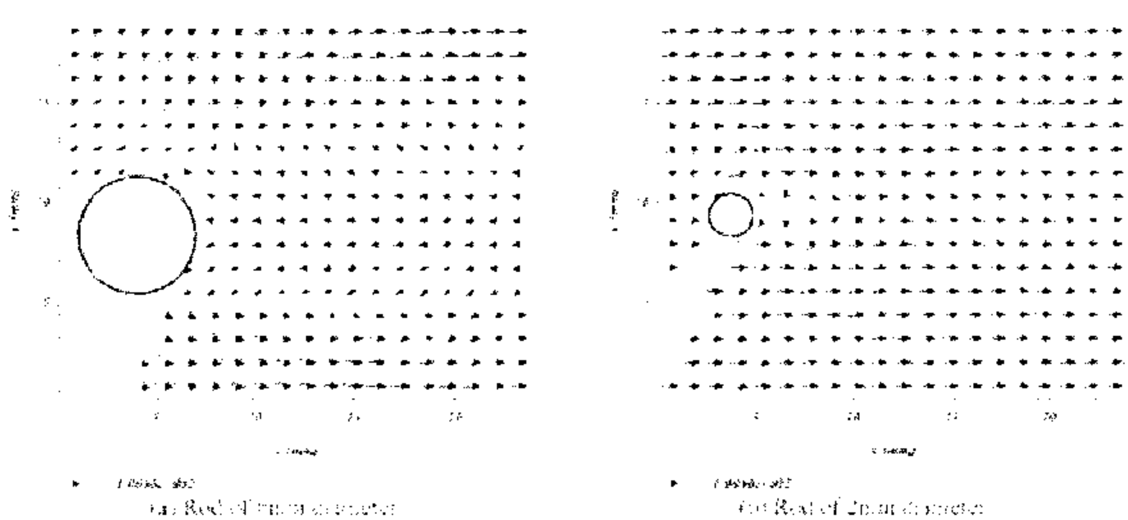
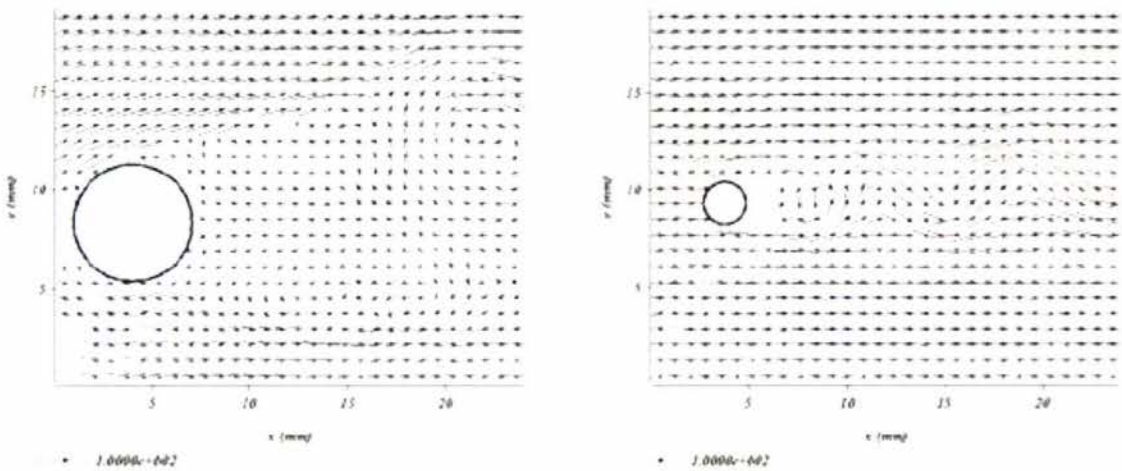


Figure 2.13: Mean velocity vector map

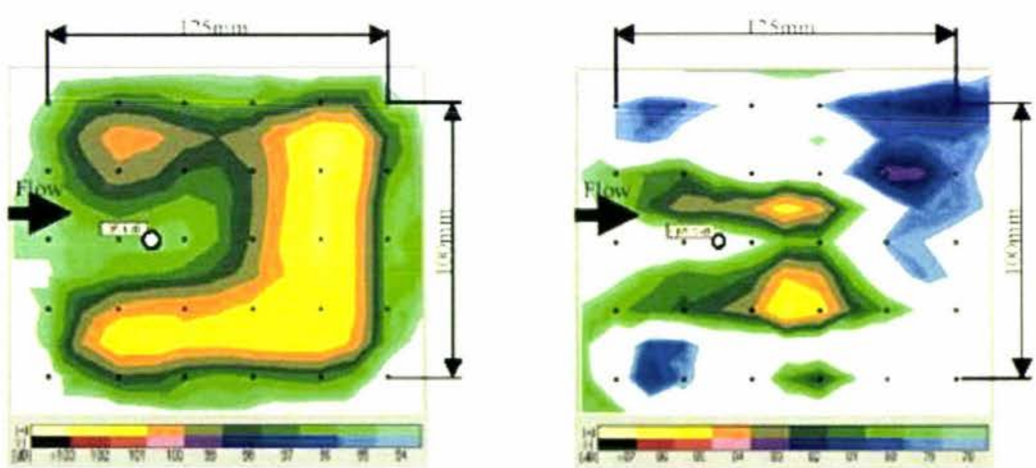
A large seperated flow region is observed behind a rod of 6mm diameter. However, a smaller wake region exists for the 2mm rod condition.



(a) Rod of 6mm diameter (b) Rod of 2mm diameter

Figure 2.14: Examples of instantanous vector map

The examples of instantaneous vector maps are shown in Figure 2.14. Various sizes of the vortexes can be seen in the flow behind a rod in 6mm diameter. On the other hand, well known Karman Vortexes are observed on the vector maps for the 2mm rod.



(a) Sound Intensity at the center of the rod for 5 kHz 1/3-octave band (6mm rod)

(b) Sound Intensity at the center of the rod for 5 kHz 1/3-octave band (2mm rod)

Figure 2.15: Time-averaged sound intensity distribution [11]

Figure 2.15 shows the time average sound intensity maps. The sound intensity distribution for the 6mm rod differs from that for the 2mm rod. In the 6mm rod case, larger values are observed in the downstream region and spread wider. However, in the 2mm rod case, the symmetrical two peak distributions are seen in the near rod region. Also, spread of the sound intensity of the 2mm rod is relatively smaller than that of the 6mm rod. The results of the sound measurements show that the map of sound intensity is of similar pattern to that of vorticity.

With these results, correlations are seen with vorticity and the sound intensity. The sound generated by the flow around a cylinder has also been quatitatively studied by some researchers. Strouhal (1878) experimentally found that the frequency f of the sound radiated from a cylinder of diameter D is related to the velocity U of a uniform flow as $fD/U = const$. The constant is now known as the Strouhal number, St.[12] and is 0.20-0.22 for the Reynolds number range from $300 \leq Re \leq 10^4$. Rayleigh (1896) recognized that the production of the sound is connected with the instability of the vortex sheets in the cylinder wake.[13] It is now known that the frequency f of the sound is the same as the shedding frequency of vortices from the cylinder into its wake.[14]

2.3 Analysis of Wind Sounds

2.3.1 The Cave Wind Sound

In the natural environment, Helmholtz resonance exists in various situations as long as a closed air column and an opening exist. The dimensions of the container may range from very small like a seashell to very large like a mountain cave, thus the Helmholtz resonant frequencies differ greatly.

When wind blows across a cave opening, a difference in pressure is created between inside and outside of the cave, which causes the air in the cave to oscillate and make low frequency sound.

Figure 2.16 shows the waveform of a 3 minutes sound signal produced by the wind blowing across a mountain cave. The sound recording was obtained from the internet and no details were given of the size of the cave nor where the microphone was placed.

The waveform appears very different from the waveform of the flask wind sound (Figure 2.5). The flask resonance shows a constant sound power peak value during the resonance process, while the cave sound power value varies with time. The differences are believed to come from several aspects:

1. The assumption made for a Helmholtz resonator is not applicable for caves. The dimensions of the mountain cave are much bigger than the idealized Helmholtz resonator, which makes the pressures of the inner air vary with the position inside the cave. In other words, P_A and $P_A + p$ are not the constant values that one would expect in this process.

2. The air jet blowing across the flask is relatively constant, while the cave wind direction and wind intensity are changing during the time history.

3. The material of the inner wall at each situation is different. For the flask, glass almost reflects the sound completely, while the cave, with porous wall, will absorb the sound signal to a large extent.

4. The shape of the inner wall for each situation is different.

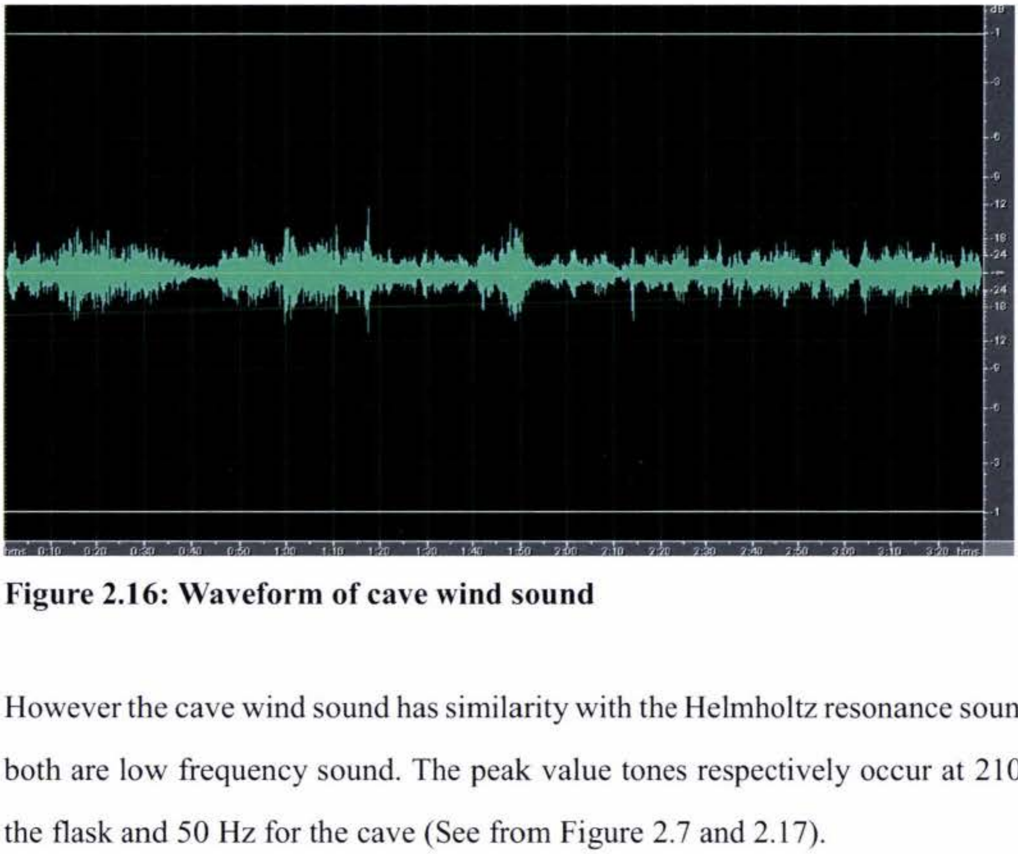


Figure 2.16: Waveform of cave wind sound

However the cave wind sound has similarity with the Helmholtz resonance sound. They both are low frequency sound. The peak value tones respectively occur at 210 Hz for the flask and 50 Hz for the cave (See from Figure 2.7 and 2.17).

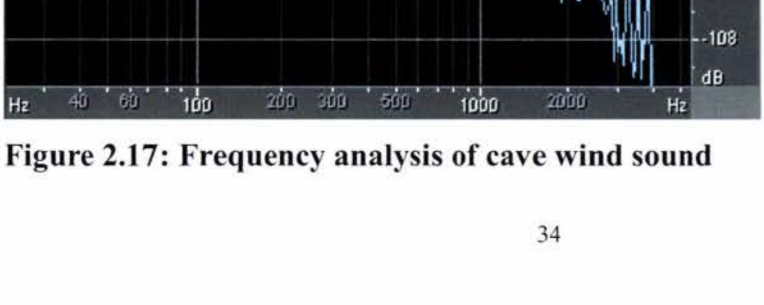


Figure 2.17: Frequency analysis of cave wind sound

The frequency analysis of the cave sound signal shows more characteristics:

1. The high intensity focuses in a very narrow frequency band below 100Hz. While compared to the flask, the band is relatively wider.

2. The peak intensity part is smoother when compared to the flask Helmholtz resonant sound.

3. In the high frequency area, the intensity of cave wind sound undulates in a large range with the increase of the frequency, while the flask sound gradually decreases with the increase of the frequency.

2.3.2 Aeolian Sounds

Three aeolian sound samples were selected from the Internet. The signals were generated by wind passing through kite lines, which can represent most situations of aeolian sound. From listening to the recording, the background sounds clearly were very low and would not affect the analyses.

The signals produced by three different sizes of diameter kite lines are shown respectively in Figures 2.18, Figure 2.19 and Figure 2.20. Figure 2.18 shows the waveform, sonogram and the frequency analysis of aeolian sound generated by polyester braided line of a diameter 1mm. Figure 2.19 and Figure 2.20 show the signals of 2mm and 3mm lines. The wind speed was not constant during the processes and the tension of the lines varies, which were indicated by the changing tones of the three signals.

Sonograms of the three Aeolian sounds display characteristics of low frequency sound. The dominant frequencies of the three signals are significant and locate below 750 Hz. Several harmonics appear in all signals, which can be seen clearly in sonograms and frequency analysis graphs.

The dominant frequency for the Aeolian sound of wind blowing through 1mm line is 690 Hz. The value for 2mm and 3mm lines are respectively 400 and 410 Hz. The result approximately reflects that the frequency f of the Aeolian sound is inversely proportional to the diameter of the cylinder D the air passes around.

The dominant frequency bands in the three conditions differ from each other. The 1mm line shows a relatively wider dominant frequency distribution than the 2mm and 3mm lines.

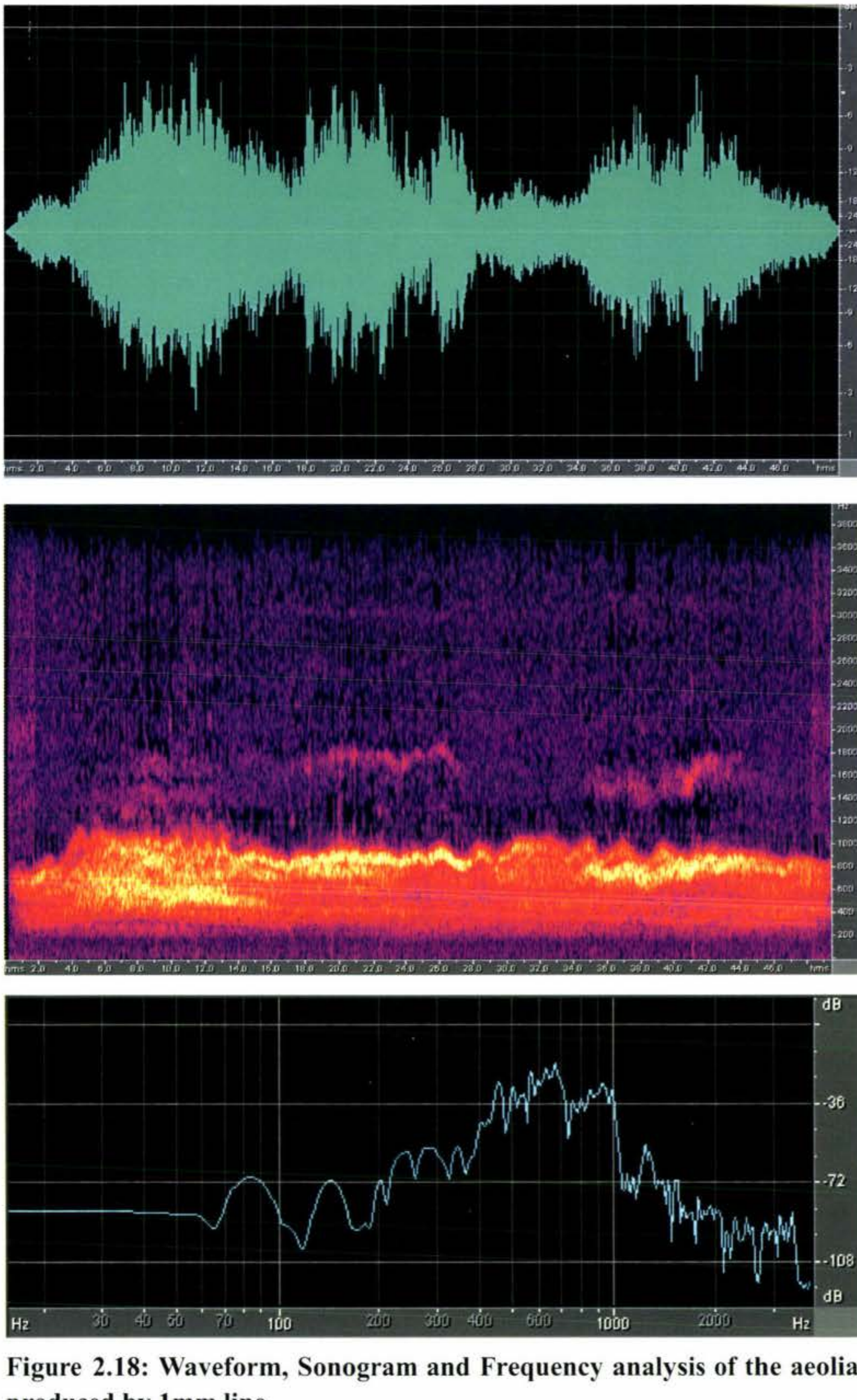


Figure 2.18: Waveform, Sonogram and Frequency analysis of the aeolian sound produced by 1mm line

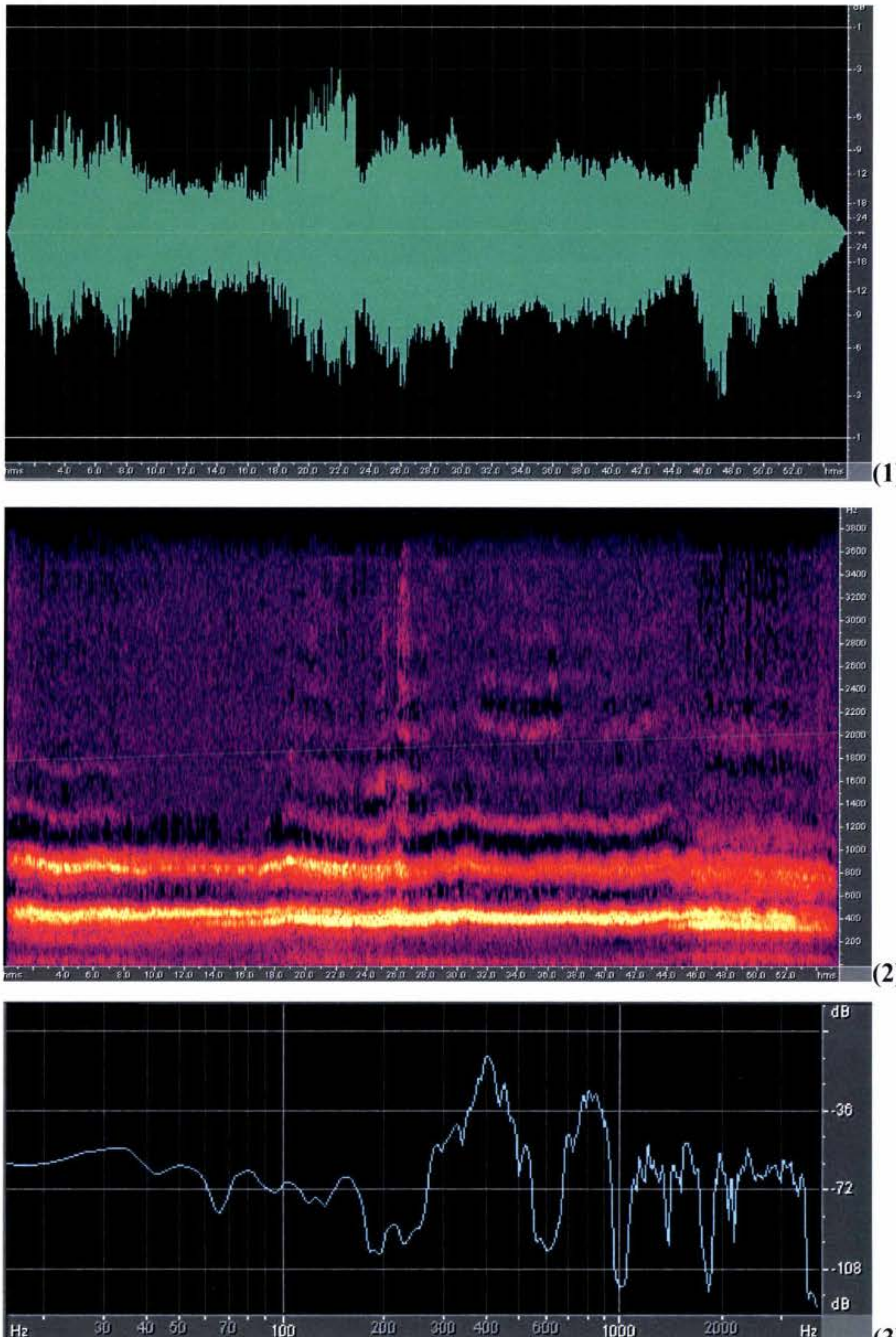


Figure 2.19: Waveform, Sonogram and Frequency analysis of the aeolian sound produced by 2mm line

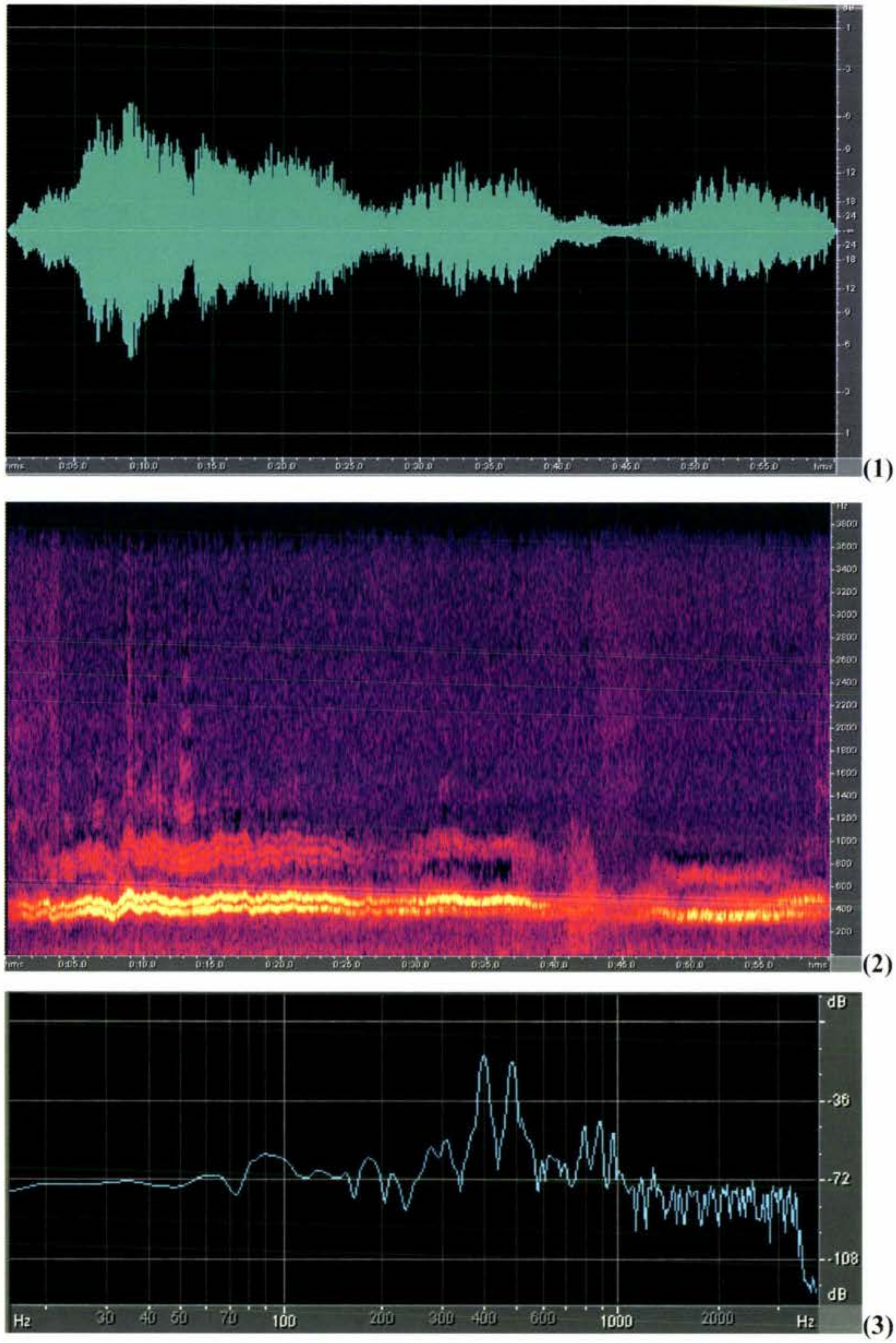


Figure 2.20: Waveform, Sonogram and Frequency analysis of the aeolian sound produced by 3mm line

2.3.3 Wind Sound through vegetation

Wind sounds through vegetation are the most common sounds produced by wind. Many factors contribute to these sounds. Aeolian sound is produced when wind passing through needle shaped leaves and thin branches, which could be the dominant factor in pine tree wind sound. Falling leaves hitting and rolling along the ground will create sounds. Higher wind blows tree stems and leaves causing them bump into each other to create sound. The entanglement of all these factors weakens the individual properties of vegetation wind sounds and makes them sound alike. However, some characteristics exist uniquely for each sort of vegetation and these different properties make them what they are.

2.3.3.1 Wind through Pine tree

Graph1 in Figure 2.21 shows the waveform of a 20-seconds sound signal recorded at three metres distance down wind from a pine tree. The weather was fine, temperatures were mild, and the background sound level very low. The sonogram and frequency analysis are shown in the following two graphs.

Sonogram and frequency analysis indicate:

The maximum sound level appears at very low frequency, ranging from a few Hz to 200 Hz, which manifests an obvious low frequency sound property.

1. Although not very clearly shown, a secondary maximum value exists in the frequency band from 1100 Hz to 1400 Hz.

2. The sound signal distributes continuously along the time history.

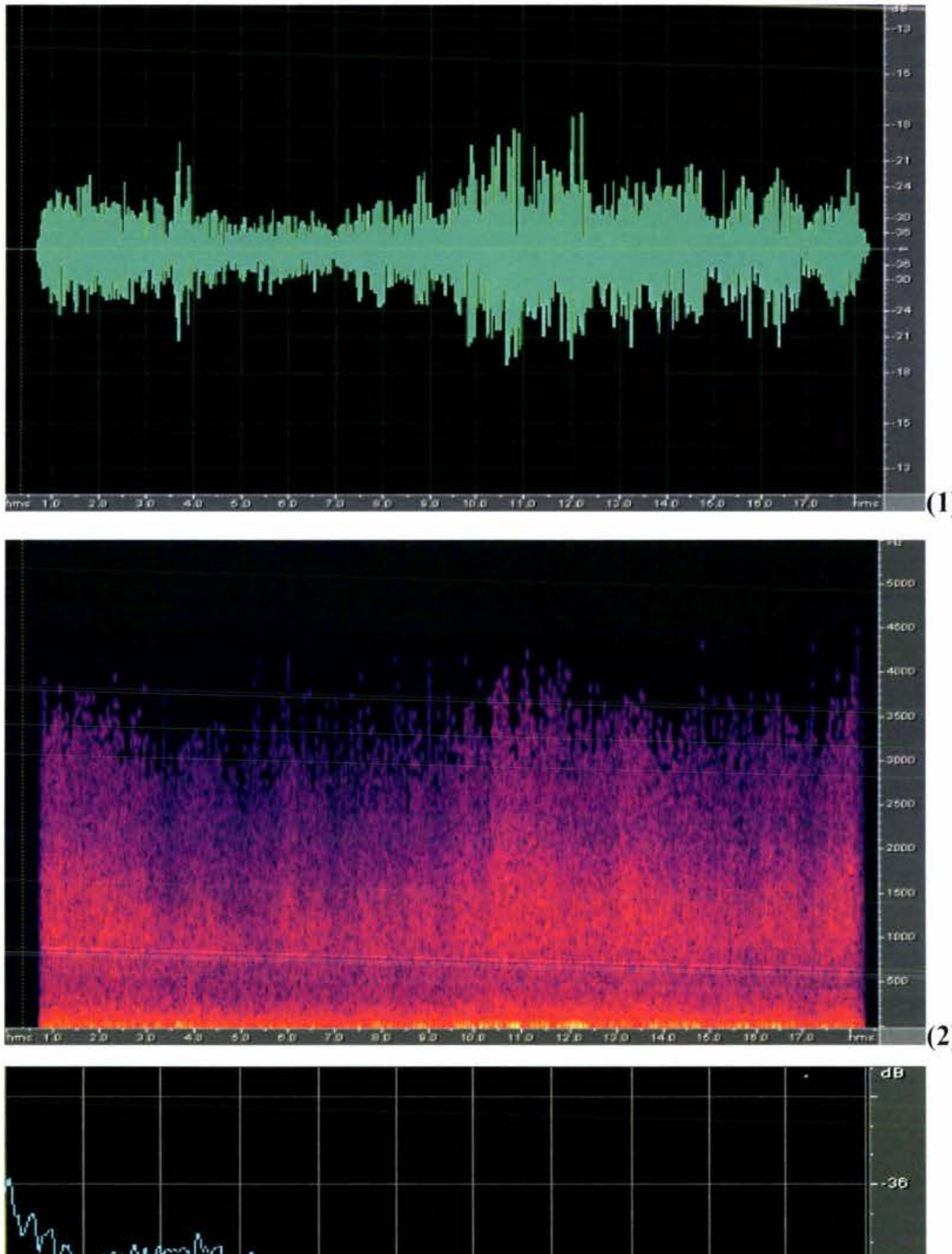


Figure 2.21: Waveform, Sonogram and Frequency analysis of wind sound through a pine tree

2.3.3.2 Wind Sound through an Aspen Tree

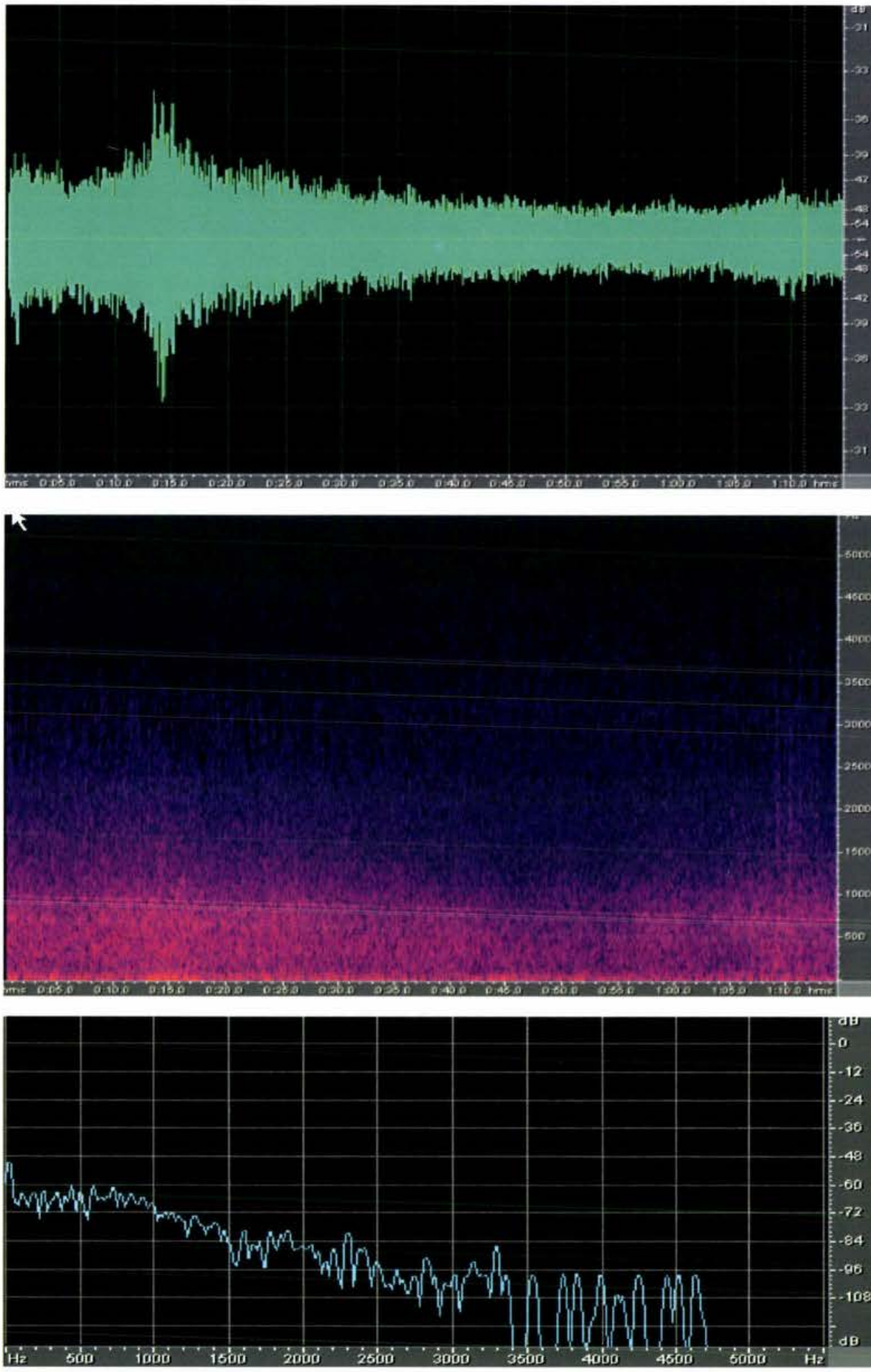
Graph (1) in Figure 2.22 shows the waveform of a 75-seconds sound signal produced by the wind blowing through an aspen tree. The recording was taken from the Internet and by listening to the sound, the background sound level clearly was very low. The sonogram and the frequency analysis are shown in the graph (2) and (3) of the figure.

The sonogram and frequency analysis indicate:

1. The maximum sound level appears at low frequency and distributes in a very narrow band ranging from 1 or 2 Hz to 90 Hz, which manifests an obvious low frequency sound property.

2. No secondary high value exists.

3. The sound signal distributes continuously along the time history.



(1)

(2)

(3)

Figure 2.22: Waveform, Sonogram and Frequency analysis of wind sound through aspen tree

2.3.3.3 *Wind Sound through Bush*

Graph1 in Figure 2.23 shows the waveform of a 210-seconds sound signal produced by the wind blowing through bush. The sound was enhancing with the intensity of the wind growing during the measure period. The sonogram and the frequency analysis graphs are shown in the following two figures.

Sonogram and frequency analysis indicate:

1. The maximum sound level appears in the low frequency range from a few Hz to 400 Hz.

2. No secondary high value exists.

3. The sound signal does not follow an even distribution with time.

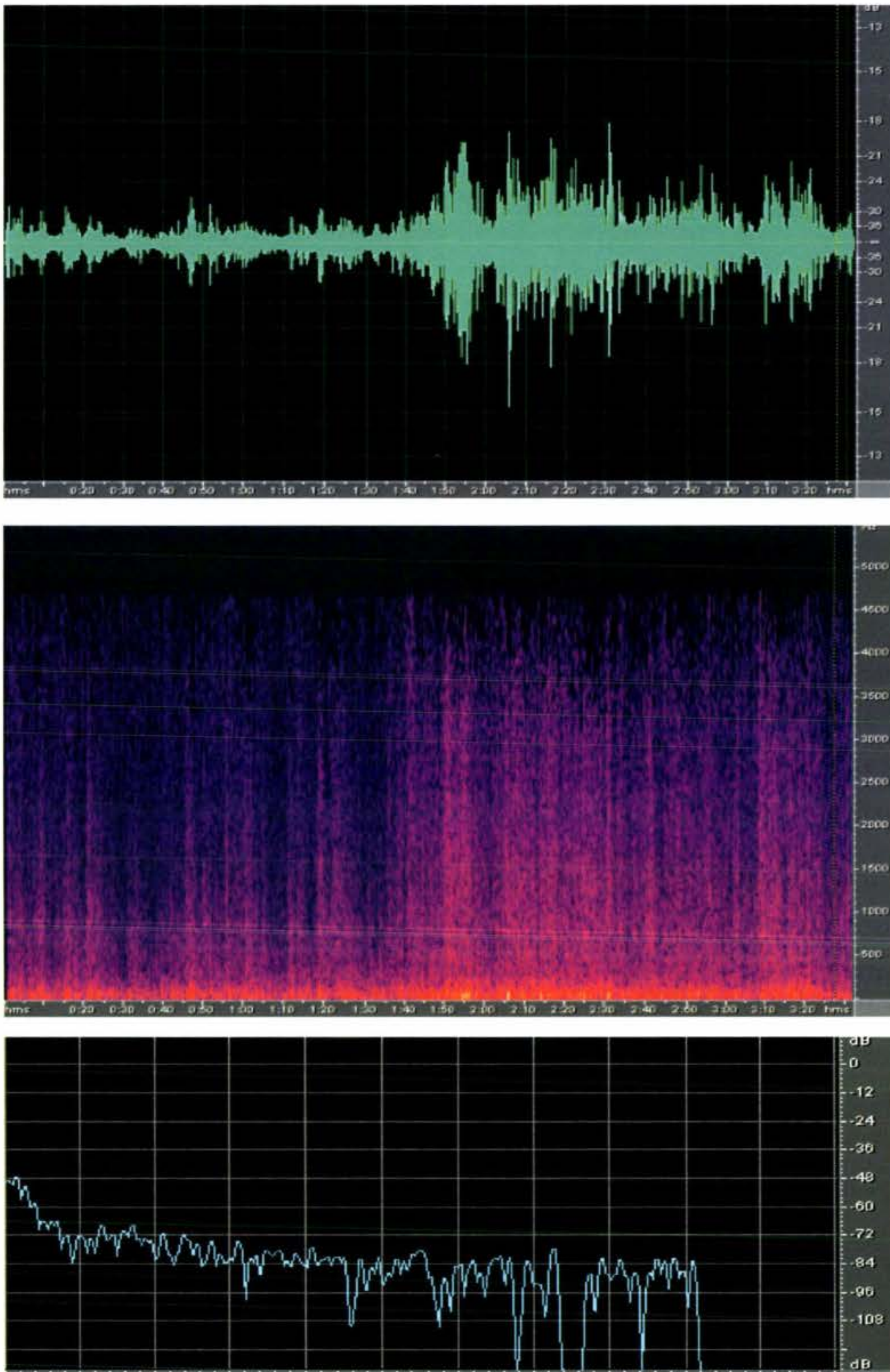


Figure 2.23: Waveform, Sonogram and Frequency analysis of wind sound through bush

Comparing the three sound signals, the following conclusions can be drawn:

1. All the three sound signals show great similarities. The sounds distribute evenly below 3000 HZ and distribute discretely in the frequency above 3000 Hz.

2. The wind through pine trees and aspen trees show more similarities when compared with the wind through bush, which is that the first two signals both have distinct gaps in the higher frequency above 3000 Hz while the wind through bush does not clearly show the same point.

3. The impact sound of objects (leaves and branches) hitting each other make these three sound samples more similar. However, the pitch of the pine tree sound is higher than the other two.

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3 THUNDER SOUNDS

3.1 Introduction

3.1.1 Overview

Thunder, maybe the most recognized natural sound by people across the planet, is the acoustic shock wave caused by the extreme heat generated by a lightning flash. Thunder is always happening together with a lightning. When there is lightning there is thunder, and when there is thunder there is lightning.

Lightning and thunder could be very dangerous. Lightning is usually only dangerous when it hits earth. There are more than a thousand people are killed by lightning every year. Lightning may damage electrical equipment, cause fire and even destroy a building. Mega-lightning is a rare type of lightning that goes from the tops of clouds upwards for thousands of metres into space. It consists of electrical discharges called sprites and elves and is very dangerous to very high flying aircraft and spacecraft. Thunder can also be dangerous. It may break windows and start avalanches. When a thunderstorm happens, it usually associates with very strong winds and air turbulence, which are destructive.[1]

Thunder is one of the nature's loudest sounds. A nearby thunderclap may reach a sound level of around 120 deciBels, equivalent to being within 60 metres of a jet aircraft during taking off or about 1 metre from an auto horn.[2]

3.1.2 Lightning and Thunder

Ancient people believed thunder and lightning came from deities, the voice and expression of their gods. Many cultures thought them as an omen of good or bad things.

Nowadays, the roots for thunder and its various voices are well known by atmospheric scientists.[3]

3.1.2.1 Lightning Formation

The cumulonimbus clouds

The sun heats the surface of the earth, drying it out and making a layer of hot, humid air around the surface. Since the atmosphere is heated from below and cooled from above, the temperature of the atmosphere decreases along with the height, at an average rate of about 6.5 °C per kilometre. This rate is called the lapse rate. The atmospheric pressure decreases rapidly as well. On some hot days, the temperature often decreases more rapidly and the lapse rate is often super adiabatic, meaning that the air cools more rapidly than a rising parcel of air cools by natural expansion. But, the rising air is still cooler than the air around it, so it will still rise higher. The hot, humid air at the surface is convecting, driven by the buoyant forces of cool air that keeps coming in from the sides to equalize the pressure. At the same time, more hot air rises from the surface. When humidity is sufficient, the convective process will pile up the cumulonimbus clouds. [4, 5]

Electrical charges

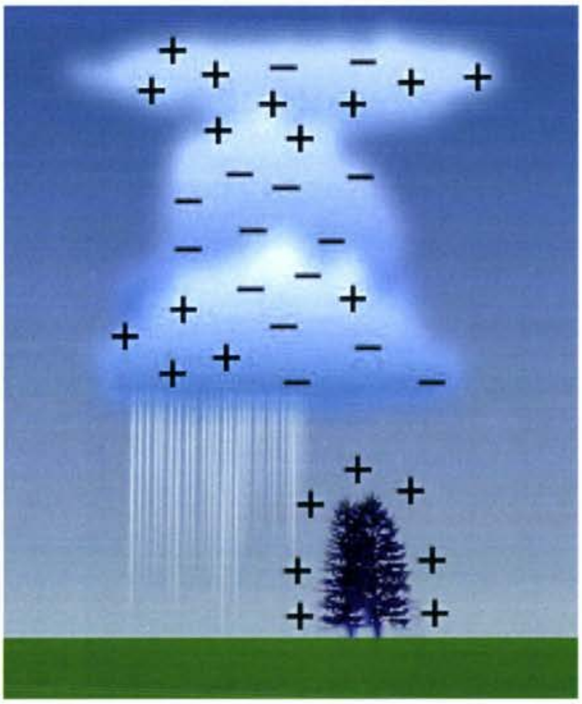

Figure3.1: Building up electrical charges [6]

In the turbulent winds inside the cumulonimbus clouds, water droplets and ice crystals collide with one another. This process builds up charges of electricity. The positive and negative electrical charges in the cloud separate from one another, the negative charges dropping to the lower part of the cloud and the positive charges staying in the middle and upper parts. Positive electrical charges also build on the ground below (Shown in Figure3.1).[4, 6]

Lightning flash

When the difference in the charges is large enough, a flow of negative charges moves from the cloud down to the ground. When the positive charges leaps upward to meet the negative charges, the jagged downward path of the negative charges suddenly lights up with a brilliant flash of light, a bolt of lightning.[6]

Thunder

Having electrical resistance, air becomes heated when an electrical current, such as lightning, pass through it. Thus, each lightning flash, which has a temperature hotter than the surface of the sun, superheats the air surrounding its path, resulting in a channel of gas at very high temperature and pressure. As the superheated gas rapidly expands into the surrounding air, first a shock wave and then a sound wave radiate from the lightning channel.[6]

3.1.2.2 Thunder Sounds

The generation of the thunder sound

Thunder can typically be heard up to many kilometres away. Heavy rain and wind will reduce this distance, while on cool, calm, and quiet nights, thunder can be heard beyond 16 kilometres.[1]

The lightning bolt heats the surrounding air as it passes through to as much as 30,000 degrees Celsius causing a nearly instantaneous increase in pressure to 10 to 100 times normal atmospheric pressure. Thunder, thus, starts as a shock wave moving at speeds in excess of the speed of sound. This initial shock wave rapidly loses its energy to the surrounding air.

When the energy that the shock wave received from the lightning stroke is expended, the wave "*relaxes*" and the pressure in the vicinity of the channel returns to normal levels. The shock wave in relaxing produces an acoustic, or sound wave, which travels through the air perpendicular to the lightning segment that produced it.

Although less than one percent of the total energy in the initial shock wave is transformed into the acoustic wave (the remaining 99 percent is dissipated into heating the surrounding air), the total energy available for that sound wave is still extremely large.[2]

Lightning stokes are composed of a series of path segments. A lightning stroke surges between its beginning and end points in a series of steps, and individual lightning flashes may occur many times along that pathway in less than a second. Each surge in the lightning flash heats the air along the lightning channel producing a series of acoustic waves. The loudness and duration of the resulting thunder is dependant on the strength of the lightning surge current. Research has found that those segments of the lightning channel between five and one hundred metres in length produce most of the audible pulses of thunder. The radius of the shock wave at the time of *relaxation* determines the characteristic frequency or *pitch* of the thunder from that stroke: the more powerful the lightning stroke, the wider the channel and the lower the pitch of the resulting thunder.[2]

The factors that influence the characteristics of the thunder sound

Thunder travels through the lower atmosphere as an acoustic or sound wave moving at a speed of roughly 1230 kilometres per hour - the speed of sound. The character of the sound of thunder, its pitch, loudness and form (crack, rumble, etc.), depends upon the lightning flash that produced it. And the order in which the various sound waves from a lightning stroke reach the observer are all primarily determined by the lightning flash's shape and location. The sound waves are also modified by the atmosphere through which they travel.

Thunder sound waves originating from the lightning flash do not radiate with equal strength in all directions from the lightning channel. More than 80 percent of the acoustic energy is radiated into zones 30 degrees above and below the surface of the plane which perpendicularly bisects the spark. Since the average change in the direction or orientation between adjacent lightning segments of the lightning stroke is only about 16 degrees (and is thus smaller than the zone into which most of the acoustic energy is radiated), the largest segments of the thunderbolt will emit their loudest sound in roughly the same direction. However, it is the degree of that orientation change between segments that determines whether thunder is heard as a sudden clap or a prolonged rumble.[2]

Sound waves from all segments of the lightning stroke are produced almost simultaneously, typically over a time interval much less than a second in length. What variations we hear in a thunder peal result from the time required for the sound from different segments of the lightning bolt to reach our ears, the nearest segments being heard before the more distant. This time differential, coupled with the length and orientation of the larger segments of the lightning flash, determines the unique character of each thunder peal sound.

For example, if the main channels of the lightning bolt are end-on to the listener, the thunder will be relatively quiet since most of the sound is being radiated perpendicular to the channel, away from the listener. Since the sound is generated from portions of the bolt progressively further from the listener, those sound waves which do reach the ear combine to produce a prolonged soft roll or rumble. On the other hand, if the channel is broadside rather than end-on to the listener, most of the sound is directed toward the listener, and the sound waves from the various channel segments arrive almost simultaneously, resulting in a short, but loud, thunderclap.[5]

Since each lightning flash is composed of a number of large segments oriented in any number of ways relative to the listener, the thunder that one generally hears is a combination of claps and rumbles. Listeners separated by some distance will each perceive the thunder in a unique way. Scientists have taken advantage of this structure by using sensitive microphones and recording devices placed in a listening array to probe the structure of the lightning bolt.[7]

Classification of thunder sounds

As mentioned above, the characteristics of the thunder sound is determined by the lightning flash that produced it. According to the form of the thunder sound, it can be mainly classified as claps, peals and rumbles. The respective characteristics of each thunder sound are shown in Table 3.1.

Table 3.1: Classification of thunder sounds

Thunder Definition	Characteristics
Claps	Sudden loud thunder sounds lasting 0.2 to 2 seconds
Cracks	Similar to claps but much faster onset and is repetitive
Rumbles	Long duration but relatively low frequencies
Rolls	Irregular sound variance

3.1.3 Shock Wave

The propagation of an ordinary sound wave in a gas is accompanied by small amplitude longitudinal displacements of gas molecules. In other words, there is no net flow of the media through which sound travels. Any physical changes in the gas are small and reversible. A shock wave, on the other hand, is a totally different situation. It is easily to be found in explosion, detonation, supersonic movements of bodies etc. In nature, the most familiar type of shock wave is the lightning electric discharge. A shock wave is a thin transitive area propagation with supersonic speed in which there is a sharp increase of density, pressure and speeds of substance.[8, 9]

A shock wave can be described as a highly nonlinear and inharmonic acoustic sound wave that is characterized by an extremely steep change in the pressure amplitude, the so-called shock front. When a disturbance is generated through the gas at a speed greater than the local molecular velocity, a shock wave arises. Since the molecules can only move away from the supersonic disturbance at the sound speed, the pressure, density and temperature must all build up ahead of this disturbance.

The parameters of a shock wave include the pressure maximum, pulse rise time, half width time of the pressure wave and a negative pressure phase of the shock wave. (Shown in Figure 3.2)

The acoustic energy of the shock wave is proportional to $P_{max} \times r^2 \times t_w$, where P_{max} is the maximum pressure of the shock wave in focus, r is the radius of the said focal area, and t_w is the half-width time of the shock wave.

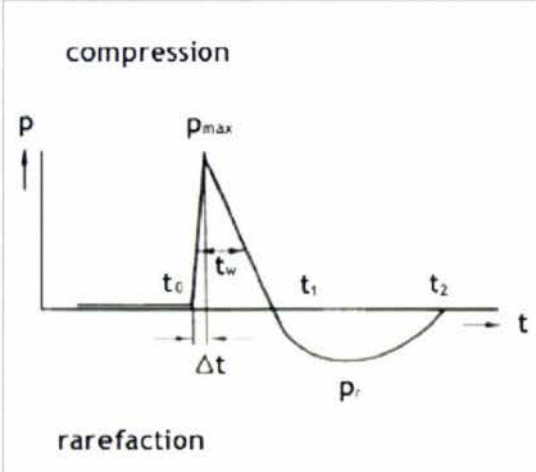

Figure 3.2: Parameters of shock wave [9]

Since the radius of the shock wave at the time of electric discharge relaxation determines the frequency of the thunder sound, the frequency analysis of the thunder can be an effective way to detect the energy contained in a lightning flash.

The variety of the thunder sound is due to the fact that multitude of factors determine its characteristics, including the length and location of the lightning stroke, the power of the shock wave produced during the discharge process, the angle of the lightning path, the wind intensity, the air temperature and the landform where the observer at.

A shock wave produces sound in a very short period. Sometime thunder lasts for a few minutes because we first hear the shock wave from the portion closest to us and then we continue to hear the shock wave from the lightning bolt farther away from us that is reaching us at a later time. Sometime, we only see lightning stroke without hearing any thunder sound. That is because either it is too far away from us or the sound has been bent by the atmosphere away from us.[2]

3.2 Thunder Sounds Analysis

Three samples of thunder sound have been recorded and analyzed. They are named as thunder clap, rumble, and crack.

3.2.1 Thunder clap

Figure 3.3 shows a 6 seconds thunder clap sound signal from the clapping to the gradually fading away. This recording was taken from a CD of natural sounds and no weather conditions were given. This is the most visible thunder that usually happened before a storm. As can be seen from the waveform, the main clapping period lasts for only 1 second with high power intensity.

The sonogram of the signal is shown in Figure 3.4, which appears in the shape of a right- angled triangle. The clap originates suddenly with the peak energy intensity and then decreases rapidly to a small value in a relatively short time. The decay period lasts for about 25 seconds with much less power intensity. The sonogram of the clap signal shows that the high value energy of the clap occurs below the frequency 300 Hz.

The sound spectrum analysis of the thunder clap shown in Figure 3.5 covers the whole process. It indicates that the peak power value is on 275 Hz. From 300Hz to 2000Hz, the energy value is decreasing evenly. The harmonic part from 2000Hz to 3700 Hz was not expected.

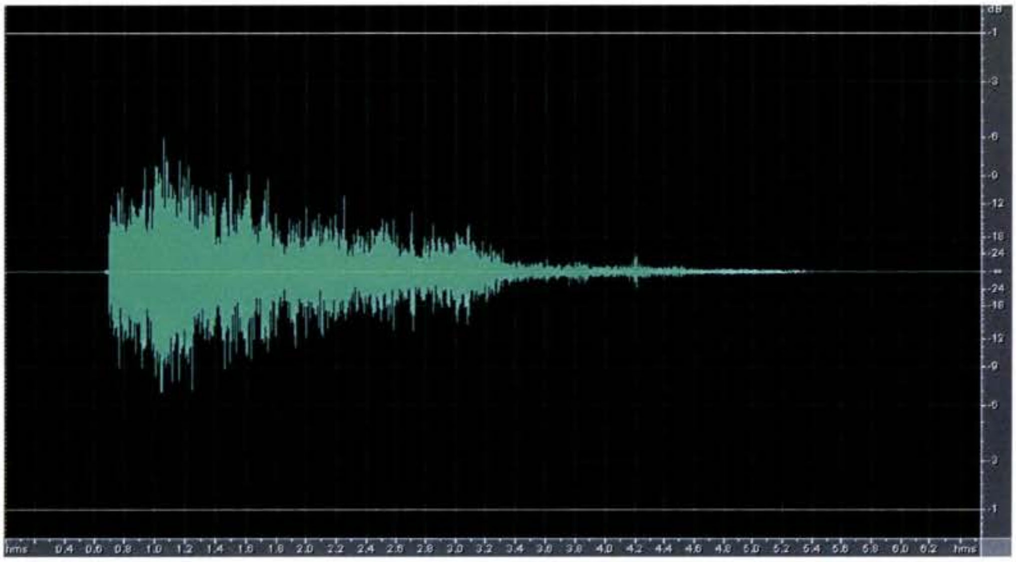

Figure 3.3: Waveform of the thunder clap

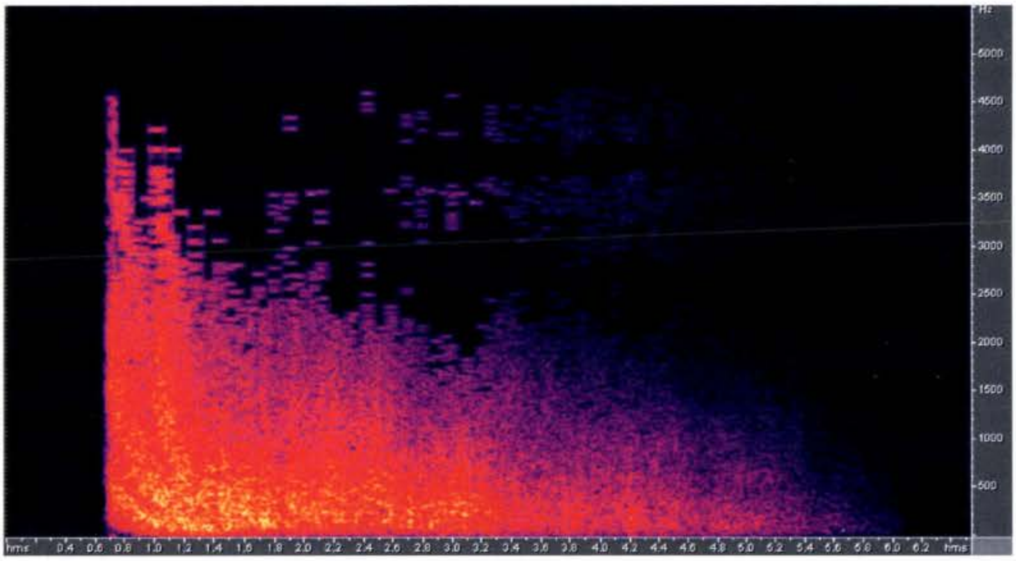

Figure 3.4: Sonogram of the thunder clap

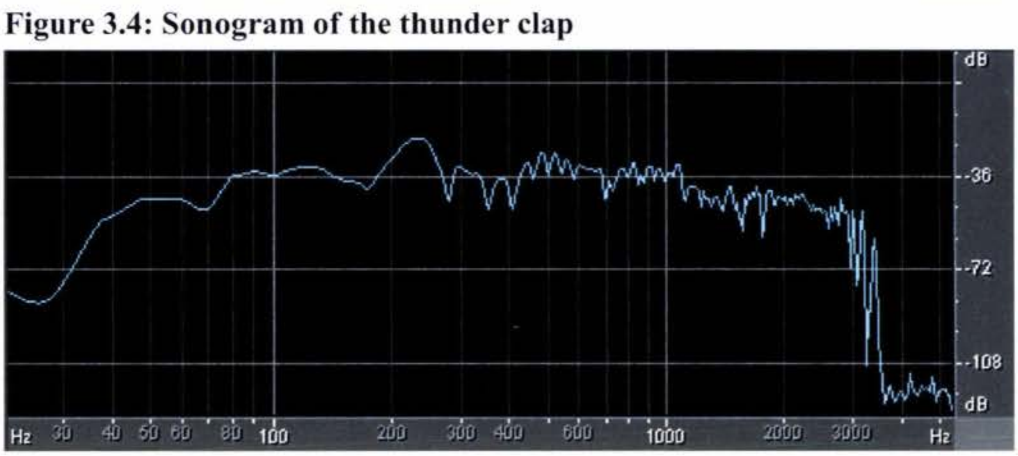

Figure 3.5: The sound spectrum analysis of the clap signal

3.2.2 Thunder Rumble

Figure 3.6 shows the waveform of thunder rumble sound signal lasting for 20 seconds. Thunder rumbles happen both before and during a heavy rain storm. As can be seen from the waveform, the power intensity is evenly distributed along the whole process. The rumble starts with a very weak power value and increases slightly. Then it lasts for a long time and vanishes slightly. The rumble signal differs from the clap signal by repeating this period several times.

The sonogram of the signal is shown in Figure3.7. It shows that the dominant energy of the sound is located below frequency 300 Hz. A relatively low energy value belt can be observed in the thunder rumble sound, which appears at around frequency 4000 Hz.

The spectrum analysis of the thunder rumble sound is shown in Figure 3.8. The curve indicates that the maximum sound occurs at around 140 Hz, which is lower when compared to thunder claps.

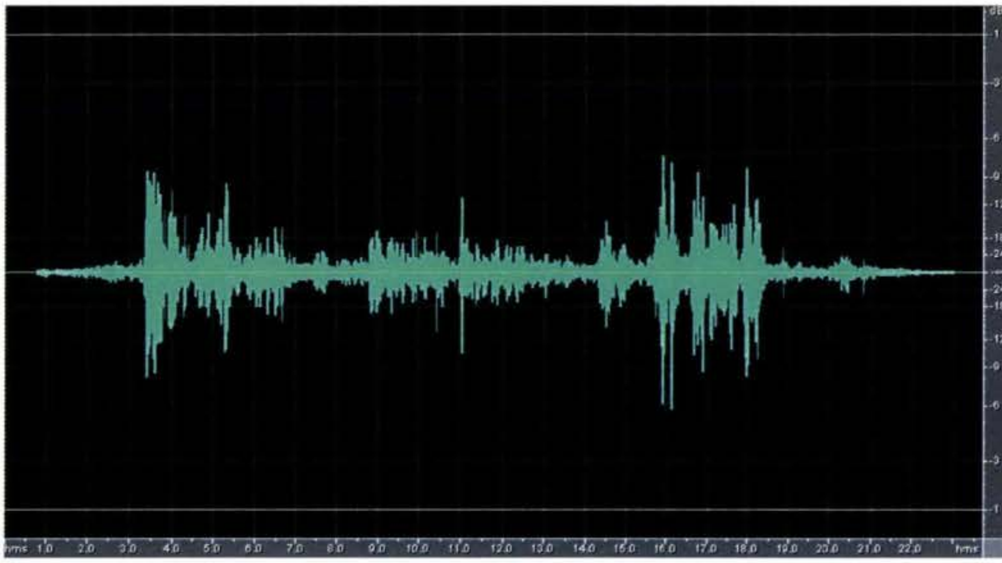

Figure 3.6: Waveform of thunder rumble

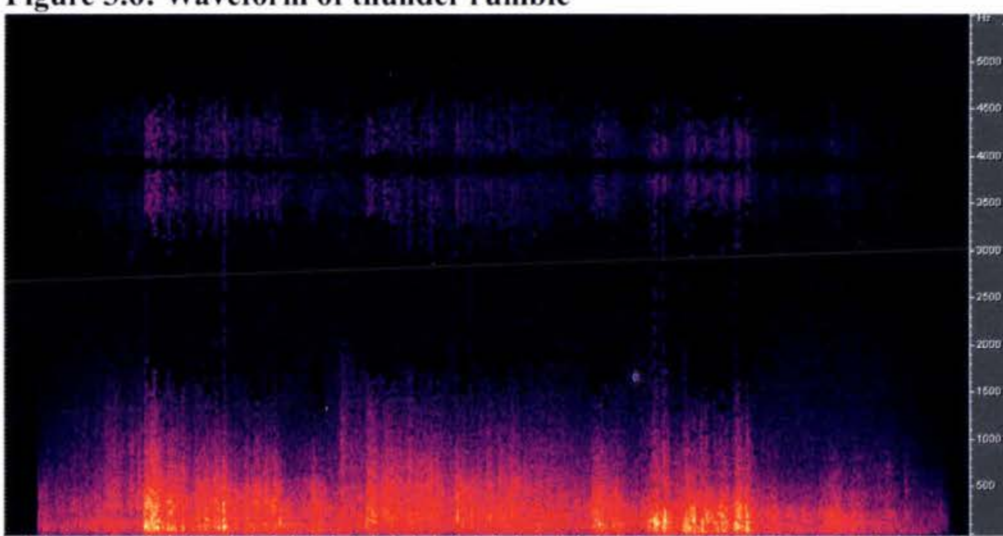

Figure 3.7: Sonogram of thunder rumble signal

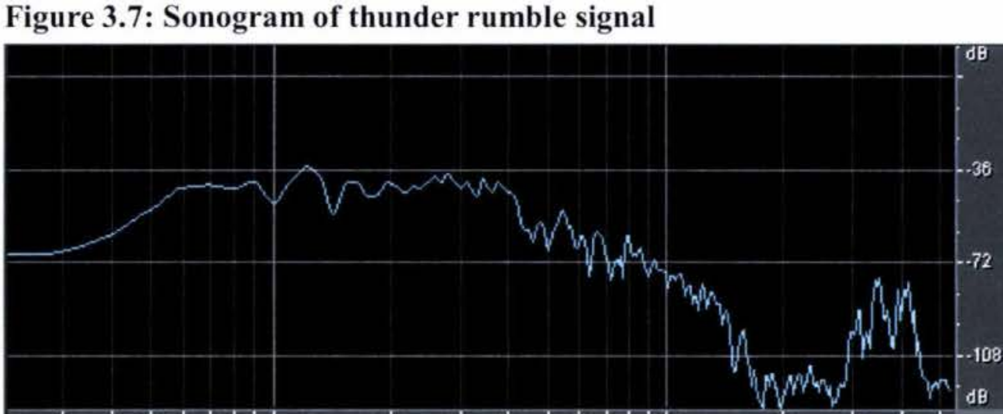

Figure 3.8: Sound spectrum analysis of the thunder rumble signal

3.2.3 Thunder Cracks

Thunder cracks usually happen before storms under a relatively dry environment.

Figure 3.8 shows a 60 seconds thunder cracks sound signal. The crack sound reaches the maximum value in a very short time. Then it repeats cracking and vanishes slightly. Taking one cracking period into account, the waveform appears in the shape of a right-angled triangle with a concaving hypotenuse, which indicates the rapid decrease of energy intensity.

The sonogram of the signal is shown in Figure 3.9. The sonogram of the cracks signal shows that at the point of cracking, the sound power is strong at all frequency with a peak in lower parts. Just after the cracking, the sound power concentrates in the low frequency areas.

The spectrum analysis that covers the whole process is shown in Figure 3.10. The curve indicates that the maximum sound occurs at around 100 Hz, which is lower than that of a thunder clap or thunder rumble.

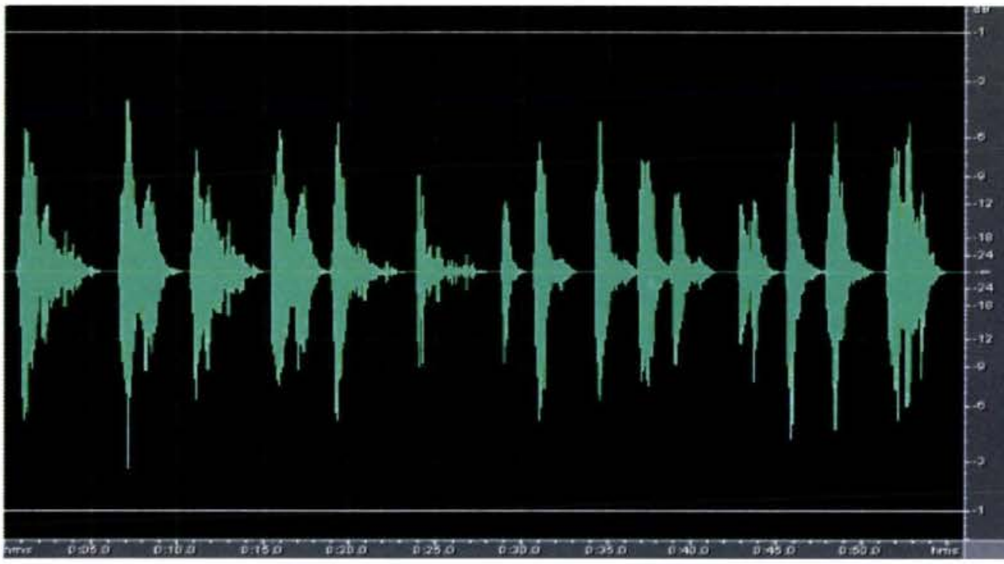

Figure 3.9: Waveform of sharp thunder cracks

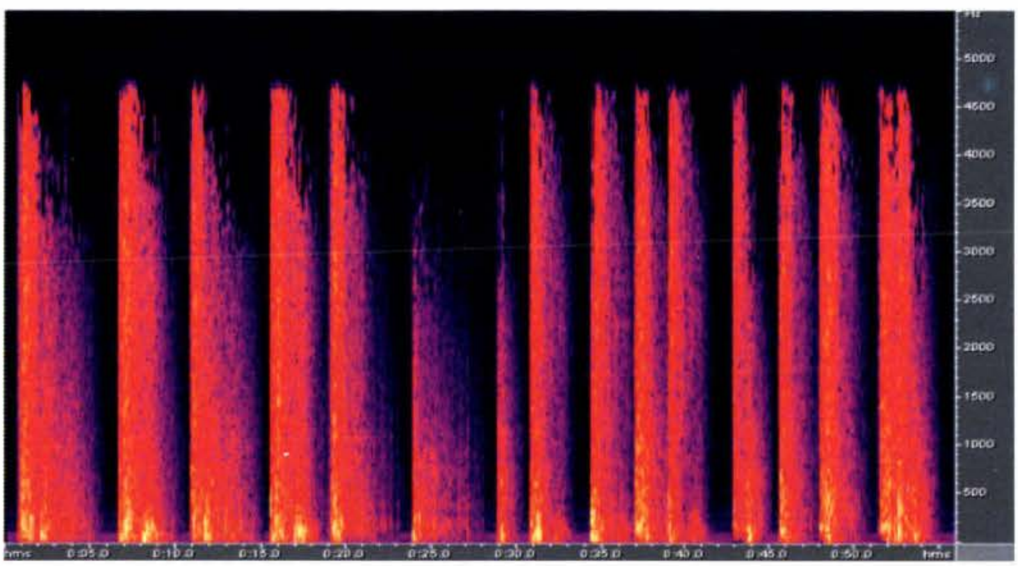

Figure 3.10: Sonogram of sharp thunder cracks

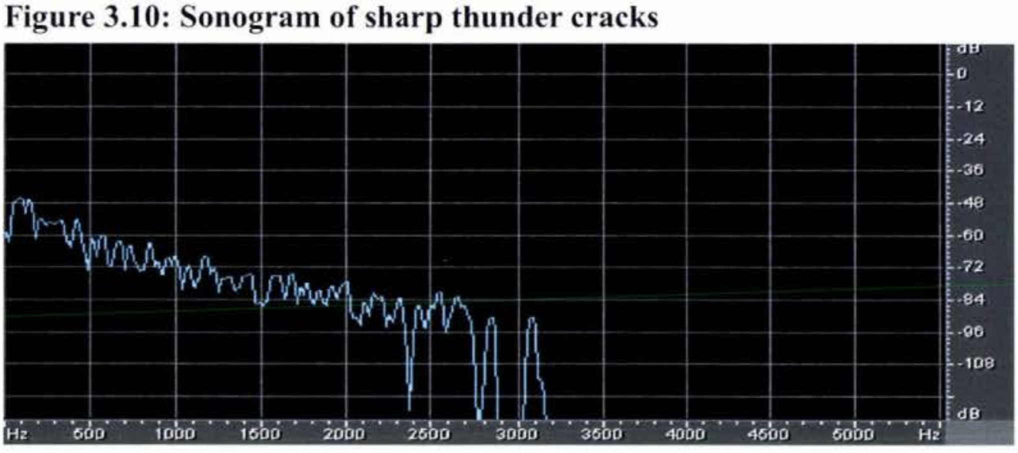

Figure 3.11: Spectrum analysis of sharp thunder cracks

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4 SEA WAVE SOUND IN THE SURF ZONE

4.1 Introduction

Ocean water covers 70 percent surface of our planet. World Resources Institution reported in 2003 that the world coastline length is totally 1634700.7 kilometres, with New Zealand 17208.6 kilometres. [1]

The sound of the sea, which focuses on the coastline, is one of the most evocative natural noises and has drawn a great deal of attention. The process of sea wave breaking when approaching the shore, involving the formation and deformation of hundreds of millions of tiny bubbles, is the process of wave sound production.

Bubbles generated through the sea wave breaking process have a considerably important role in many physical, chemical and biological processes occurring at the air-sea interface. Bubble formation increases gas transfer between the air and sea, and rising bubbles scavenge organic material and bacteria from the water column and transport them to the ocean surface.[2] Bubbles are both source and scatters of underwater sound. When they rise back to the surface, they burst and eject tiny droplets into the atmosphere. The resulting marine aerosols influence cloud and hurricane dynamics, as well as earth's radiative balance and biogeochemical cycles. [3, 4]

The research on breaking wave sounds provides an effective way to study the bubbles formed during the ocean wave breaking process and the investigation of sea wave sound contributes to understanding the motion of the ocean water, the erosion effect of sea waves to the coastline and provides helpful information for the weather prediction.

4.1.1 Sea Wave

Wave Formation

The sea is forever moving. Sea surface waves are those waves occur at the interface between atmosphere and ocean. Ocean waves can be generated by multitude of mechanisms. The most common sea waves are caused by the wind blowing over the sea surface. Other factors, such as submarine earthquakes, volcanic eruptions and the tide also cause waves.

Ocean waves produced by various origins have different natures of their own. Figure 4.1 shown below illustrates the relationship between the wave characteristics and the forces that caused them.

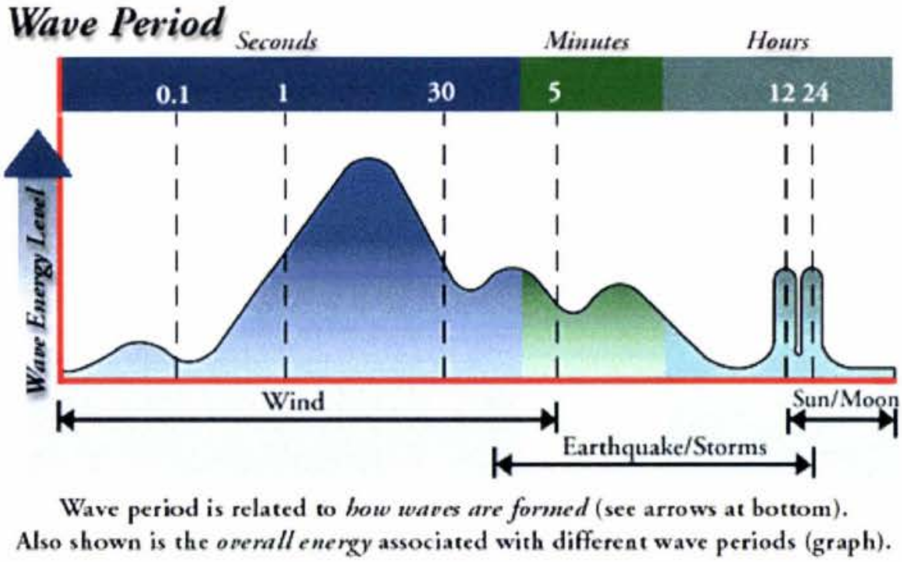

Figure 4.1: Characteristics of waves formed by different forces [5]

The graph shows the distribution of wave energy in Earth's oceans. The greater the area of the graph means the higher energy level for that wave period. The graph also shows that most common ocean waves, which have a relatively small period, are caused by the wind.

The height of a wind generated wave is determined by the speed of the wind, the length of time it blows and the distance over which the wind continually acts on the water's surface. As wind blows across the surface, it tries to drag the water moving with it. Since the water cannot move as fast as the air blowing, it rises in height. Gravity then pulls the water back. The fully developed wind generated wave reaches an equilibrium state in deep water under an unvarying extra force situation: waves with a constant wave steepness progress in a constant speed (See wave attributes in this chapter for wave steepness).

In reality, since wind varies in time and space, the wave height and length are not constant. They vary randomly in time and space as well. Sea level also changes from time to time. On a period of a day, sea level increases and decreases by about a metre. This slow rise and fall of sea level is due to the tides. Tides, with wavelengths of thousands of kilometres, are generated by the slow, very small changes in gravity due to the motion of the sun and the moon relative to earth. [6]

Due to the large differences on period of waves caused by different forces, one can tell a wind generated wave easily by observation. The current thesis focused on the sea waves produced by wind.

Wave Attributes

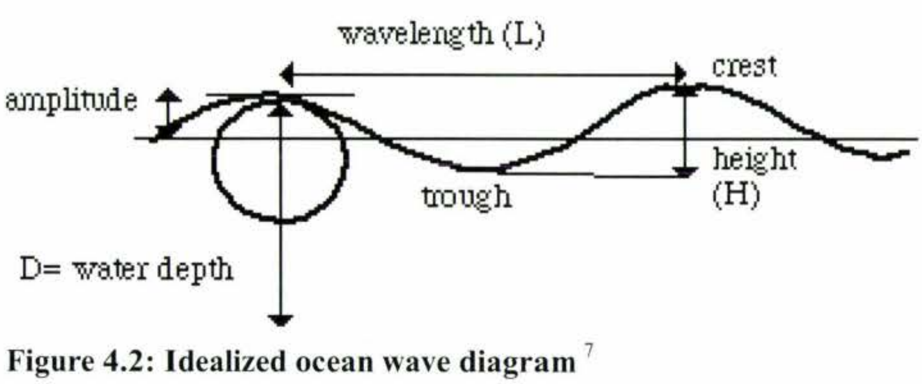

Figure 4.2: Idealized ocean wave diagram [7]

Ocean waves are very nearly in the shape of an inverted cycloid as shown in Figure4.2. The highest parts of waves are called crests, and the intervening lowest parts, troughs. Since the crests are steeper and narrower than the troughs, the still water level is a little lower than halfway between the crests and troughs. The vertical distance between trough and crest is called wave height, labeled H in the diagram. The horizontal distance between successive crests, measured in the direction of travel, is called wavelength, labeled L. The time interval between passages of successive crests at a stationary point is called the wave period (T). Wave speed (V) is dependent on wavelength but not on height. [8]

Wave steepness (H/L) defined as the diagonal connecting the crest of one wave and its intercept along a line drawn from the crest into the previous wave, is another important parameter in the wave motion. If the steepness exceeds 1/7, ocean breakers form, therefore, $H/L>1/7$ is called the "breaking criteria".[6]

4.1.2 Breakers

White Caps

Ocean surface wind waves are generated by transferring some of the wind's energy, in the form of momentum, from the air to the water. Even after the wind waves are fully developed, the wind may continue to transfer momentum to the ocean, but because the wave cannot grow any larger due to the breaking criteria, the excess energy supplied by the wind must be dissipated. This dissipation occurs when the waves break and through the turbulent dissipation of energy, white caps are created.[2] (See details in section 4.2.2). Unlike breakers in the surf zone, these open-ocean, deep-water breakers are not caused by decreasing water depth, but because they are too steep. The white caps usually appear as an area of foamy water in the open ocean.

Wave breaking in the Surf Zone

After waves enter shallow water, they slow down, grow taller and change shape. The water near the bottom of the wave begins to feel bottom, and is retarded by friction, causing the wave to increase in height until it becomes too high for its motion, and falls over into the preceding trough. This is the formation process of breakers and the depth of water that gives rise to breakers is half of the wavelength. A series of breakers is surf. The surf zone is defined as the area between the first breaker shoreward to the beach. (See Figure 4.3)

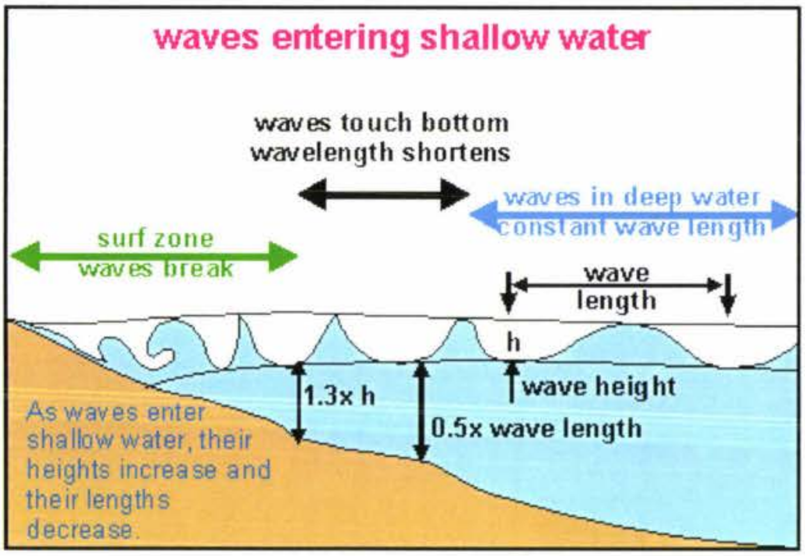

Figure 4.3: Waves entering shallow water [9]

When a wave breaks, the energy the wave contains is dissipated. Some energy is reflected back out to sea. Most of the energy is transferred to heat and sound in the final small - scale mixing of foaming water, sand and shingle.

Classification of Breakers

Three major types of breaker can be identified in the surf zone.

1. **Spilling breakers**

These are the breakers that gradually run over a distance. Spilling breakers are characterized by foam and turbulence at the wave crest. Only the top portion of the wave curls over. Light foam may wash gently up the shore. This type of breakers is normally found with a flat bottom beach (See in Figure 4.4).

2. **Plunging breakers**

These are the breakers arched with a convex back and concave front. The crest curls over and plunges downwards with considerable force, dissipating its energy over a short distance and a short time interval. This type of breakers is usually found on a medium to steep sloping beach, with little wind or an offshore wind (See in Figure 4.5).

3. **Surging breakers**

This kind of breaker is found on the very steep beaches. Surging breakers are typically formed from long, low wave, and front faces and crests thus remain relatively unbroken as the waves approaching the beach.

Figure 4.4: Typical spilling breakers at Kapiti Beach New Zealand

Figure 4.5: Predominating plunging breakers and occasional spilling breakers in Happy Valley Beach New Zealand

Figure 4.6 shows the three types of breakers and Figure 4.7 illustrates the relationship between wave steepness, beach steepness and beaker type.

The way breaker shape changes from top to bottom of the picture depends on:

1. Increasing beach slope (if considered independently from wave characteristics).

2. Increasing wavelength and period and correspondingly decreasing wave steepness, if these characteristics are considered independently of beach slope.

In practice, the wave type in surf zone is not that simple. "It is not always possible to consider 1 and 2 separately, because the beach slope is partly influenced by prevailing wave type and partly by the particle size of the beach sediments, which in turn depend upon the energy of the wave erode, transport and deposit them".[10]

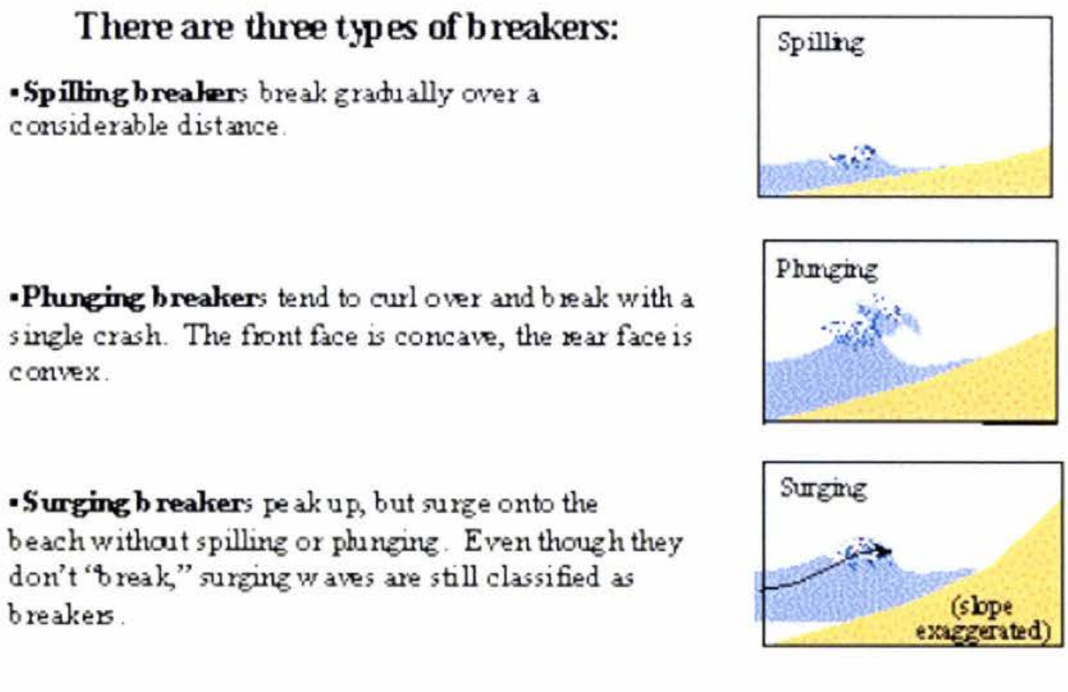

Figure 4.6: The type of the breaker depends on the slope of the bottom and the steepness of waves offshore [10]

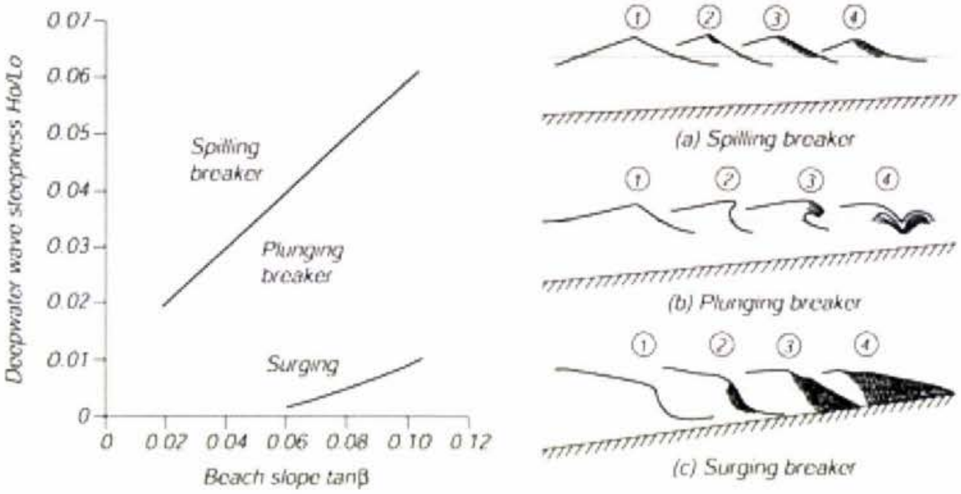

Figure 4.7: Three types of breaker [11]

4.2 Wave Sound Generation Mechanism

4.2.1 Wave Energy

Kendall (1997) stated that surface wave played an important role in the exchange of mass, momentum and energy between the atmosphere and the ocean. The energies are released partly by being transferred into sound signals through the formation and deformation of the bubbles.[12]

The energy a fully developed ocean wave contains is made up of kinetic energy and potential energy, which can be represented by the equation:

$$T_E = K_E + P_E$$ [13]

Where T_E is the total energy of an ocean wave, K_E and P_E are relatively the kinetic energy and the potential energy.

The potential energy of a wave is related to the vertical distance of each water particle from its still position. Therefore, potential energy moves with the wave. In contrast, the kinetic energy of a wave is related to the speed of the particles, distributed evenly along the entire wave.

The motion of water particles in a wave is shown in the following figure 4.8, in which the forward displacement is greatly exaggerated.

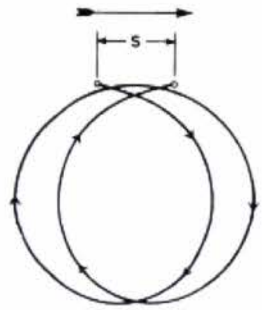

Figure 4.8: Motion of a water particle in a wave [14]

A particle of water on the surface of the ocean follows a somewhat circular orbit as a wave passes, but moves very little in the direction of motion of the wave. As the crest passes, the particle moves forward, giving the water the appearance of moving with the wave. As the trough passes, the motion is in the opposite direction. The radius of the circular orbit decreases with depth, approaching zero at a depth equal to about half the wavelength. In shallow water the orbits become more elliptical, and in very shallow water the vertical motion disappears almost completely.[13]

The "wave energy period" is given by the following formula: [14]

$$T_E = \frac{1}{4}\rho g c a^2$$

We can see that the wave energy period is related to:

1. The density of the water ρ
2. Gravity g
3. The wave speed c
4. The square of the amplitude a

Sound produced in the process of wave motion or breaking, is part of the wave energy. As reported by Tkalich and Chan [15], Loewen and Melville (1991) [23] experimentally found that the fraction of dissipated wave energy radiated as sound is of order 10^{-8}.

Relating the wave speed and to the wind speed, some empirical studies show the dependence of sound intensity on the wave height and wind velocity. Several approaches have been made to develop qualitative and quantitative descriptions of the phenomenon. Marsh (1963) depicted that the noise intensity (I) was evaluated as a function of wave height (H) and acoustic frequency (f): $I \propto H^{6/5} f^{-5/3}$.[16] Kerman (1984) developed the relationship between sound intensity (I) and wind velocity (U) for large wind velocity (U): $I \propto U^{1.9}$.[17]

4.2.2 Sound Source Mechanism

Possible Mechanisms

The breaking waves in the surf zone are noisy and the sources of the sound are located in the breaking region. The possible mechanisms include the sound associated with the entrainment of air, including free bubble oscillations and collective oscillations, splashes, sediment disturbance and "surfseisms," turbulence. Deane (1997) in his report concluded that: [18]

1. Sediment disturbance results in the generation of sound caused by colliding particles. When it occurs, probably makes a significant contribution to the wave noise in the region of roughly 50-400 kHz and it is reasonably confident that sediment disturbance is not a significant source of sound in the region below 50 kHz.

2. The sound frequency of splashes is observed in the hundreds of Hz band and the splash noise is not a significant source of sound in the breaking region at frequencies below 100 kHz.

3. Collective oscillations provide the low frequency sound below 100 Hz.

4. Individual bubble oscillations are the primary source of sound between 500 Hz and 50 kHz.

Bubbles development in the Breaking Region

Lamarre and Melville (1991) reported that wave breaking transferred momentum from the atmosphere (winds) to the ocean and entrained air in bubbles which are believed to generate and scatter sound. [19] Numerous researches have been conducted about the relationship between bubble acoustic frequency and radius. Leighton and Walton (1987) suggested that the sound spectrum produced by bubbles in the environment could be used to calculate the bubble size spectrum.[20]

The process of the bubble formation and deformation was depicted by Loewen (2002) as: When ocean waves break, air and sea water mix to form whitecaps. Beneath the surface of the whitecap, a mixture of air and sea water forms a violent turbulent flow known as a bubble plume. The plumes generated by typical breaking waves evolve rapidly for approximately 10 seconds as large bubbles rise quickly back to the surface. After this time, a relatively diffuse plume of small bubbles persists in the ocean for up to several minutes.[2, 21]

Deane and Stoke (2002) used a unique instrument "BubbleCam" to track the process. Through the observation, they found that plume lifetime could be divided into two main phases, the acoustic phase when bubbles are formed, and the quiescent phase that begins when active bubble formation ceases. Figure 4.9 illustrates the development of the two phases along with logarithmic timeline. Three high-speed video images of a breaking wave acoustically active phase are shown in Figure 4.10. They reveal the details of the acoustically active phase. [22]

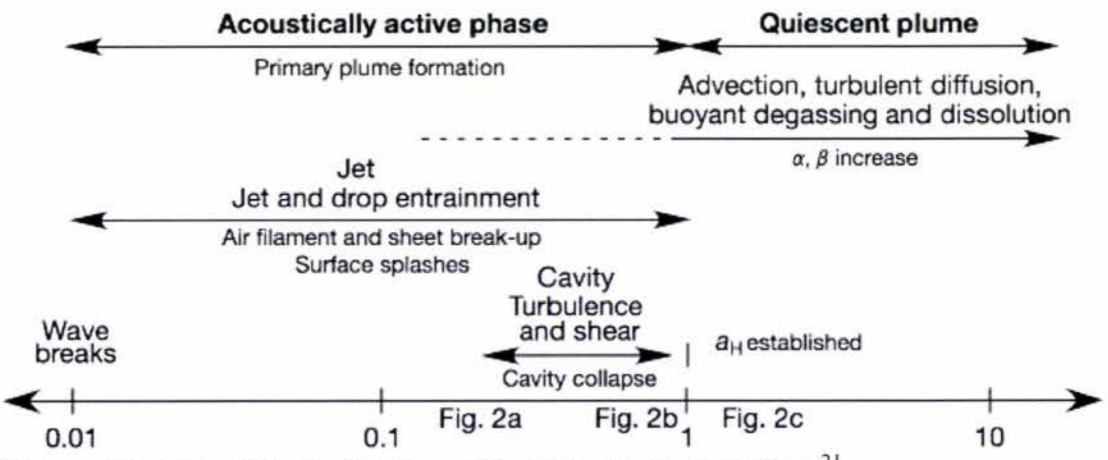

Figure 4.9: Logarithmic timeline of bubble plume evolution [21]

Figure 4.9 shows that the acoustically active phase is the period of primary plume formation. The jet and drop entrainment is active during the entire acoustic phase while the wave cavity collapse takes place after the jet and drop entrainment in the acoustic phase.

In Figure 4.10, image a and b are taken in the acoustically active phase marked in figure 4.9 as fig.2a and fig.2b. Through the observation, they found that the jet and drop period was mainly associated with the creation of bubbles from 0.1mm to 2mm radius and the cavity period was associated with the creation of much larger bubbles from 2mm to 10mm radius. The sound characteristics of different size bubbles will be depicted in details in chapter 6 with water drops falling into the water surface.

Bubble sizes are dependent on various aspects, and therefore, the wave sounds on the beach are considerably different along with its time and location. The main reason for the differences is the type of breakers, which are decided by parameters such as wave steepness and beach bottom steepness.

Since the spilling breakers do not contain a process of jet while the plunging breakers contains the whole process of jet and cavity. Deane and Stokes' finding indicates that the spilling breakers produces most small bubbles with radius below 2mm and the plunging bubbles produces small and large bubbles.

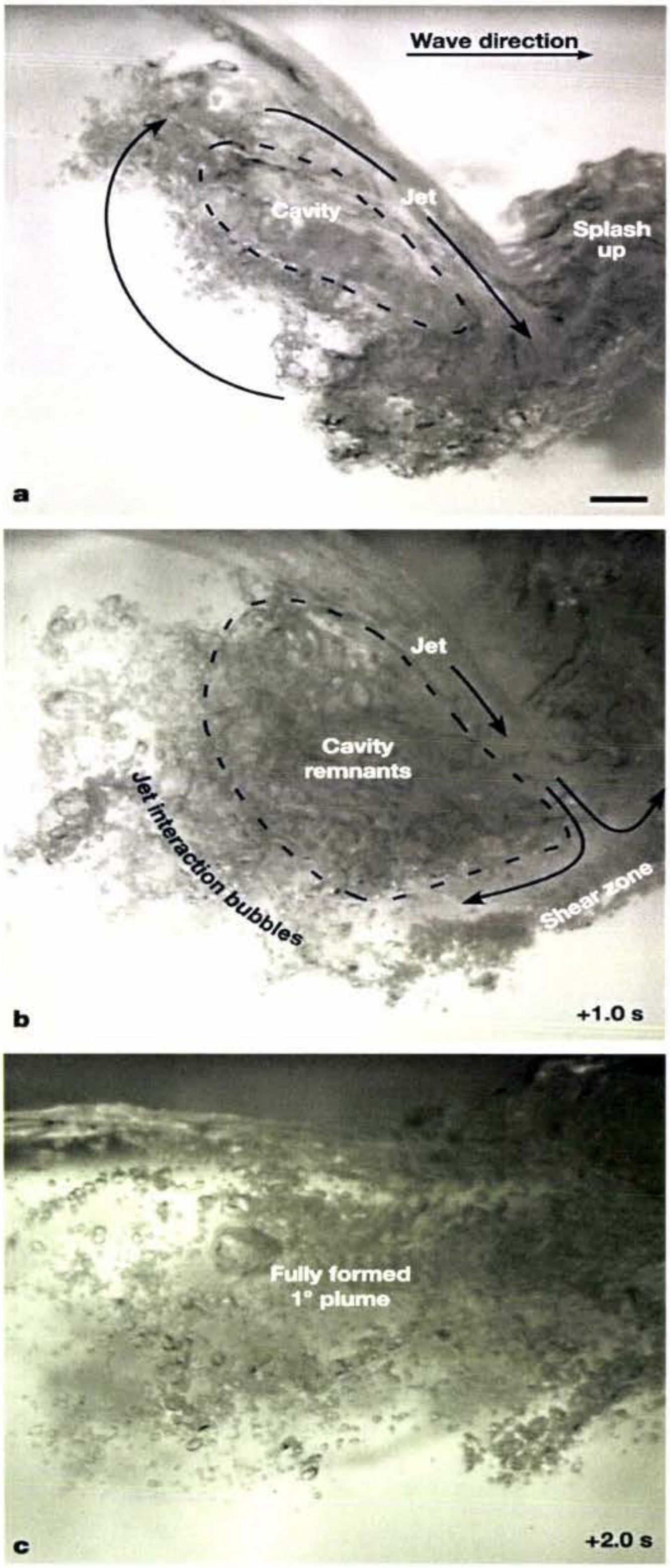

Figure 4.10: High-speed video images of a breaking wave acoustically active phase [22]

4.3 *Wave Sound Analysis*

4.3.1 *Process*

To investigate the characteristics of the wave sound in the surf zone and to find out the relationship between wave sound characteristics and the types of the breakers, various field measurements and recordings were taken in different locations, at different times, under different weather situations. The 5 analysis samples, respectively representing 5 types of beach wave sound: sand beach wave sound, rock beach wave sound, spilling breaker wave sound, plunging breaker wave sound and surging breaker wave sound, were selected from the 37 recordings taken.

Two typical breakers sound samples, spilling breaker and plunging breaker were selected to be compared. The sonogram of each type breaker was obtained through the computer analysis; spectrum analyses were taken to show the details for each breaker.

Sand beach wave sound in Seatoun and rock beach wave sound in Lyall Bay were chosen to be compared to show the differences and influences by the beach material to the surf sound.

Observations and measurements on the Seatoun trestle indicated no significant sound produced in the deep water area, which means the sea wave is relatively quite before it enters the surf zone. However, the open ocean waves do break when the steepness of the wave exceeds the breaking criteria.

4.3.2 Results and Discussion

Comparison of Plunging and Spilling Breaking Surf Sound

A 75 seconds time period containing 12 distinct breaking surf occurrences was recorded at Happy Valley beach in New Zealand with a wind speed 7m/s. The recorder was settled approximate 20 metres away from the main plunging breaker point. The sediment material is tiny gravels shown in the following picture.

Figure 4.11 Waves at Happy Valley Beach New Zealand

Figure 4.12 shows the sonogram of the recording signals. The observation along with the recording period showed that the second (~9s), fourth (~23s), tenth (~55s) and twelfth (~72s) vertical bar were generated by plunging breakers and the remaining eight vertical bars were generated by spilling breakers.

In a spilling breaker, the energy which the wave has transported over many miles of sea is released gradually over a considerable distance, while in a plunging breaker, the energy is released suddenly into a downwardly directed mass of water and the breaker is characterized by a loud explosive sound. The plunging and spilling breaker generated signatures show that the plunging breakers usually hold more energy when compared to the spilling breakers. Spilling and plunging surfs were observed to occur randomly in the same surf zone during a certain time period, which means they seldom take place alone.

Figure 4.12 also indicates that higher energy levels of the sea wave sound are predominantly at frequencies below 1500 Hz.

The differences between the two breaker-type signatures may be seen in comparing the enlargement of two signatures in Figure 4.13 the plunging surf signal (the forth surf) and Figure 4.14 the spilling surf signal (the fifth surf).

The signature in Figure 4.13 was generated by a large plunging breaker. The sharp onset of the signature is characteristic of the impulsive nature of plunging breakers. The low frequency tail, evident in this figure, is observed in most of the signatures independent of breaker type.

The spilling breaker's signature, Figure 4.13, has both a low frequency precursor and low frequency tail.

The existence of the low frequency precursor is the most difference between two type breakers. This difference indicates that at the beginning of the wave breaking, the spilling and plunging breakers have their own nature with spilling breakers developing gradually to reach the highest value of energy dissipation and then suddenly plunging down. The common low frequency tails shows that the two type breakers are very much similar when they are fading away.

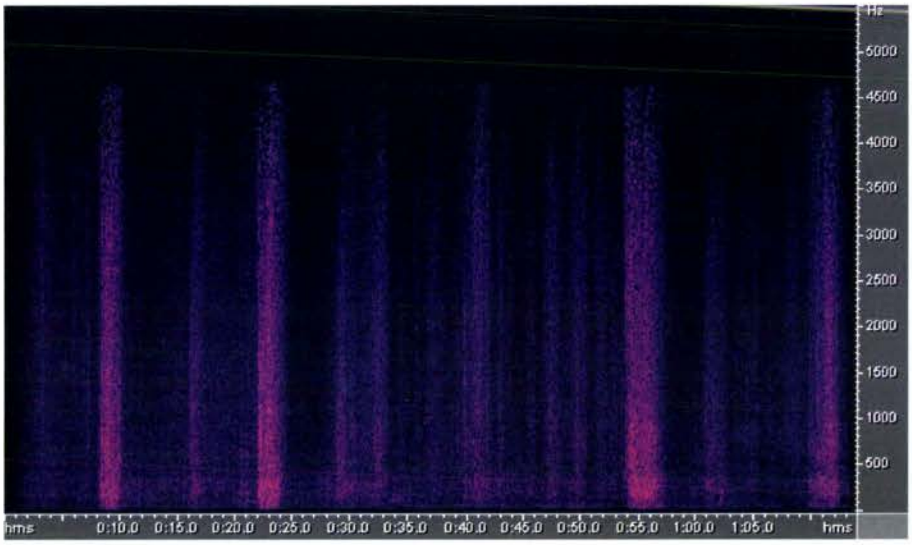

Figure 4.12: Sonogram of sea wave sound

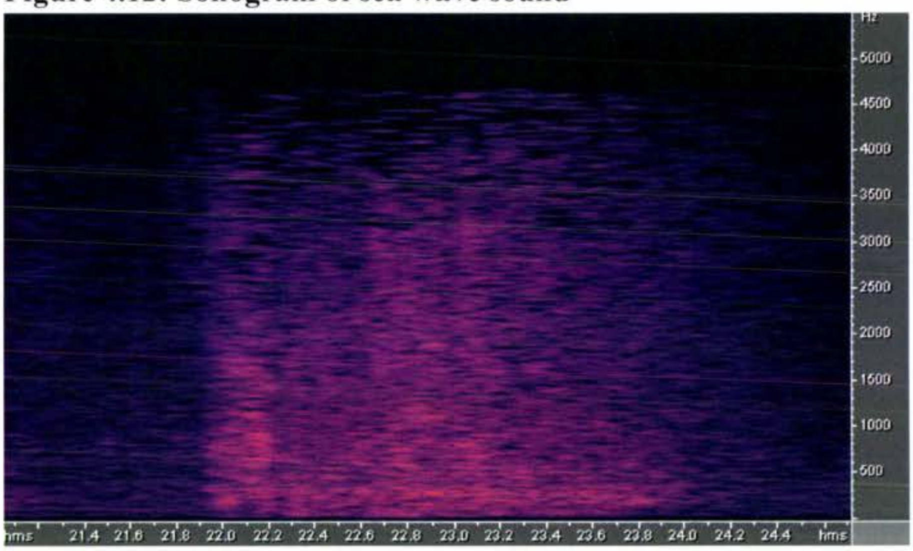

Figure 4.13: Signature of plunging surf sound

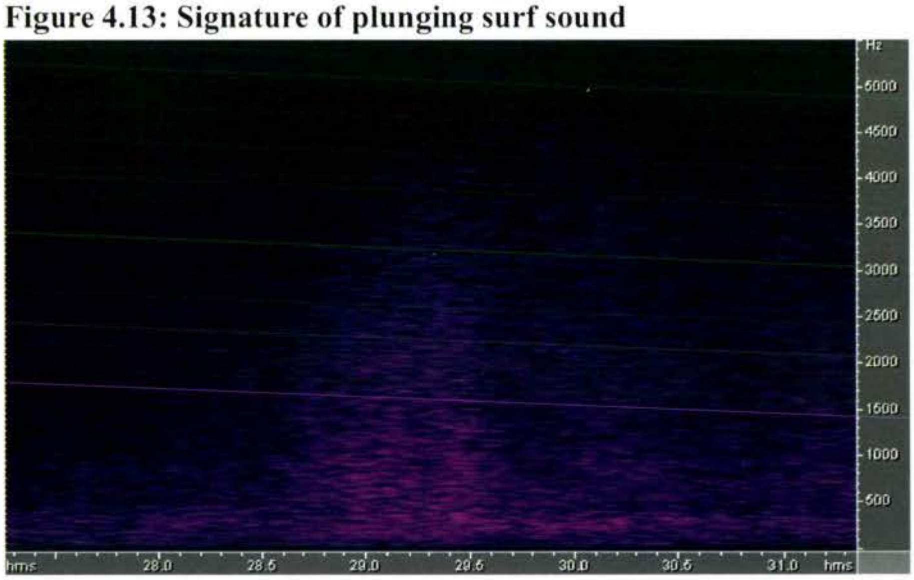

Figure 4.14: Signature of spilling surf sound

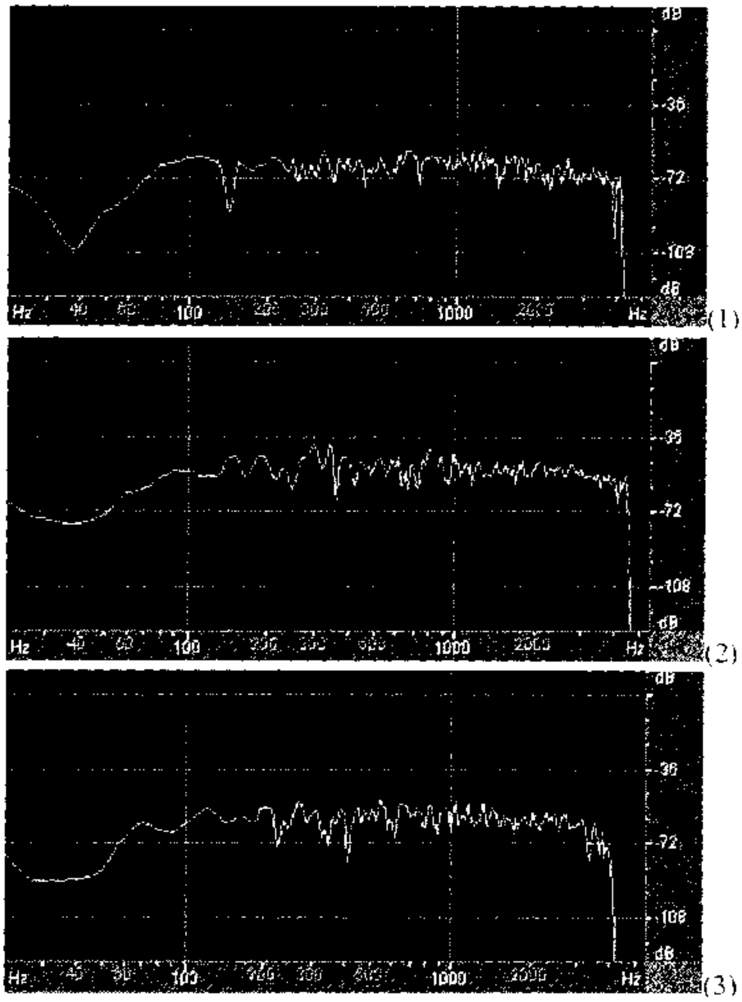

Figure 4.15: Spectrum analysis of the entire process (1), the plunging breaker (2) and the spilling breaker (3)

The spectrum analyses were conducted respectively on the entire recording process, the chosen plunging surf (the fourth) and the chosen spilling surf (the fifth) (See Figure 4.15).

Graph 2 and 3 both cover the whole process of wave breaking. They show great similarities except for the higher sound levels in the plunging breaker. The entire process analysis shows some differences:

1. At frequency around 40 Hz, the sound level shows a greater drop when compared to the single surfing signal.
2. At frequency around 150 Hz, the sound level shows a greater drop when compared

to the single surfing signal.

Sonograms and spectrum analysis of the two typical breaker type indicate the different sound characteristics between spilling and plunging breaker waves:

1. Plunging breakers show a much longer period than spilling ones, which makes the individual breaking sound more easily distinguished.

2. The sound pressure levels of the two type breakers indicate that plunging breakers produce a louder sound than the spilling ones when they break. However, the sound level of the spilling breakers is more than that of the plunging ones.

3. The two types of breakers can both be labeled as low frequency sound with the high energy centralized among the low frequency part. However, the plunging breakers' energy is more centralized than the spilling ones.

Comparison of sand beach and rock beach wave sounds

A 9 seconds sound generated by a large wave clapping on the rock was recorded at Lyall Bay beach in New Zealand. Figure 4.16 shows the waveform, spectrum analysis and sonogram of the recorded sound signal.

When waves hit rocks, a loudly impulsive sound generates, which can be seen from the sonogram. The sound contains two discrete parts, the impact signature shown in Figure 4.17 and the splashing signal shown in Figure 4.18. The impact sound is generated by the wave hitting the rock and numerous bubbles formation and collapse. The wave hitting the rock bursts, ejecting droplets into the atmosphere, and the droplets hitting the rocks disperse causing the splashing sound. The duration of the impact sound is relatively shorter than the splashing, but the energy released is believed larger than the splashing, which makes the impact signal louder.

Figure 4.17 shows that the impact sound is more concentrated in low frequency than the splash sound. The highest energy in impact sound is located at the frequency band from 110 Hz to 130 Hz and the energy in this band prevails during the whole impact process. Figure 4.17 indicates that the splashing sound is characteristic of white noise. Except that the energy level in 200 Hz to 300 Hz band is slightly higher than other frequencies. A low frequency tail is evident in the sonogram. This may be due to the lessening splashing intensity

Comparing the sonogram of Figure 4.17 to the sonograms of spilling and plunging breakers in Figure 4.13 and Figure 4.14, the following conclusions can be drawn:

1. Breaker sounds are distributed in a narrower frequency band than the impact sound. Spilling and plunging breaker sounds show very weak energies at frequency above 4000 Hz while the impact sound signature is still evident at frequency 7000 Hz.

2. The highest energy band in breaker sounds are located around 300 Hz while the impact sounds around 120 Hz.

3. The impact signature shows a slight decrease in power after reaching the peak value while Breaker sounds remains an almost straight line.

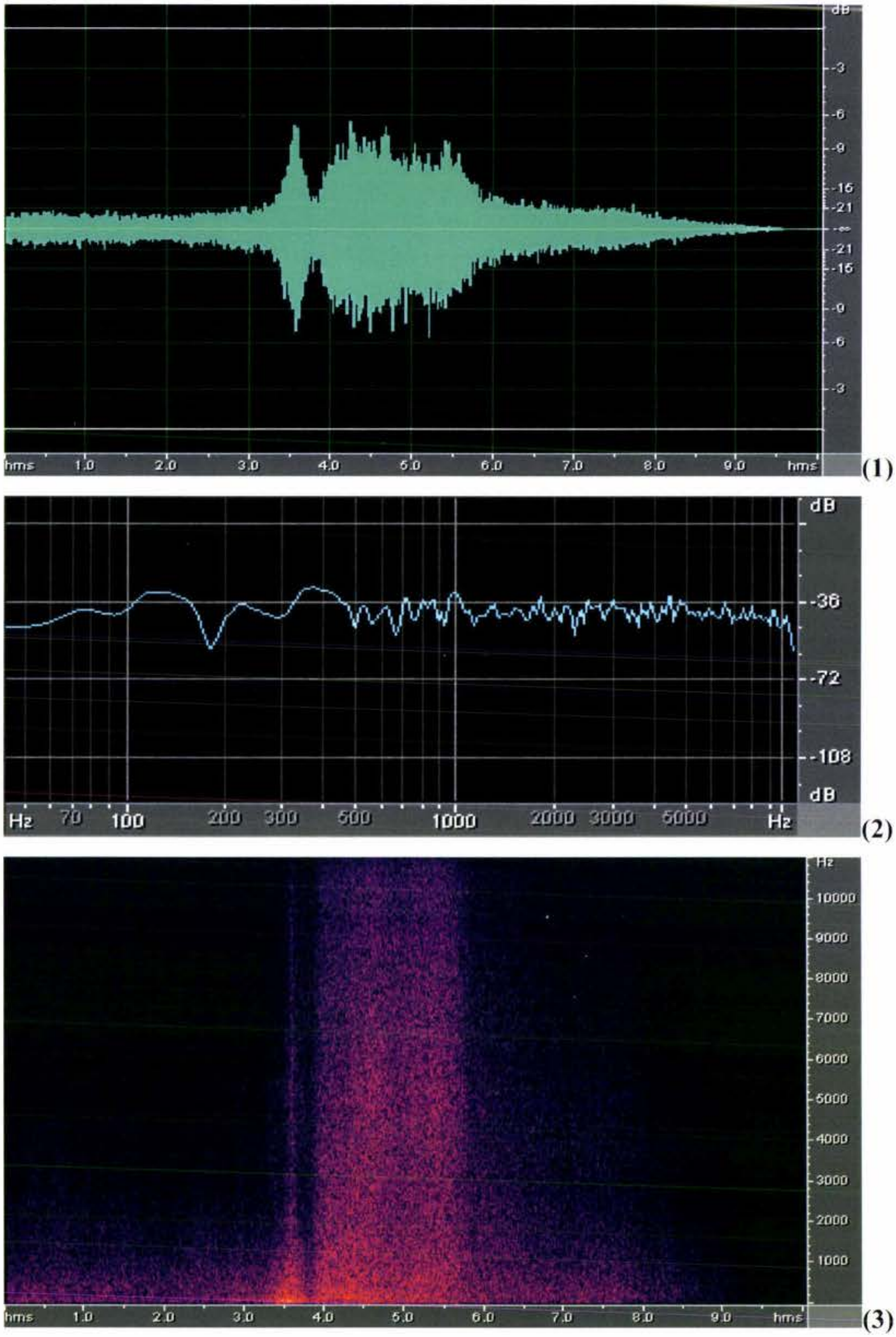

Figure 4.16: Waveform, spectrum analysis and sonogram of the sound generated by a sea wave clapping on the rock

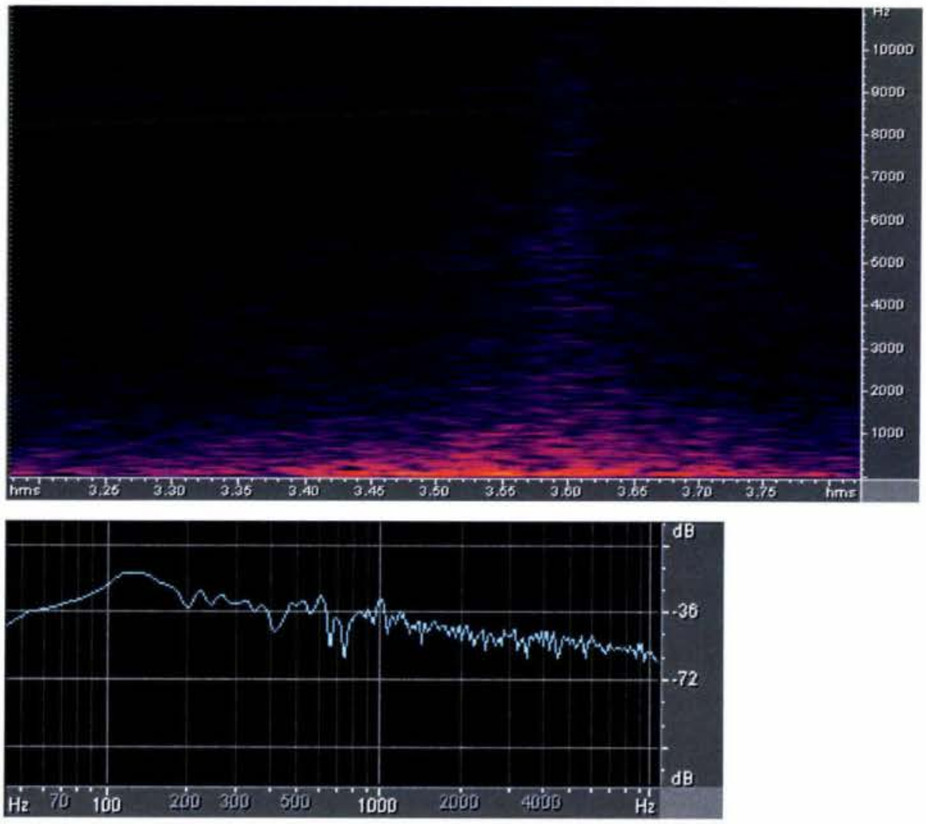

Figure 4.17: Enlargement of the impact signal

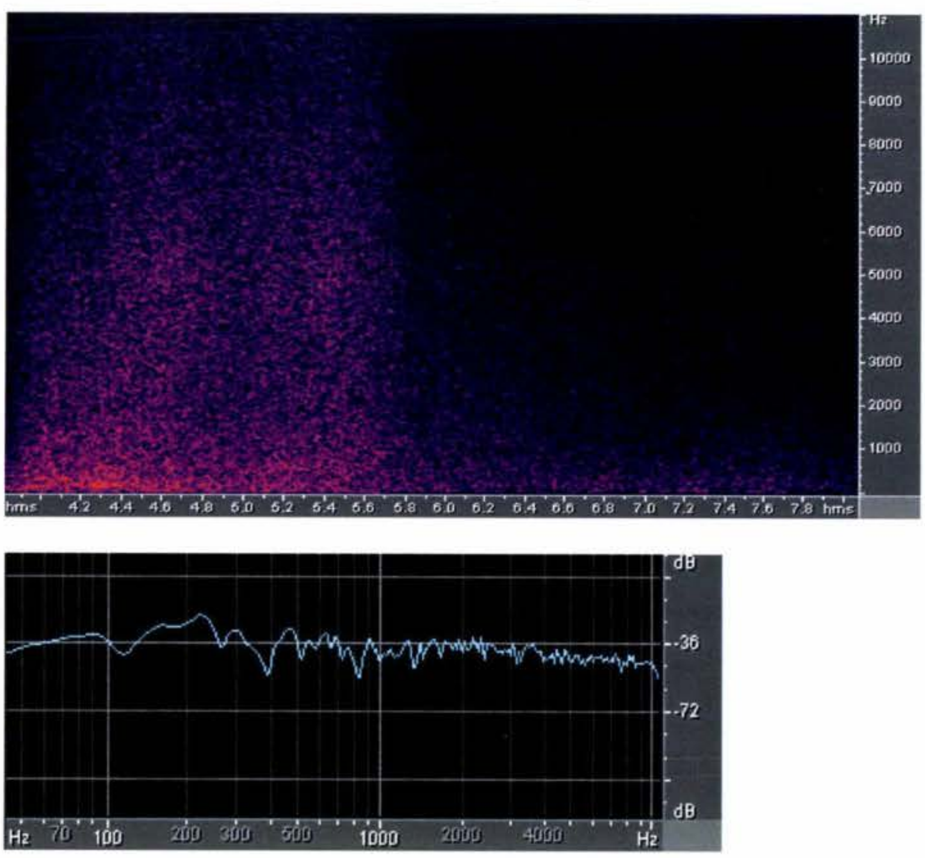

Figure 4.18: Enlargement of the splashing signal

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5 GEOTHERMAL SOUNDS

5.1 Introduction

5.1.1 Geothermal

As it is becoming increasingly clear that traditional energy resources would not be always available, alternative sources include solar and geothermal energy are getting more and more concern. Natural releases and exploitation of geothermal energy have been utilized for a long time. Italy has been generating electricity from natural steam sources since 1904, but the geysers steam plant in California constitutes the largest geothermal installation in the world at present and it produced almost 1000 MW in 1976. Traditional utilization of it includes therapeutic bathing, domestic services and mineral extraction. [1]

5.1.1.1 Geothermal Activities

Geothermal features are caused by water and molten rock on the earth's crust. The heat from the earth's core continuously flows outward. It transfers to the surrounding layer of rock, the mantle. When temperatures and pressures become high enough, some mantle rocks melt, and become magma. Because it is lighter (less dense) than the surrounding rock, the magma rises (convects), moving slowly up toward the earth's crust, carrying the heat from below.

Sometimes, the hot magma reaches all the way to the surface, where we know it as lava. However, most often the magma remains below the earth's crust, heating nearby rock and water to as hot as 700 degree F. Some of this hot geothermal water travels back up through faults and cracks and reaches the earth's surface as hot springs or geysers, but most of it stays deep underground, trapped in cracks and porous rocks. This natural collection of hot water is called a geothermal reservoir (See in Figure 5.1).[2]

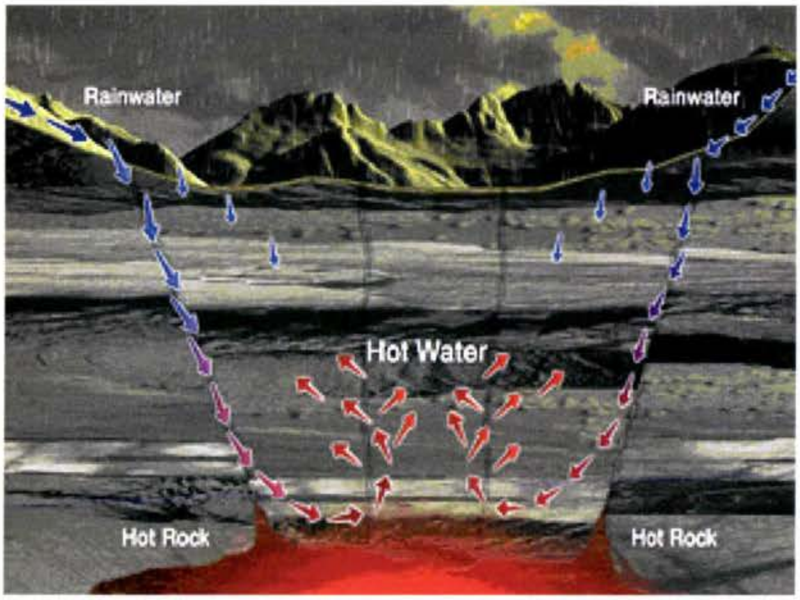


Figure 5.1: Illustration of a geothermal reservoir

Geyser

Geysers are some of the most unusual geologic phenomena in the world. The conditions for a geyser to erupt are extremely strict, which make the known geysers in the world less than 700. While geysers are rare, they are not impossible for the average person to observe. They exist on every continent in the world.

Technically the U.S. Geological Survey defines a geyser as: A hot spring characterized by intermittent discharge of water ejected turbulently and accomplished by a vapor phase. [3] Figure 5.2 shows a photograph of an erupting geyser that was taken in Rotorua, New Zealand. Steam and hot water are rushing into the air with considerable noise. The shooting height was reaching about 10 metres and this geyser eruption lasts for 20 minutes everyday.

Figure 5.2: Photograph of geyser

In order for a geyser to exist, there are four conditions that must be met. [4]

First there must be an abundant supply of surface water over a long period of time. The water mostly comes from snow and rain. When precipitation hits the ground, most of it runs off into rivers and streams. A small portion, perhaps five percent, soaks into ground. Moving slowly through tiny cracks, it finds its way into the underground tunnels that make up the plumbing of a geyser, then is shot to the surface during an eruption.

Secondly, there must be a volcanic heat source. All geyser field sites are above recently active volcanic areas. The surface water works its way down to a depth of around 7,000 feet where it meets up with hot rocks. The water is heated up to 500 degrees Fahrenheit or more, but cannot turn into steam because of the pressure it is under.

Though the water is hot and under pressure it would never be ejected from geysers with such tremendous force if it were not for the special quality of the rocks in the geyser fields. The rocks produce a material called geyserite. Geyserite, which is the third necessary condition, mostly silicon dioxide, is dissolved from the rocks and deposited on the walls of the geyser's plumbing system and on the surface around the geyser. The deposits make the channels carrying the water up to the surface pressure-tight. This allows the pressure to be carried all the way to the top and not be leaked out into the loose gravel, soil or sand that is normally under the geyser fields.

The final condition needed to produce a geyser is a plumbing system below it with a special shape. All springs must have a set of channels below them that allow water to flow to the surface. In a geyser there must be a constriction at some point near the top. The water sitting in this narrow spot acts as a valve or lid that allows pressure to build up in the water below. When enough pressure builds up to overcome the constriction, the geyser erupts.

Fumaroles

The requirement for the right combination of conditions: abundant water, volcanic heat, geyserites and a special underground shape, are why geysers are so rare. If there is heat, but not enough water a fumarole appears. A fumarole is a steam vent. There is so little water in this type of hot spring that while coming to the surface it boils away, and all that you see is a hole in the ground with steam coming out of it, often accompanied by a roaring or rushing sound. Fumaroles often have the smell of "rotten eggs" because small amounts of hydrogen sulfide get mixed in with the steam. Figure 5.3 shows a photograph of a fumarole taken at craters of moon in Taupo.

Figure 5.3: A fumarole's sound being measured by a sound level meter

Figure 5.4: Photograph of a mud pot

Mud pot

A fumarole that comes up in a wet surface area can become a mud pot. As the steam bubbles up through the water, the hydrogen coming up with the steam reacts with the water to form sulphuric acid. This melts the surrounding rock to turn the water into muddy clay. Mud pots bubble and can throw lumps of clay for some distance when they are active. Figure5.4, a photograph taken at Craters of the Moon in Taupo, shows the bubbling mud pool that makes boiling mud sound.

Geothermal areas

The ring of fire, which is formed by a continuous line of volcanoes and earthquake locations on the periphery of the Pacific Ocean, is the main geothermal areas in the world. New Zealand is located in this ring.

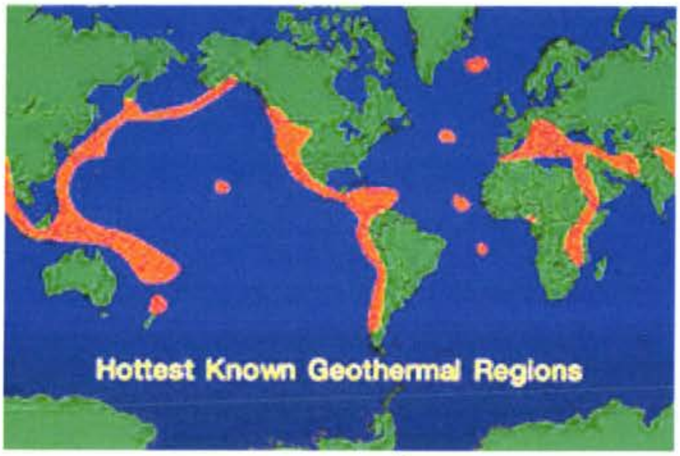


Figure 5.5: The Ring of Fire [5]

New Zealand has a good number of geothermal area and the most active ones are significant by world standards. It is one of the few places in the world where geysers can be admired. Several of these geothermal fields are easily accessible and have been developed for tourism purposes.

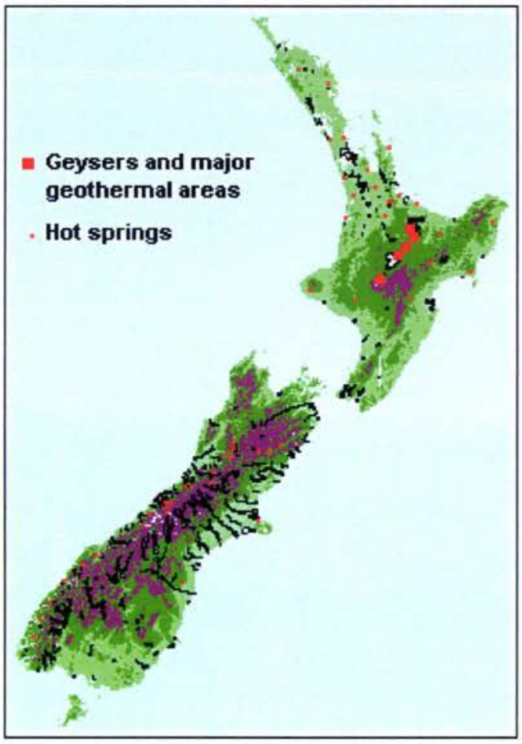


Figure 5.6: Geothermal fields in New Zealand [6]

An inventory has found 30 geothermal fields with 49 significant features within them, and 67 isolated hot springs. Five of the geothermal fields have been found to be of international significance: Ketetahi, Rotorua, Waimangu, Waitopu and White Island. A further 8 are of national importance, and 17 of regional importance.[7]

All main types of geothermal features are to be found in New Zealand. [7] They include geysers, hot springs, mud pools, fumaroles, and deposits (sinters, silica terraces).

Most intensive geothermal systems are associated with young and active volcanism, and are therefore located in the Taupo Volcanic Zone, between Ruapehu and White Island. They include all the geysers and other features that discharge boiling water. A few smaller intensive systems are associated with other areas of young volcanism: in Northland, Hauraki Plains, and the coastal Bay of Plenty. Many hot springs, particularly in the South Island, are associated with faults and tectonic features.

5.1.2 Geothermal Sounds

Surveys and research on the geothermal activities are able to obtain some important information. They can help to make the prediction of eruption, to estimate the energy ejected and the potential energy a geothermal field contains. Among the geothermal activities, most make specific sounds, which make the sound feature a most useful observation tool for monitoring geothermal phenomena.

The sounds during geothermal activities can be mainly classified into two types according to their generation mechanisms: boiling sound and eruption sound.

5.1.2.1 Boiling sound

The familiar process of boiling is actually very complex in terms of the physical changes that occur and the sound generated. The whole process can be divided into two phases, in which the cavitations and boiling respectively are the generation mechanisms. The boiling activities in geothermal areas, mud boiling and water boiling belong to the latter.

In simplest terms, cavitation is the process in which a liquid changes to a vapor due to a reduction in pressure.

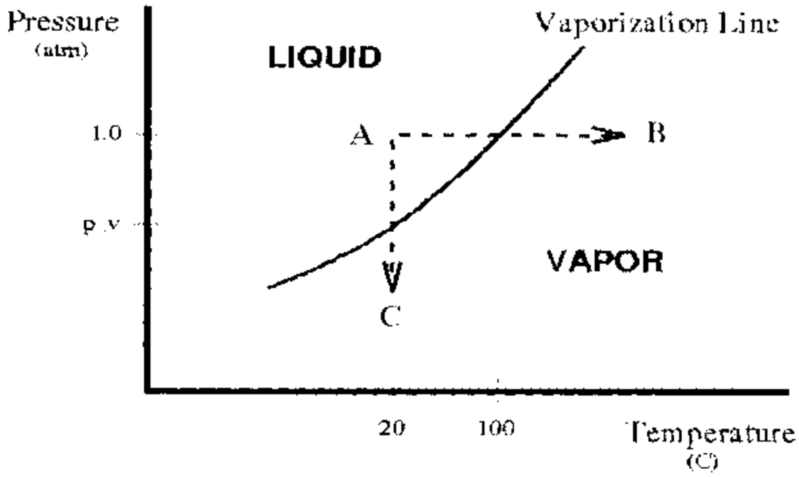


Figure 5.7: Water vaporization [8]

Each point in the diagram represents a specific pair of temperature and pressure. For example, typical room conditions, with a pressure of 1 atmosphere and a temperature of 20 degrees C, are represented by point A.

Suppose we have a water sample at point A, and we begin increasing its temperature. Eventually, its temperature will reach a point (100 degrees C) where it will change from a liquid to a vapor. The water boils. In the diagram above, this corresponds to process $A \rightarrow B$. This process crosses the "vaporization line", indicating that the water has changed from a liquid to a vapor.

Cavitation, existing in many natural and mechanical circumstances, is the dynamic process of gas cavity formation, growth and collapse in a liquid. These cavities are "due to the presence of dissolved gases or volatile liquids which are formed at the point where the pressure is less than the saturation pressure of the gas (gaseous cavitation) or vapor pressure (vaporous cavitation)".[8]

Water boiling is the most familiar cavitation phenomenon that we would meet everyday in the kitchen. The whole process is not that easy as it appears. When we heat up water in a vessel and observe the gradual progress, "we shall perceive that, after a time, very minute bubbles are give off. These are bubbles of dissolved air. Soon after, at the bottom of the vessel, and at those parts of the sides, which are most immediately exposed to the action of the fire, large bubbles of vapor are formed, which decrease in volume as they ascend, and disappear before reaching the surface. This stage is accompanied by a peculiar sound, indicative of approaching ebullition, and the liquid is said to be singing. The sound is probably caused by the collapsing of the bubbles as they are condensed by the colder water through which they pass. Finally, the bubbles increase in number, growing larger as they ascend, until they burst at the surface, which is thus kept in a state of agitate, and the liquid boils." [8]

Boiling and cavitation are defined more accurately as follows according to Figure5.7:

Boiling (A → B)

Change from liquid to vapor due to increase in temperature.

Cavitation (A → C)

Change from liquid to vapor due to decrease in pressure.

But in the process of boiling (A → B), the part from point A to some point before the vaporization line also is cavitation.

5.1.2.2 Eruption sound

The eruption sound can be found usually in the geothermal activities as geyser and fumarole. Geyser and fumarole are all jet flow, which means a high-velocity fluid stream forced under pressure out of a small-diameter opening or nozzle.

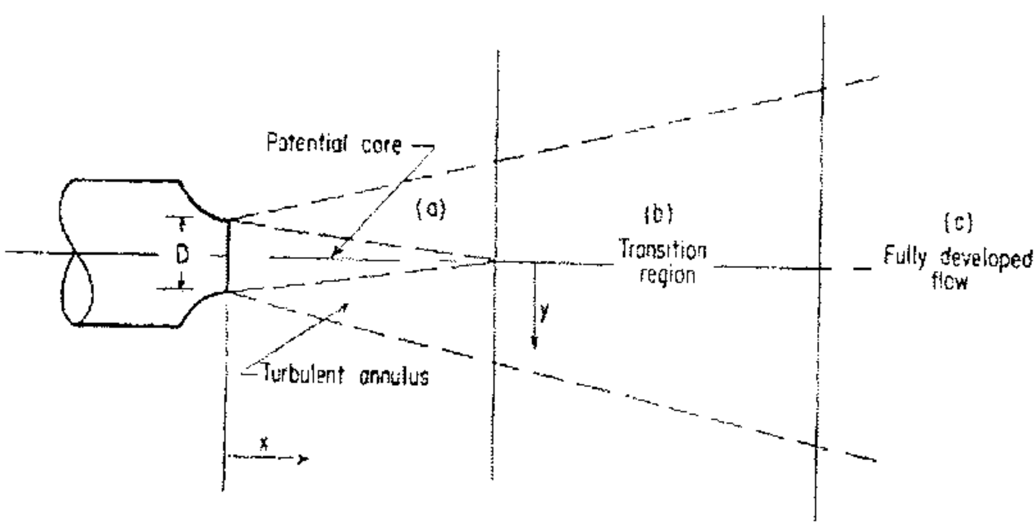


Figure 5.8: Schematic diagram of the flow issuing from a circular nozzle in still air [11]

"The total sound power radiated by a gas jet flow may be expressed in terms of the mechanical stream power in the jet, equal to

$$W = \frac{1}{2} m u^2$$

where m = mass flow of gas, kg/sec

u = speed of flow at exit nozzle, m/sec" [9]

A lot of experiments were conducted to get the information on sound source by using statistical methods to give the distribution of the jet sound power along the whole jet. [11] Turbulent mixing noise nowadays gets the most acceptance. The velocity difference between the adjacent particles of jet flow generates shear forces and thus produces the jet structure convection, which brings the turbulence in the form of eddies.

Hileman and Samimy (2000) described the process as "the large turbulent eddies have been shown to evolve and interact in three ways. First, structures convect downstream entraining fluid from the ambient and as such grow in size. Second a fast moving structure will catch up with a slower structure that is downstream. When they approach one another, they begin to rotate about a common point; this leads to the two structures "pairing" together. Third, individual structures have also been torn into two or more separate structures." [10]

The relationship between turbulence and sound level is a key point to reveal the mechanism of jet noise generation. An experiment by Hubbard and Lassiter (1952) is a good example. [11]

In their experiment, "Pressure measurements have been made with a microphone at locations near the jet in an attempt to correlate the near field noise with the turbulence data which were measured inside the jet stream by the use of hot wire equipment." A series of pressure distribution was measured along a line parallel to the jet boundary, as shown in the following figure.

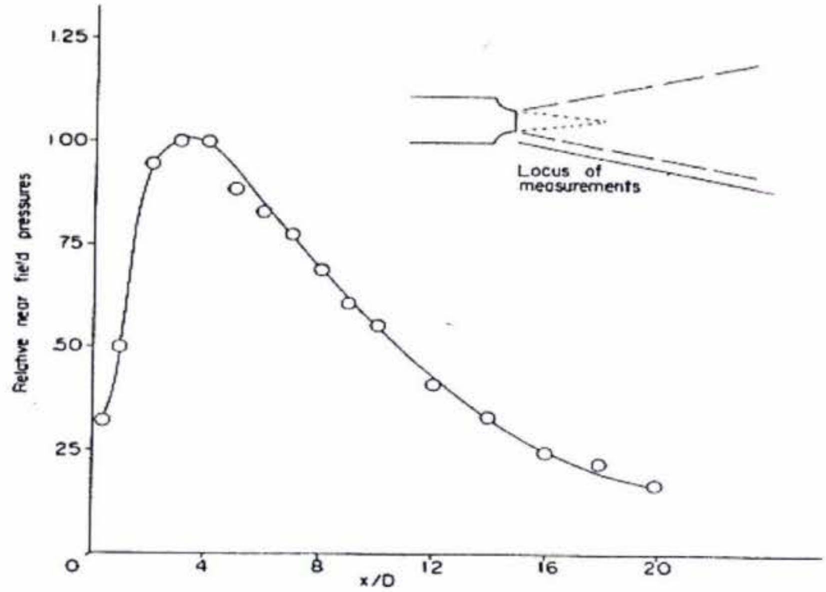


Figure 5.9: Relative over-all pressure in the near field of a model air jet as a function of the axial distance

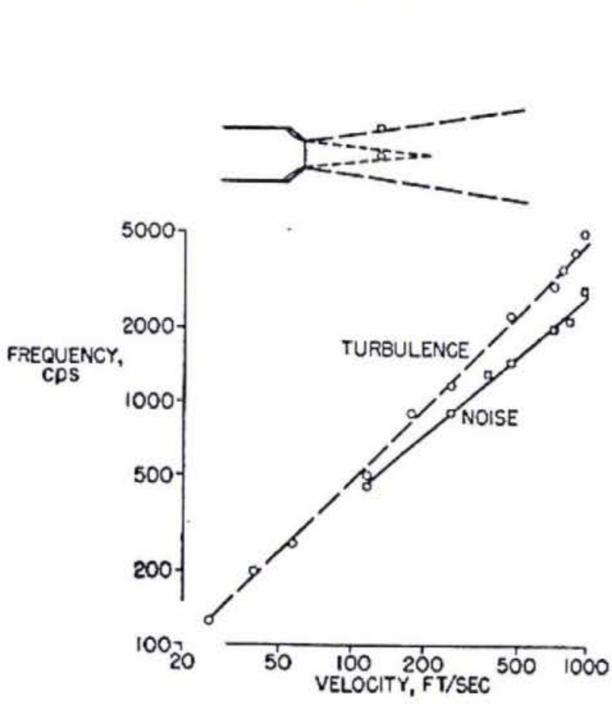


Figure 5.10: Comparisons of noise and frequencies as a function of exit velocity for a model jet

The obtained curve and data indicate "the pressure magnitudes have a low value near the orifice, increase rapidly to a maximum a few diameters downstream and then decrease rather gradually as axial distance is further increased." [11]

When we compare the pressure distribution curve with the jet turbulence profiles curves especially the y/D = 0.5 one, we can see their shapes are very similar, which indicate that "the maximum pressure values are associated with the region of the jet where the highest velocity fluctuations exist." that means the main source of jet noise is from region (a) and region (b) about axial range from 4D to 10D, where the jet transition happens. (See Figure 5.8)

Figure 5.9 shows that the jet noise frequencies are also results of jet flow style. Heller and Franken (1988) explained "the very high frequencies of such jet noise are predominantly radiated from the flow region close to the nozzle where the eddy sizes are small. Lower frequencies are radiated further downstream where eddy sizes are much larger". Figure 5.10 from Hubbard and Lassiter shows the relationship between the jet noise frequencies and axial distance downstream the jet nozzle.[11]

There are several parameters that can affect the jet noise intensity and many experiments have been done to find out the effect of these parameters. Internal noise, jet velocity, observer's distance, azimuth of field point, jet temperature, jet nozzle size medium density and jet turbulence, all contribute to the jet noise level.

5.2 Boiling Experiment

To investigate the boiling process, an experiment was conducted by means of recording the sound of the whole process and then analyzing the sound at different stages.

Time-frequency analysis was conducted to show sound characteristics in different stages.

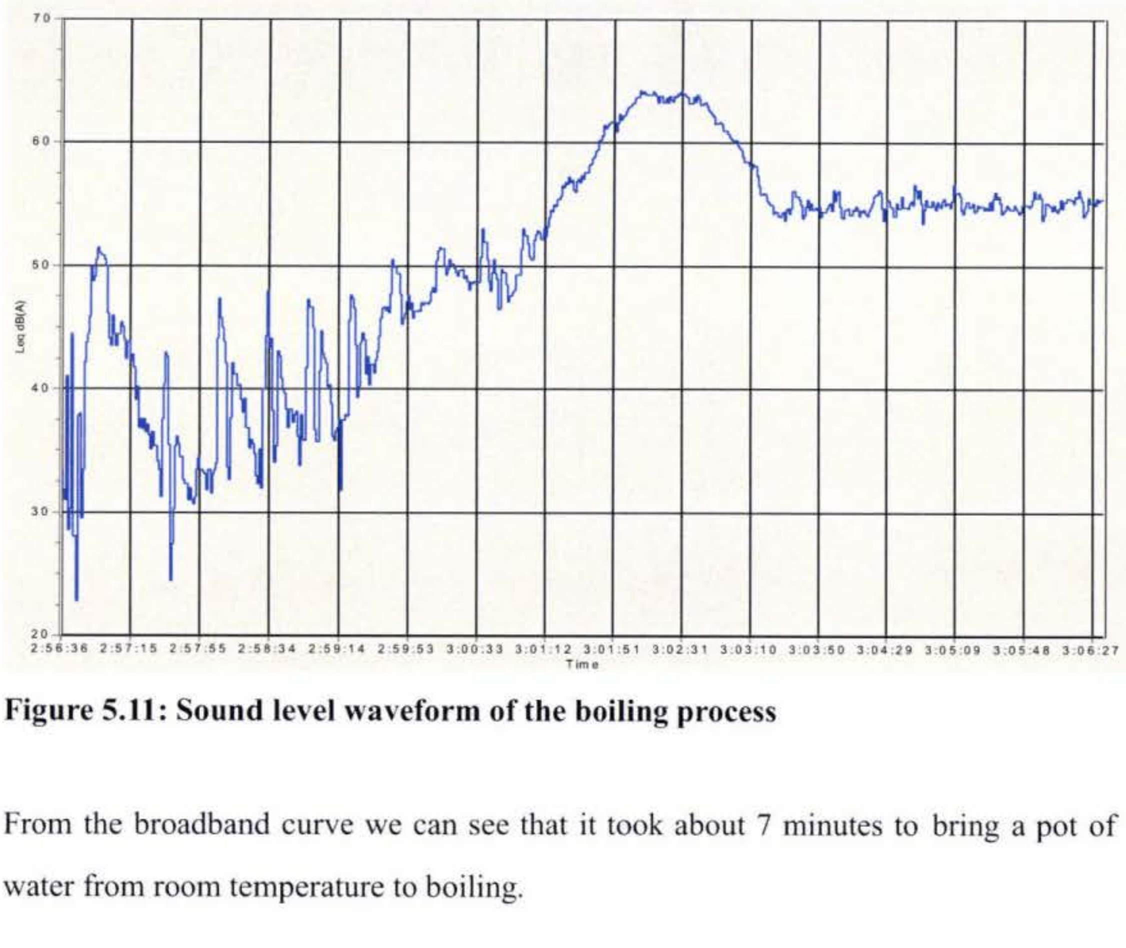


Figure 5.11: Sound level waveform of the boiling process

From the broadband curve we can see that it took about 7 minutes to bring a pot of water from room temperature to boiling.

The difference between the maximum and minimum sound pressure level is about 30 dB, with the minimum at the beginning about 35 dB and maximum just before the rolling boiling point about 65 dB.

According to the curve, different stages can be clearly observed.

The seven points in each curve were selected to represent the different seven stages:

1. No or very few bubbles before the visible boiling begin
2. At the beginning of the visible bubbles coming out
3. In the middle of the boiling process
4. The peak sound area
5. In the middle of sound decline
6. At the beginning of the rolling boiling
7. Rolling boiling stage

The whole boiling process can be divided into five stages according to the sound level–time history waveform:

Stage 1 (00:00:-00:00:30) No cavitations sound appearing

Stage2 (00:00:30-00:03:20) Cavitations getting more

Stage3 (00:03:20-00:05:30) Sound level ascending to a peak value

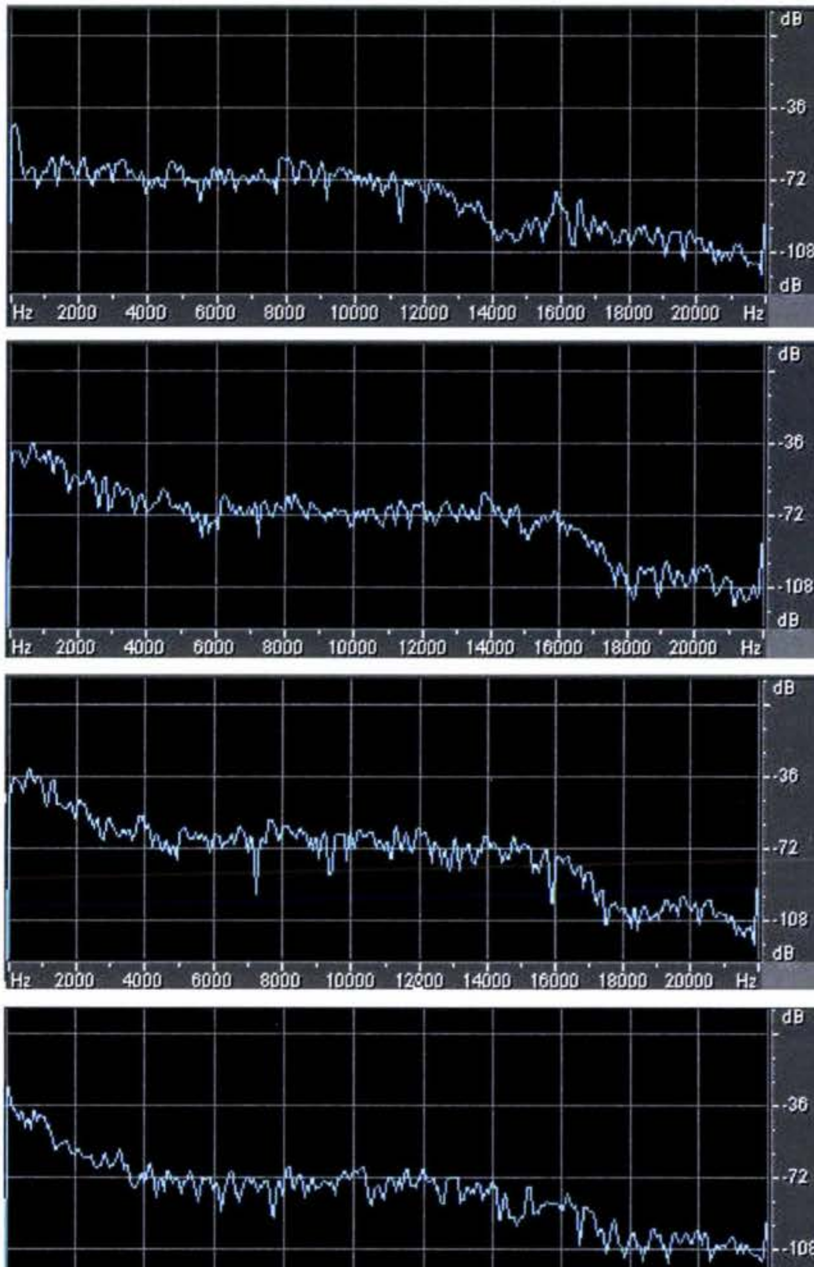
Stage4 (00:05:30-00:06:30) Sound level descending to a relatively constant value

Stage5 (00:06:30-00:10:00) Steady rolling boiling stage

The first 30 seconds shows irregular shape. It was influenced by the unbalanced state of the water or the deformation of the heater element during heating.

After that the signal shows a slightly increase to a local peak value. Then it goes through an arc to a local minimum and increases in a relatively sharp curve to the maximum value. After maintaining in the maximum value for 40 seconds, it drops again and reaches the final constant rolling boiling stage.

Five different points were taken from the above period to show the different frequency distributions in different stages.



(1) (2) (3) (4) (5)

Figure 5.12: Spectrum analyses of five selected points

Graph 1

The very low frequencies hold the maximum value and it drops rapidly in this narrow scale. From 100 Hz on, it remains a relatively constant level until 12000 Hz, and decreases slightly in the high frequency part 16000 – 22000 Hz. Between 12000 Hz and 16000 Hz, it appears as an arc shape.

Graph 2

The very low frequencies hold the maximum value and it drops slightly below 6000 Hz. From 6000 Hz on, it remains a relatively constant level until 16000 Hz, and decreases slightly in the high frequency part 16000 – 18000 Hz. After that it maintains a relatively constant level.

Graph 3 and Graph 4

The difference compared to the last curve is that in the high frequency part the sound level slightly increases and decreases before and after 20000 Hz.

Graph 5

The beginning very low frequency holds the maximum value and it runs decreasingly to the high frequency with two relatively rapid drops at 6000 Hz and 17000 Hz.

Discussion

1) *The curve of waveform indicates the characteristics of each above stage*:

Stage 1 shows the characteristics of steady noise, of which the dispersion of sound level between lower and maximum value is confined to 5 dB

Stage 2 shows the characteristics of impact noise, which is characterized by a rapid rise to a peak level followed by a series of increases and decreases in pressure that decays in a finite time.

Stage 3 and stage 4 show the time-varying noise characteristics. In stage 3 the sound level is increasing along with the time history and decreasing in stage 4.

Stage 5 shows a higher-level steady noise.
Between stage 4 and stage 5 a subtly lower level lasts for around 10 seconds, which is termed the silence before boiling.

2) *The sound sources of different stages*:

At the first stage, the main sound sources should be the distortion of the steel pot by the heating and the background noise.

The intermittent cavitations' popping sound is the main sources during the second stage.

Increasing cavitations make the sound level ascending continuously in the third stage.

When the water's temperature is increasing, the cavitations is decreasing in numbers, thus the total sound is decreasing during the fourth stage.

When the water is hot enough, the bubbles will burst at the surface, which is the main source of the sound. The sound remains a steady level.

3) *The common and different points of different stages in the same process*:

Even the values and patterns of different stages in a whole process are quite different; there are still some common points. Of all the five different points, the highest part focuses in the low frequencies. This common point indicates the characteristics of boiling process.

5.3 Geothermal Sounds Analysis

5.3.1 Boiling Mud Pot Sound

A recording of mud bubble collapse sound was taken on a fine day in the Taupo geothermal field. The boiling mud was about 5 metres down from the microphone and no other sounds were evident. The mud bubbles were coming out from the pool continuously. The size of the bubbles and the distances from the bubbles to the microphone varied along with the time. Due to the different nature of bubbles between mud and water, the mud bubbles were distinctively visible. The following Figure 5.13 was taken from the recording showing 2.5 seconds waveform of the mud bubble collapsing sound. There was a major bubble collapsing sound happened at 0.6 second and some other mud bubbles collapsing happened all the time that cannot be heard clearly. This can be seen from Figure 5.14 more clearly.

The major collapsing sound happened at 0.6 second creates a tiny vertical bar in the sonogram in Figure 5.14. Another vertical bar at 1.3 second indicates another major bubble collapsing. As can be seen, the two distinct bars dominate at different frequencies, which can be explained by different sizes of the two bubbles.

Figure 5.15 gives out the spectrum analysis of the mud pot sound which covers the whole recording process. The sound shows the characteristics of low frequency sound with the peak value of sound power residing at 50 to 60 Hz. The curve slightly increases the value from 0 to 60 Hz and reaches the top at 50 to 60 Hz. After that, the value begins to slightly decrease.

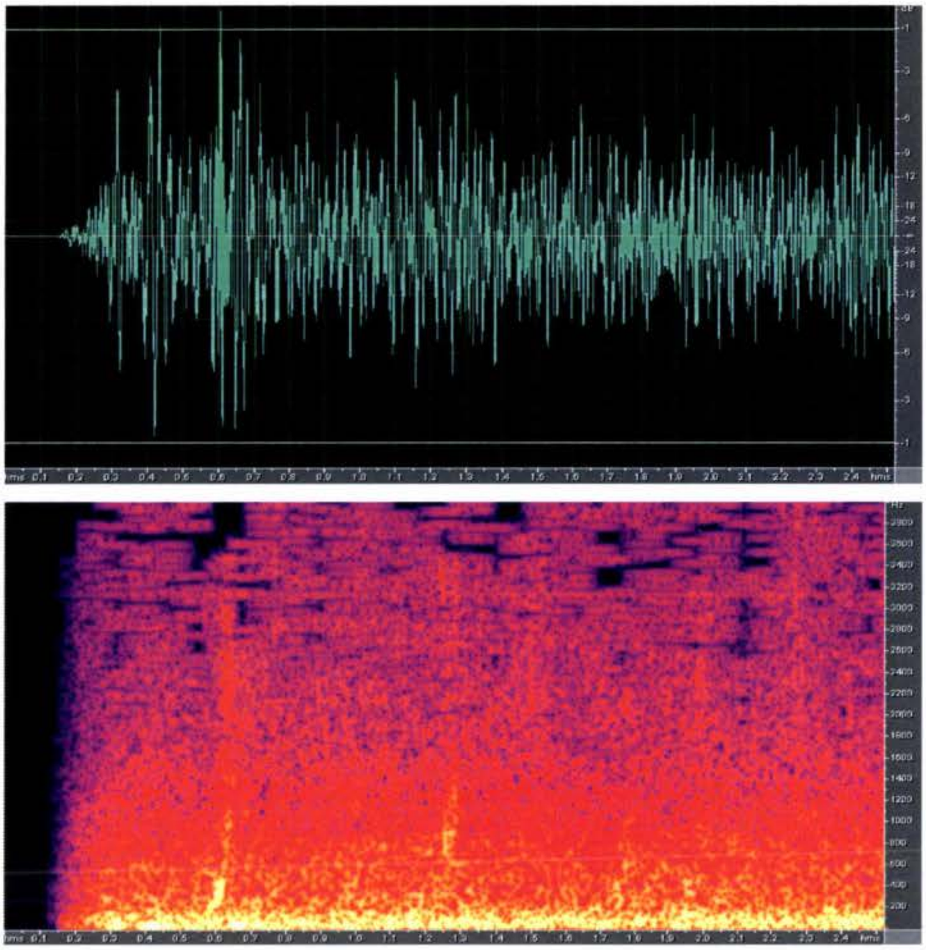


Figure 5.13: Waveform and sonogram of mud bubble collapse

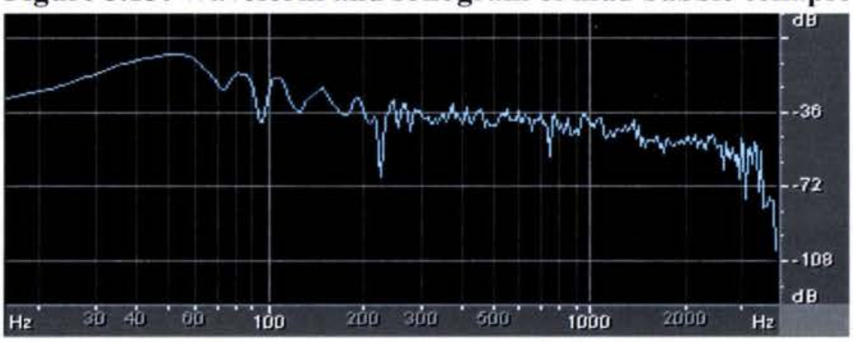


Figure 5.14: Whole process spectrum analysis of mud bubble collapse sound

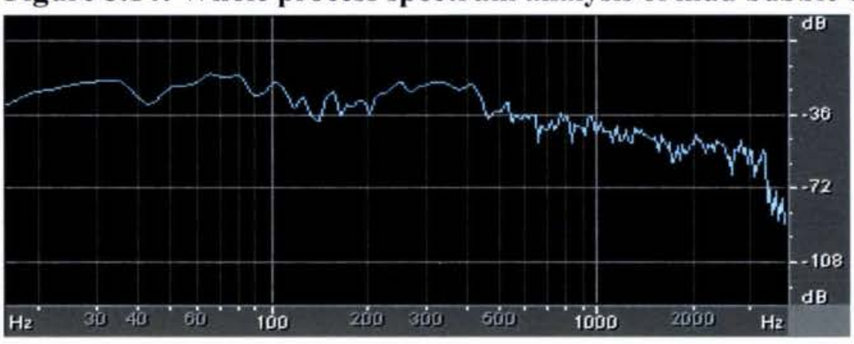


Figure 5.15: Spectrum analysis of mud bubble collapse sound at 0.6 second

A spectrum analysis was conducted for the 0.6 second mud bubble collapsing sound to show the characteristics of the sound. In Figure 5.16, the collapsing sound shows two maximum values respectively at 70 to 80 Hz and 300 to 400 Hz. This indicates that the collapsing sound of major single bubbles is showing a higher frequency nature than the whole process sound.

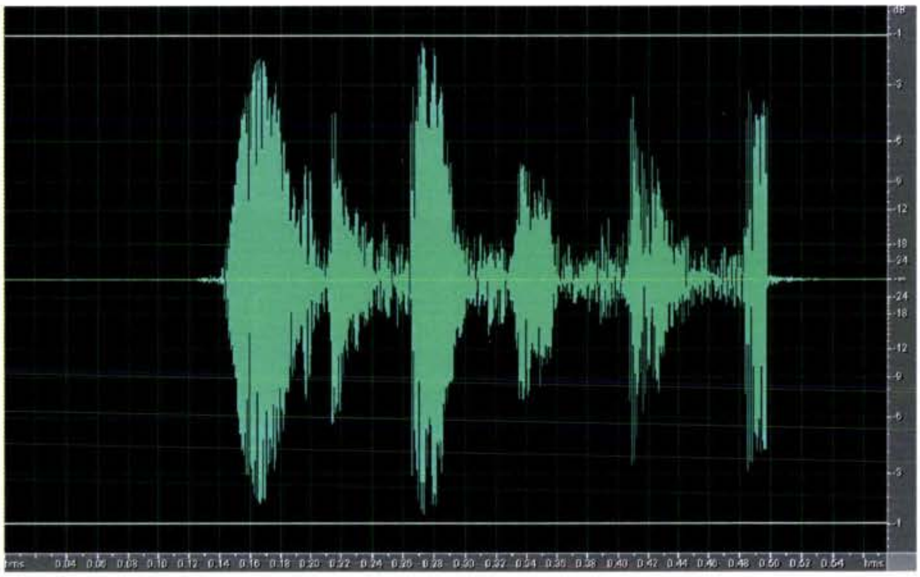


Figure 5.16: Waveform of water bubble collapse sound

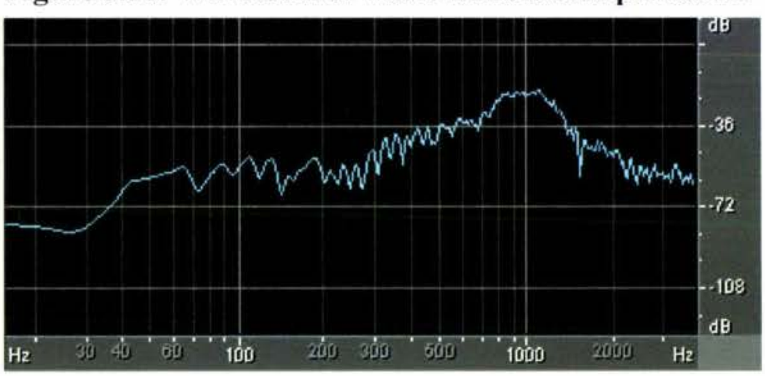


Figure 5.17: Spectrum analysis of water bubble collapse sound

When compared the water boiling bubble sound to the mud bubble sound, great differences show up. Water bubbles in the pot come out much more frequently than the mud bubble in the pool. The size of the water bubble is much smaller than the mud bubble.

The spectrum analysis of water bubble shown in Figure 5.17 is considerably different from Figure 5.15. The dominant value happens at about1000 Hz.

5.3.2 Eruption Field Sound

5.3.2.1 Geyser Eruption Sound

A recording of geyser eruption sound was taken in Taupo geothermal field. The waveform of the sound is shown in Figure 5.18.

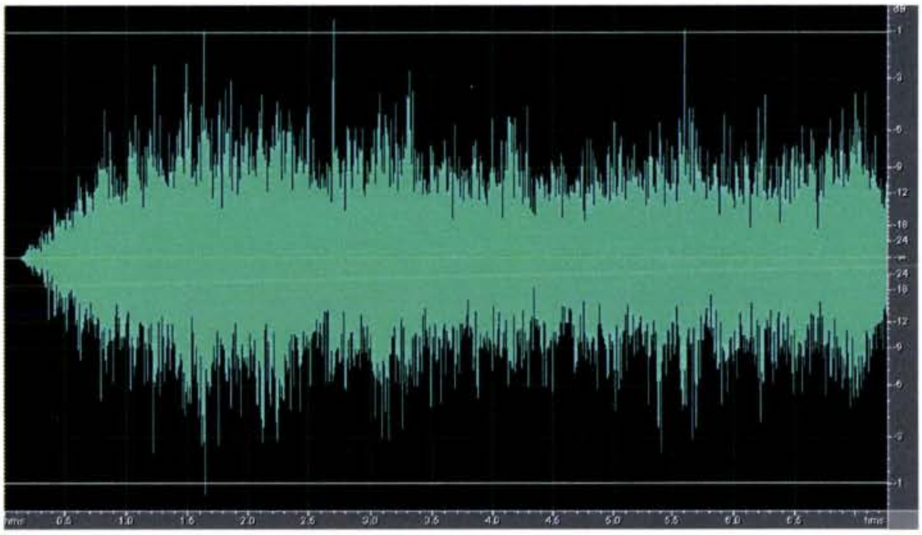


Figure 5.18: Waveform of geyser eruption sound

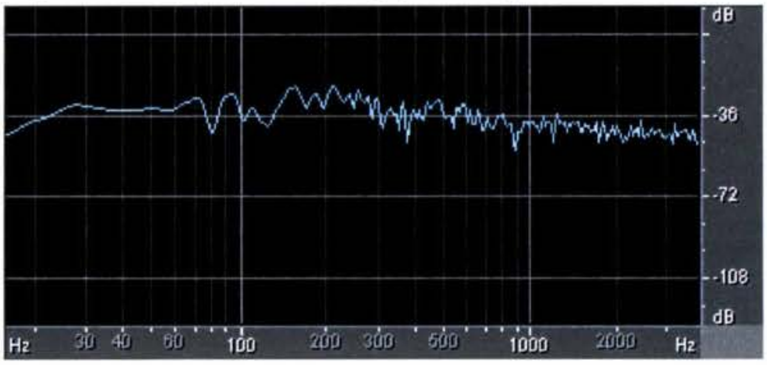


Figure 5.19: Spectrum analysis of geyser eruption sound

The spectrum analysis of the geyser eruption sound shows characteristics of white noise. The curve undulates slightly from low frequency part to high part with no distinctive peak appears. However, the highest value happens around 200 Hz.

5.3.2.2 Fumarole Eruption Sound

A recording of fumarole sound was taken in Taupo geothermal field. The waveform of the sound is shown in Figure 5.20.

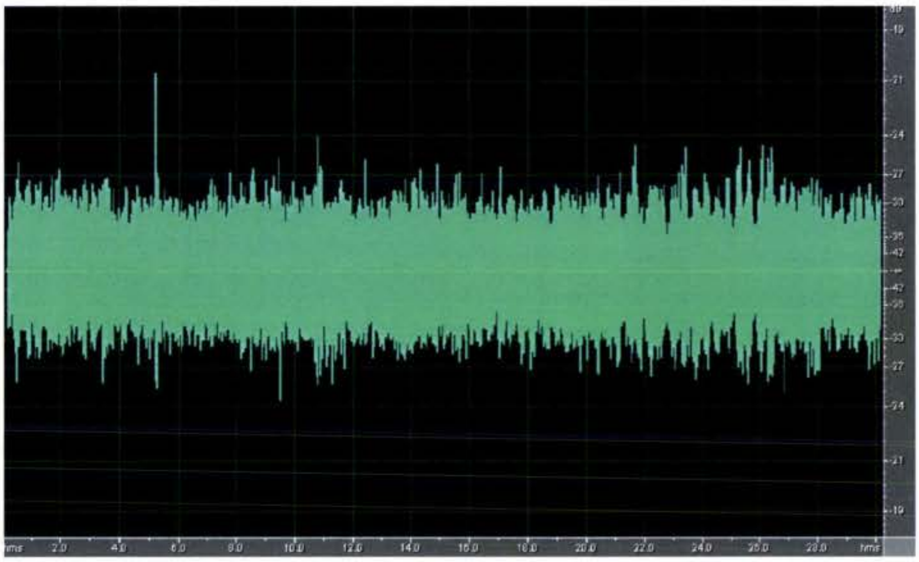


Figure 5.20: Waveform of steam vent sound

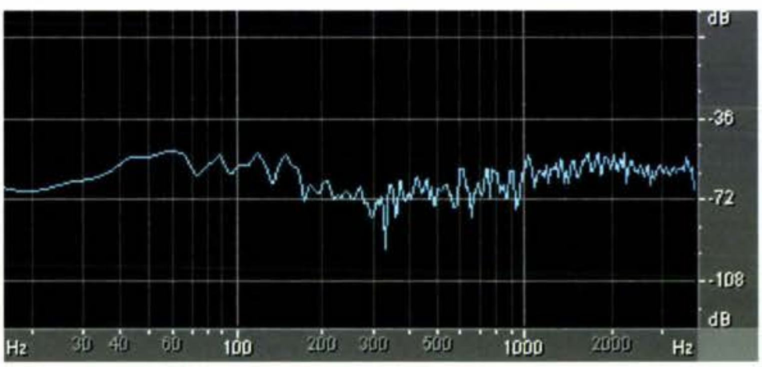


Figure 5.21: Spectrum analysis of steam vent sound

The power level of the steam vent sound is much lower than the geyser eruption sound due to the difference of pressure underground and the difference of the material that comes out. Figure 5.21 shows that the steam vent sound level has two maximum. The largest is at about 60 Hz, the other is in the region of 2000 Hz.

5.4 References

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6 BUBBLE ACOUSTICS

6.1 Introduction

Breaking wave sounds, boiling water sounds, river sounds, waterfall sounds and rain sounds have a great deal of similar points when looked through the frequency spectrum. Bubbles also get involved in almost all the water sounds, which makes bubbles worth being investigated thoroughly to reveal the mechanisms of all the water sounds.

Bubbles are familiar from daily life and occupy an important role in physics, chemistry, medicine and technology: the production and transportation of oil, in which bubbles are purposely injected to help lift heavy oil to the surface; energy generation, in which boiling is the key process in producing the steam to drive turbine; the chemical industry, in which gas-liquid reactors rely on bubbles to increase the contact area between the phases.

Bubbles are also readily found in nature. The oceans, in which bubbles generated by breaking waves are important sinks for atmospheric carbon dioxide. Rains, which create numerous bubbles, are the key process in the hydrological cycle of the earth.

However, bubble's behaviors are still not understood in a great extent. The research about bubble sounds is a useful approach to reveal some important characteristics of bubbles. With their ubiquitous occurrence in a multitude of fluid systems, bubble studies occupy an important place in contemporary science and technology. Furthermore, the bubble acoustics itself is worth being investigated in depth.

6.1.1 The Two Types of Natural Bubbles

Naturally bubbles can be classified as air bubbles, which are filled with air, and vapor-filled bubbles.

6.1.1.1 Air bubbles

Bubbles due to the decrease of external pressure

Under a pressure of one atmosphere, about 15 milliliters of air will dissolve in a liter of water at 20 Celsius. At higher pressures, the solubility of any gas in water increases. When the external pressure of the water decreases, bubbles usually appear immediately. Sometimes the bubbles are very small and make the water look cloudy, but the water clears after the bubbles float to the surface. The examples can be readily seen in daily life: cloudy water coming from a kitchen faucet is due to the decrease of the pressure from the air tight pipe to the open atmosphere. Tiny bubbles rising up to the top always can be seen when a bottled soda is opened, which is also due to the decrease of the external pressure. In nature, air bubbles usually happen imperceptibly. Sometimes bubbles with other gases instead of air can be seen more easily.

Entrapped bubbles

When a liquid drop falls onto a water surface, a bubble is created. The following serial photographs shown in Figure 6.1 illustrate the progression of the entrapped bubble evolution.[1] Frazier and Christie (2001) depicted the formation process of this kind of bubbles.[2] After the drop penetrates the surface, a crown begins to form around the point it penetrates. As the drop displaces more of the water, the displaced water is fed into the walls of the crown. What happens at this point is the defining factor in determining whether or not a bubble will form. As water is being fed into the walls of the splash, the walls grow higher and can eventually curl inwards and meet directly above the point of penetration. This meeting of the walls is what we refer to as the dome of the splash. Without a dome, a bubble can never form.

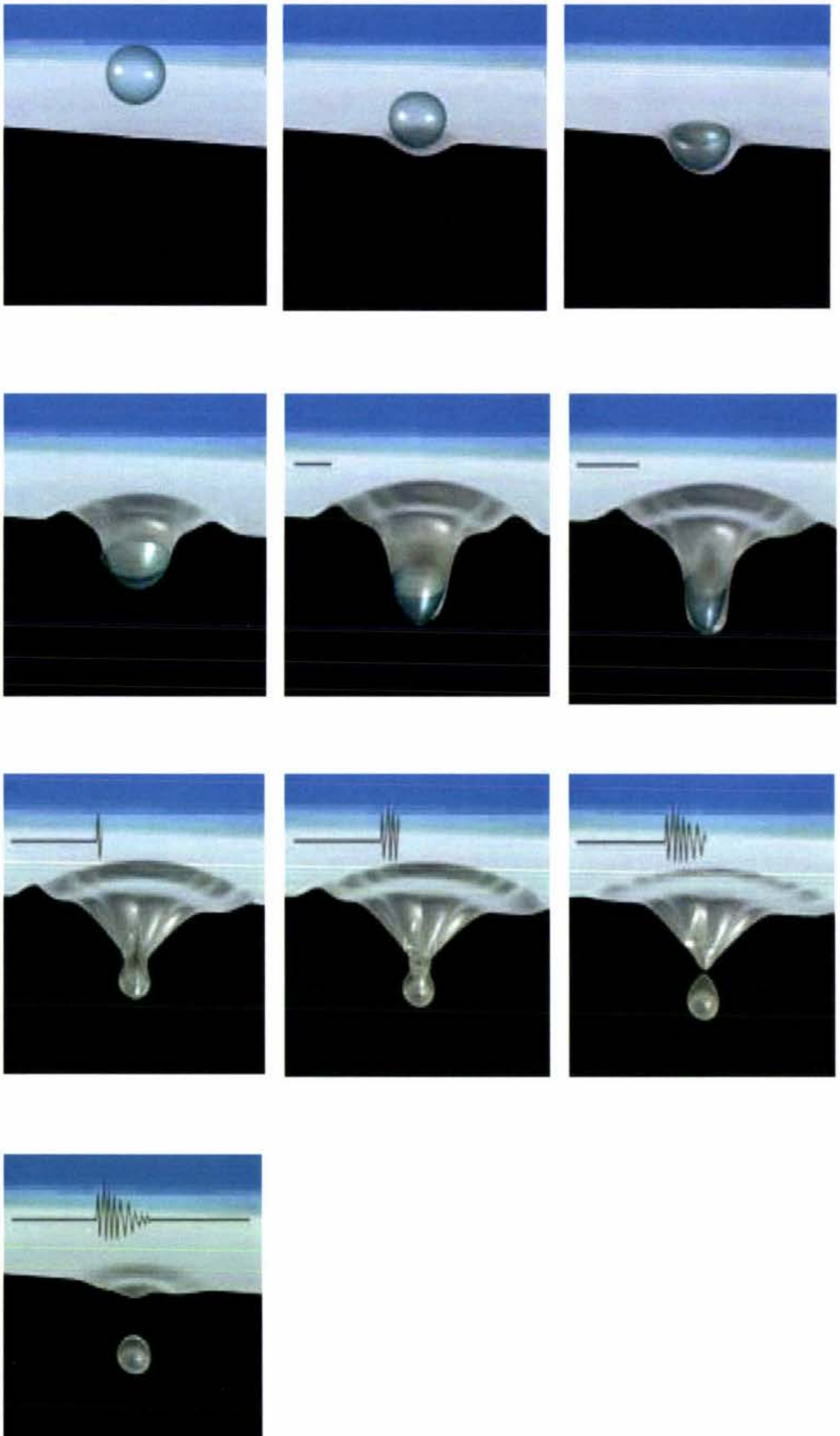


Figure 6.1: The evolution progression of a drop bubble [1]

6.1.1.2 Vapor-filled bubbles

Bubbles can be injected in some fluids, but they can also form spontaneously. Such spontaneously formed bubbles mainly contain liquid vapor instead of some other gases. This process of bubble formation, familiar to all of us from boiling water, is called cavitation or nucleation.[3] Cavitation can occur in a liquid when the local pressure $P(X)$ drops below the vapor pressure P_V of the fluid.[4]

One way to achieve cavitation is to increase the liquid's temperature, because the vapor pressure is temperature dependent: For water at 20°C, the vapor pressure is 0.023 bar (2.3 kPa), but at 100°C, it is 1 bar, and thus the water boils.

Another way to achieve cavitation is to increase the local flow velocity $U(X)$.[5] An easy experiment is to reduce the cross section of a pipe in one region, making a so-called diffuser that produces large local flow velocities due to mass flux conservation. For steady potential flow, the corresponding local pressure $P(X)$ can be estimated from Bernoulli's equation.

$$P(X)+\frac{1}{2}\rho U^2(X)=constant$$

At an ambient reference pressure of 1 bar and at room temperature, a water velocity of about 14 m/s is sufficient to nucleate bubbles.

Bernoulli's estimate does not consider viscous effects, the gas content of the fluid, impurities, or walls and other inhomogeneities. Indeed, in extremely purified water, cavitation occurs at much larger tensions ("negative pressures") than in normal water, but still far from the value calculated from the attractive van der Waals forces between the water molecules. Crevices at surfaces or remaining impurities to which submicron gas bubbles attach seem to play a prominent role in the bubble nucleation process, but the understanding of cavitation is still incomplete.[5]

Water boiling is the most familiar cavitation phenomenon that we would meet everyday in the kitchen. The whole process is not that easy as it appears. Deschanel (1891) depicted the process of boiling as follows. [6] When we heat up water in a vessel and observe the gradual progress, "we shall perceive that, after a time, very minute bubbles are given off. These are bubbles of dissolved air. Soon after, at the bottom of the vessel, and at those parts of the sides which are most immediately exposed to the action of the fire, large bubbles of vapor are formed, which decrease in volume as they ascend, and disappear before reaching the surface. This stage is accompanied by a peculiar sound, indicative of approaching ebullition, and the liquid is said to be singing. The sound is probably caused by the collapsing of the bubbles as they are condensed by the colder water through which they pass. Finally, the bubbles increase in number, growing larger as they ascend, until they burst at the surface, which is thus kept in a state of agitate, and the liquid boils."

6.2 Bubble sounds mechanism

Bubbles produce much of the noise that accompanies numerous natural phenomena involved in water.

Bubbles natural sources

1. Ocean breaking waves cause atmospheric gases to mix with the sea, creating air bubbles near the water surface.

2. Raindrops create air bubbles as they impact the ocean or lake surface.

3. Rushing rivers create air bubbles as they flow through the watercourse.

4. Waterfall water creates volume bubbles when they heavily hit the water.

Natural Frequency

A bubble is analogous to a simple spring mass system. The compressible gas in the bubble forms the spring. The fluid surrounding the bubble provides the mass.

The bubble's first mode shape corresponds to an alternating compression and expansion of the gas in the bubble. The displacement is symmetrical in the radial direction.

The natural frequency f_n of a spherical bubble [7] is

$$f_n = \frac{1}{2\pi R_0 \rho^{\frac{1}{2}}} \left[3kP_0 - \frac{2\sigma}{R_0} \right]^{\frac{1}{2}}$$

Where

$P_0 =$ absolute liquid pressure

$R_0 =$ mean radius of the bubble

$k =$ polytropic constant of the gas in the bubble

$\sigma =$ surface tension constant

$\rho =$ mass density of the liquid surrounding

Surface Tension

The surface tension constant for air/water at $20\,^{o}C$ is $\rho = 7.27 \times 10^{-2}\,N/m$. The effect of the surface tension on frequency diminishes as the radius becomes larger.

Density

Density values for selected liquids are given in Table 6.1.

Table 6.1: Liquid density

Liquids	Temp. (^{O}C)	Density (Kg/m^3)
Water (fresh)	20	998
Water (sea)	13	1026

Polytropic Constant [1]

The dimensionless polytropic constant k can vary within the range $1 \le k \le \gamma$.

Note that γ is the ratio of specific heat of the gas in the cavity at constant pressure to that at the constant volume $\gamma = 1.4$ for air.

The value $k = 1$ corresponds to an isothermal process where heat can transfer into and out of the bubble rapidly enough to keep the gas at a constant temperature. Very small bubbles tend to behave in an isothermal manner.

The value $\gamma = k$ corresponds to an adiabatic process whereby no heat energy can transfer into or out of the bubble cavity. Large bubble tends to behave in an adiabatic manner.

Absolute Liquid Pressure

The pressure P_0 at a given depth h in a static liquid is a result of the weight of the liquid acting on a unit area at that depth plus any pressure acting on the surface of the liquid.

$$P_0 = P_{atm} + \rho g h$$

In the nature, raindrop sounds, river sounds, breaking sea wave sounds and waterfall sounds are all involved with bubbles formation, oscillation and collapse. From the foregoing chapters, we can see that they all somehow show low frequency sound characteristics. What makes them different from each other? Great deals of research and experiments have been conducted and one conclusion has been drawn that the bubbles size and contribution are the key factors to determine a water sound.

6.3 *Bubble sounds analysis*

6.3.1 *Single bubble sound*

The 52 seconds sound of single drops falling into water gives out a wealth of information about bubbles that are created by water drops hitting a water surface. The waveform graph in Figure 6.2 shows 18 drops of water falling onto a water surface.

Two different types of falling consequence can be identified: one is a signal with a single wave, which is illustrated in Figure 6.3 by zooming out the tenth drop water signal. The other is a signal with two adjacent waves, which is illustrated in Figure 6.4 by zooming out the fifth drop water signal.

Since the only variable here is the size of the water drop, it can be deducted that some sizes of water drops make consequence while others do not.

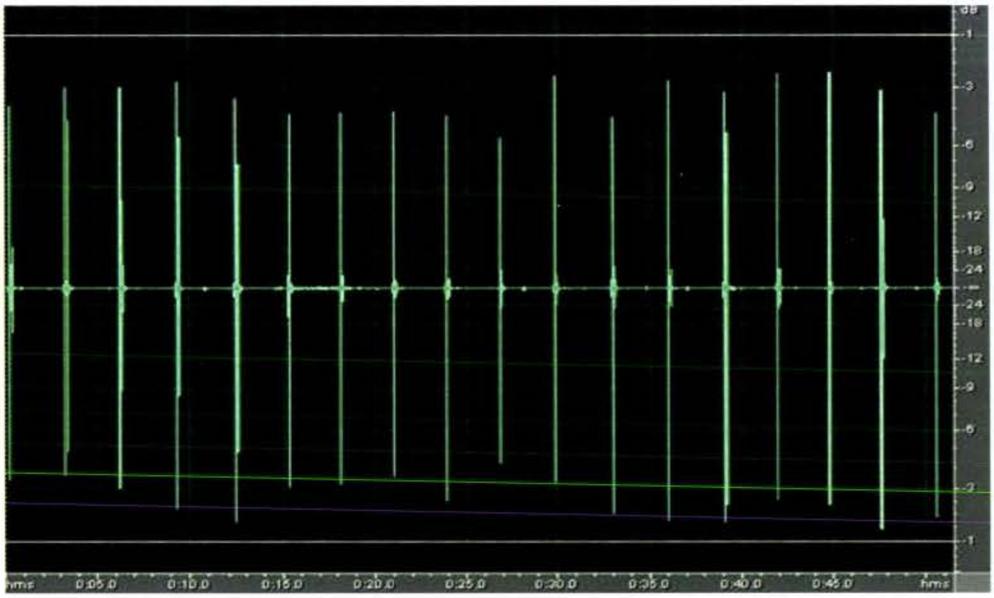


Figure 6.2: Waveform of single drops into water

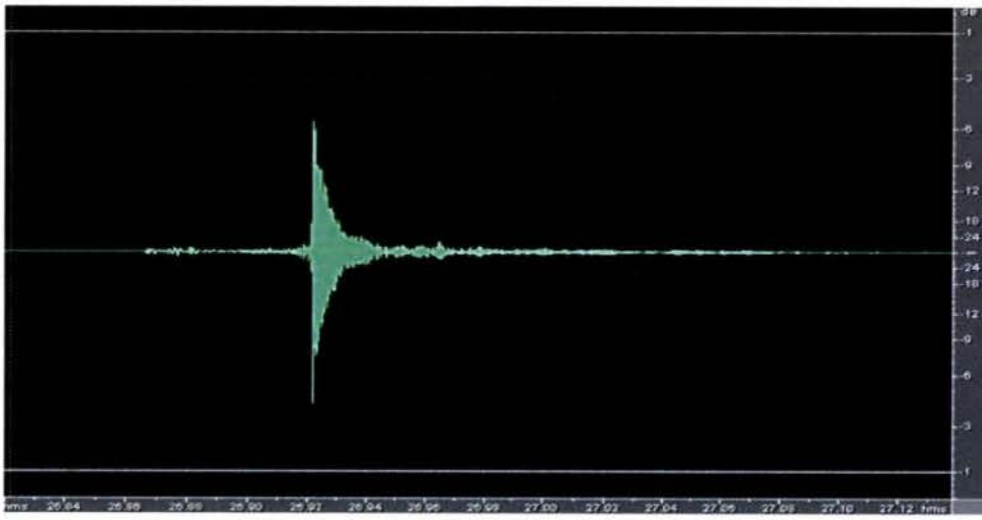


Figure 6.3: The enlargement of the tenth drop of water signal

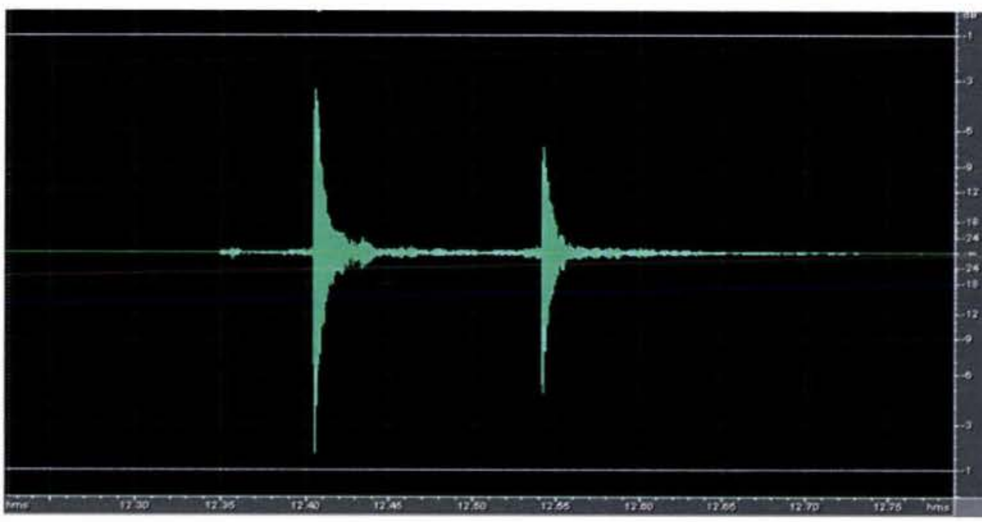


Figure 6.4: The enlargement of the fifth drop of water signal

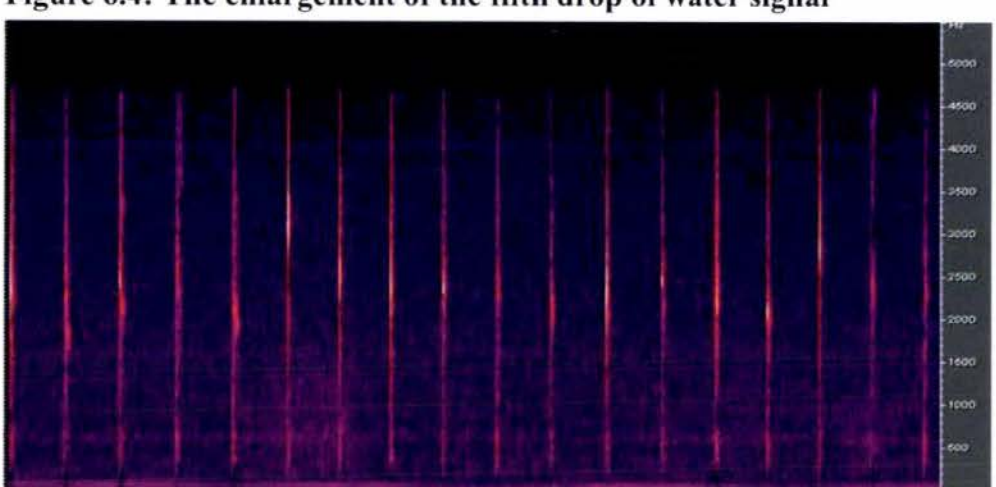


Figure 6.5 Sonogram of single drops into water

The sonogram of single drops falling into water surface shows that each drop produces different pinch sound.

Take the fifth and tenth water drops as examples; the enlarged sonograms are shown as Figure 6.6 and Figure 6.7.

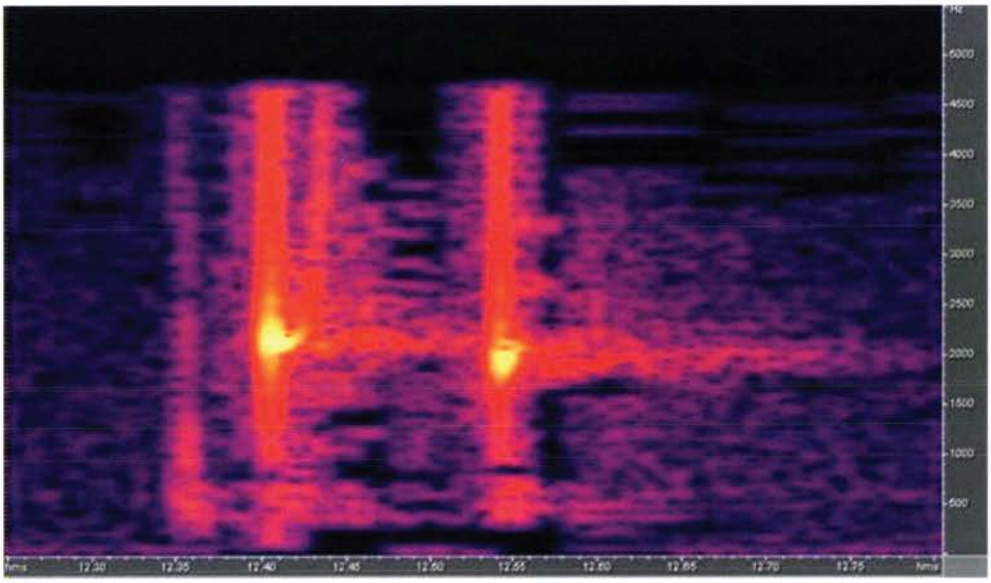


Figure 6.6: The enlarged sonogram of the fifth drop

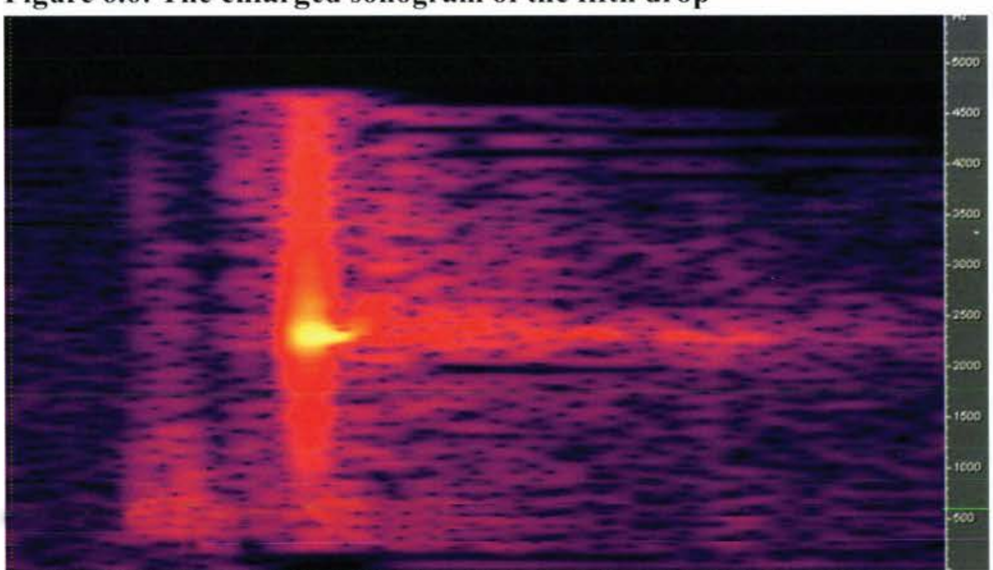


Figure 6.7: The enlarged sonogram of the tenth drop

From the above sonogram (Figure 6.6), we can see that the fifth water drop makes two similar adjacent signal waves. They all show a strong vertical bar being followed by a horizontal tail. The strong vertical bars correspond to a distinctive signal which I believe are bubble breaks, and the horizontal signals show harmonic characteristics in their relatively high frequencies, 3600 Hz, 3900 Hz, 4100Hz and 4400 Hz, which can be seen clearly in Figure 6.8.

The differences between these two adjacent signals are:

1. A relatively weak vertical signal is showing 5 milliseconds before the first bubble break sound, while the second does not. The signal is believed to be the impact sound when drops hit the water surface.

2. The dominant frequency of the first signal is 2150 Hz, while the second 1900 Hz. The difference can be seen clearly from the two graphs in Figure6.9.

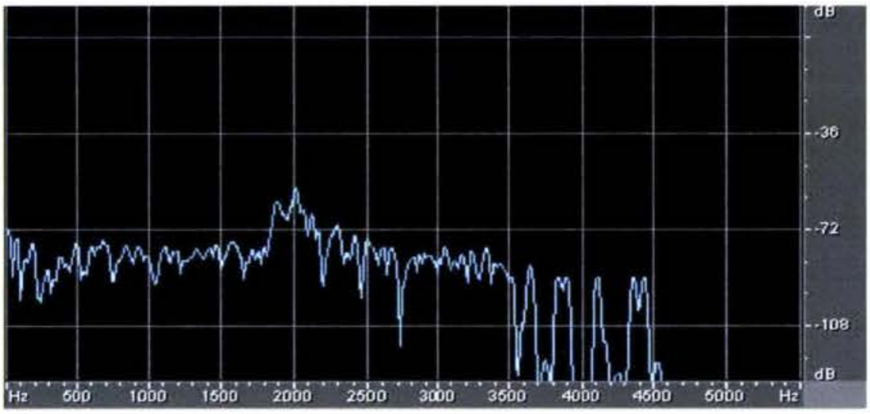
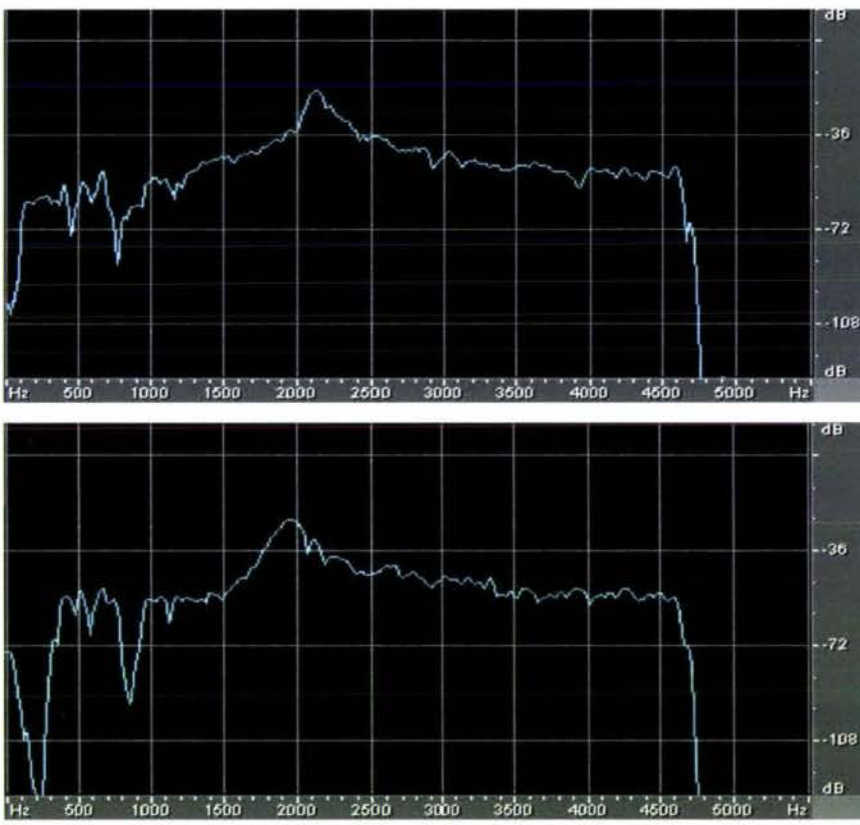


Figure 6.8: Frequency analysis covered the entire process



(1)

(2)

Figure 6.9: Frequency analyses of the two adjacent signals by the fifth drop

The single signal sonogram (Figure 6.7) is similar to the first of the two adjacent signals. The impact sound has the maximum magnitude in around frequency 670 Hz, while the bubble sound is around 2300 Hz. The harmonics can be seen clearly in the relatively high frequency above 3500 Hz 3milliseconds after the bubble breaks.

From all above analysis, following conclusions can be drawn:

1. When water drops fall onto a water surface, different size bubbles will be created showing different dominant frequencies. The dominant frequency of the bubble sounds is focused in the range of 1600 Hz to 4000 Hz.

2. There are two components to the sound generated by a raindrop splash: The impact sound produced when the drop hits the surface, and then there is the subsequent formation of a bubble under the water during the splash. The relative importance of these two components of sound generation depends on the raindrop size.

3. The bubble evolution interval can be estimated as from the impact sound to the bubble break sound. All the drops indicated the bubble's life time is between 4 milliseconds to 6 seconds.

4. The bubble break sounds show obvious peak magnitude in the frequency range from 1600 Hz to 2400 Hz.

5. After the bubble breaks, the sound lasts for about 12 milliseconds and shows harmonic characteristics in the final stage.

6.3.2 Release of underwater bubble

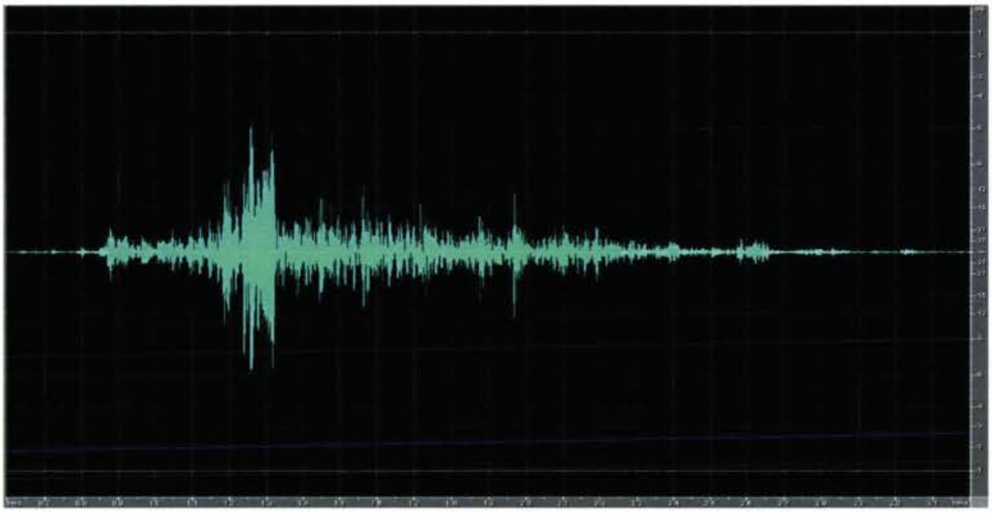


Figure 6.10: Waveform of one quick releasing underwater bubble

The 2.6 seconds sound signal of a release of underwater bubble is shown in the waveform graph as above. The sonogram is shown in the following graph. When air is released under water, some bubbles formed and then rose to the surface under the effect of buoyancy. The bubbles here are much bigger than the bubbles caused by drops and show obvious differences than the aforementioned drop caused bubbles.

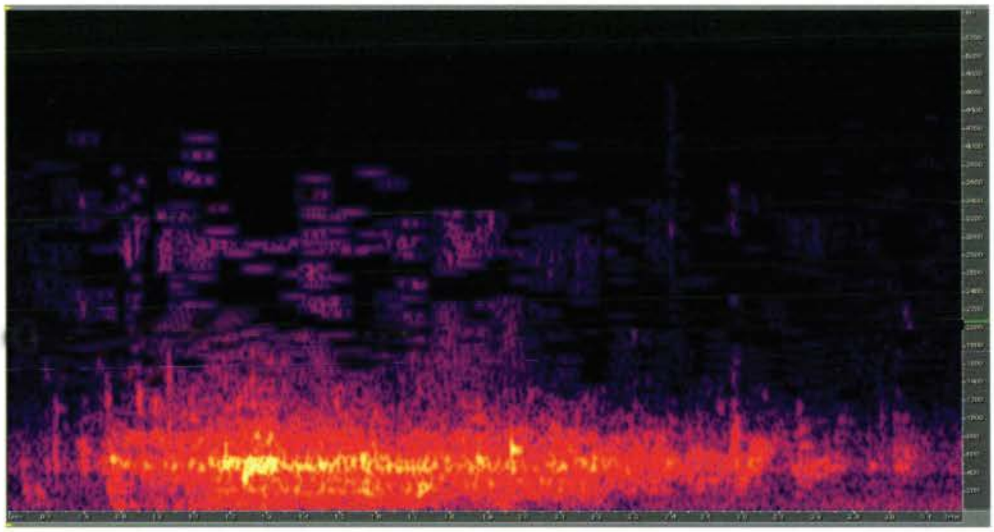


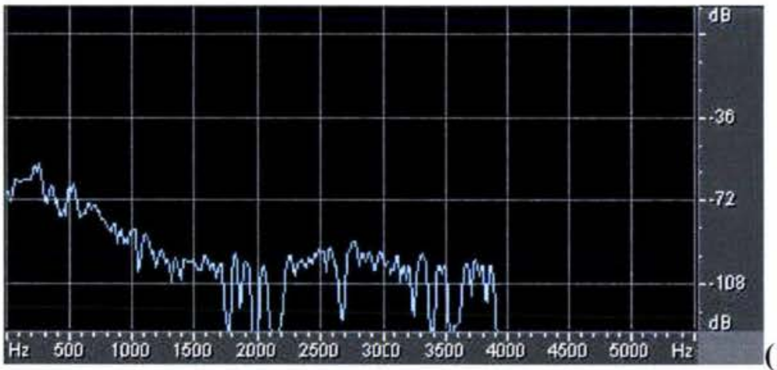
Figure 6.11: Sonogram of one quick releasing underwater bubble

The sound can be assumed to be produced by the formation and oscillation of the air bubbles.

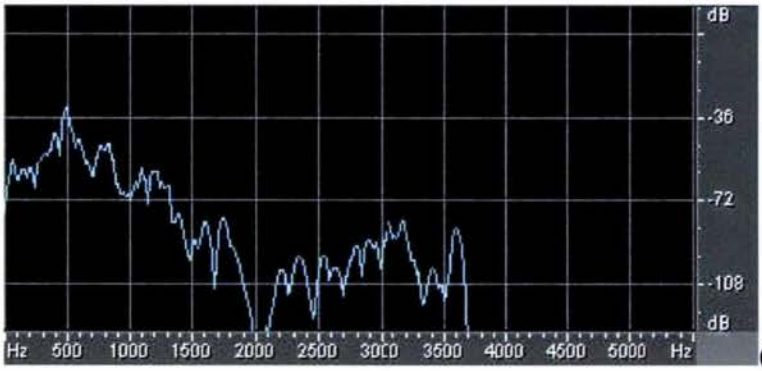
The sonogram indicates that:

A strong horizontal cross band shows that the release of the underwater bubbles sound magnitude reaches a peak at a narrow range of frequency along the time history.
The dominant frequency range is from 400 Hz to 600 Hz, which is much lower than the drop cause bubbles.

Along the time history, the signal shows harmonic characteristics in the higher frequency range. Different points along the time history are chosen to show the frequency spectrums as following 6 graphs.



(1)



(2)

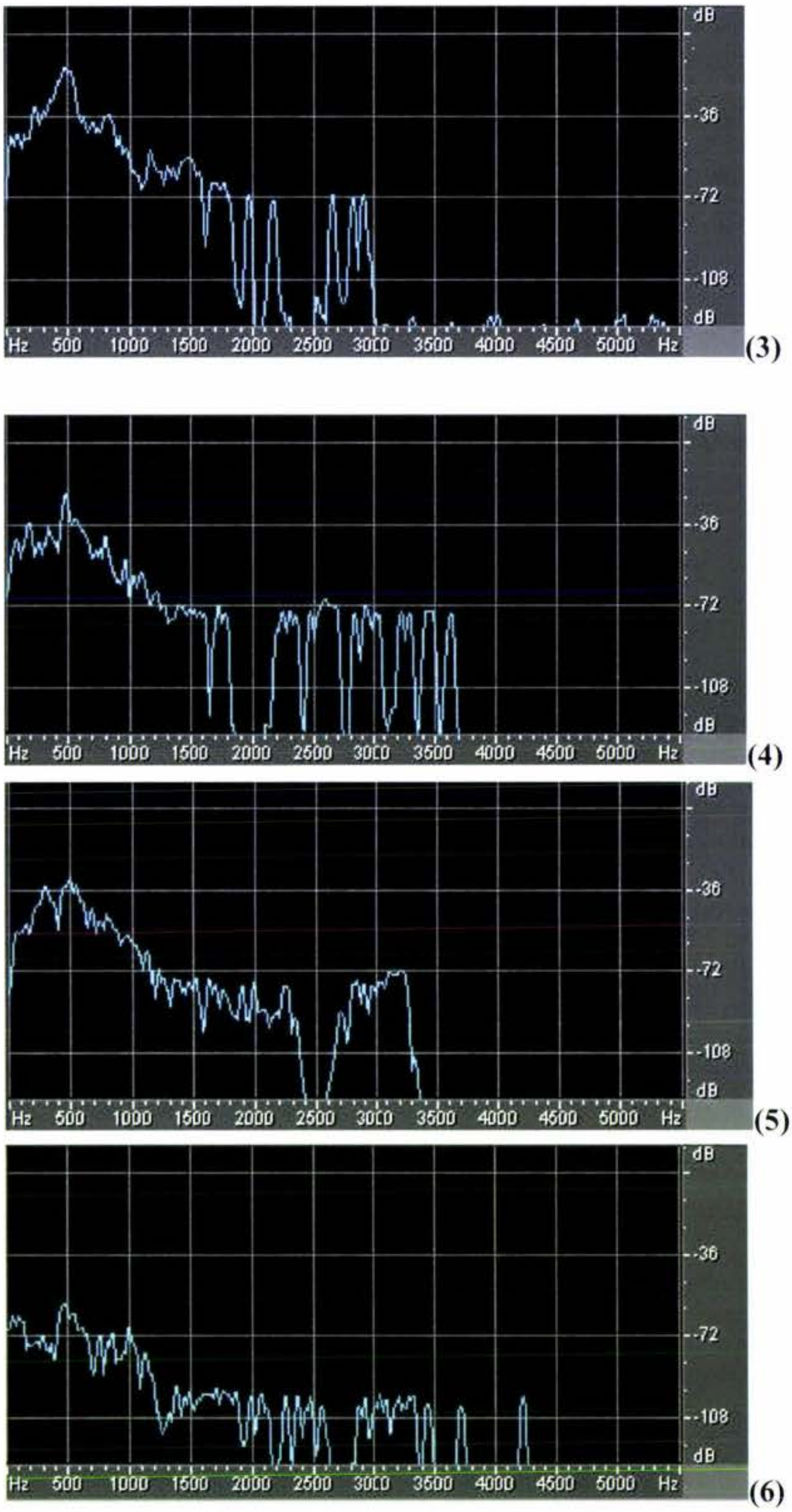


Figure 6.12: Frequency analysis of the releasing bubble sound along time history

6.3.3 Rain sound

Different sizes of raindrops produce dramatically different sounds as they hit water, primarily because some sizes of drops generate bubbles and others do not. Because the sound of rain underwater is loud and distinctive, it can be used to detect and measure raindrop sizes and amounts of rainfall over the ocean. Data from remote ocean areas is currently sparse, and this new recording technique will add new data and contribute to a global picture of rainfall. Scientists need these measurements to support climate studies of the distribution and intensity of global rainfall patterns.

Rain is one of the most important components of climate.[8] Knowledge of its distribution and intensity is important not only to farmers and flood control planners, but also to meteorologists, oceanographers, and scientists who study climate (climatologists). Of particular interest to climatologists is the release of latent heat each time a raindrop forms. It takes energy to evaporate liquid water and this energy is stored in water vapor as "latent heat." The formation of raindrops releases latent heat, which is one of the primary sources of energy that drives atmospheric circulation. Thus, scientists need to improve their understanding of the global distribution and intensity of rainfall to improve weather and climate forecasts. Furthermore, layers of relatively fresh water due to rain at the ocean surface are now thought to significantly affect oceanic circulation,[9] another important component of global climate. Unfortunately, rainfall is very difficult to measure, especially over the ocean where few people live and where rain gauges commonly used on land don't work. But we know that rain falling onto a tin roof makes a lot of noise, and so does rain falling onto water. In fact, rain falling onto water is one of the loudest sources of underwater sound, therefore we can measure oceanic rain by listening to it from below the ocean surface.

Surprisingly, for most raindrops, the bubble is by far the loudest source of sound. Bubbles are one of the most important components of underwater sound.[10] They have two stages during their lifetimes: "screaming" infant bubbles and quiet adult bubbles.

When a bubble is created, the pressure inside it is not at equilibrium with the pressure of the surrounding water. The water pushes against the bubble, compressing it. As the bubble shrinks, the air trapped inside increases in pressure. This occurs so rapidly that the pressure inside the bubble becomes higher than that of the water, so it expands to equalize, again overshooting. The bubble oscillates between high and low pressure at a high frequency, creating a distinctive and well-quantified sound. The sound radiates energy, so the bubble eventually reaches equilibrium with its surroundings.

The frequency of the sound was well defined by Minnaert[11] in 1993 as:

$$f_r = \frac{1}{2\pi a}\sqrt{\frac{3\gamma P_0}{\rho_0}}$$

The frequency depends on bubble radius, local pressure, local water density, and a geophysical constant. The important observation is that the size of the bubble is inversely proportional to its resonance (ringing) frequency. Larger bubbles ring at lower frequencies and smaller bubbles ring at higher frequencies. The sound radiated is often loud and narrowly tuned in frequency (a pure tone). But quickly, after just tens of milliseconds, a bubble in water becomes a quiet adult bubble and changes its role—it absorbs sound and is especially efficient at absorbing sound at its resonance frequency.

Naturally occurring raindrops range in size from about 300 microns in diameter (a drizzle droplet) to more than 5 millimeters in diameter (often at the beginning of a heavy downpour). As the drop size changes, the shape of the splash changes and so does the subsequent sound production. In laboratory and field studies (Medwin et al. 1992) [12], scientists identified five acoustic raindrop sizes (see Table 6.1). For tiny drops (diameter less than 0.8 mm), the splash is gentle and no sound is detected. On the other hand, small raindrops (0.8—1.2 mm diameter) are remarkably loud. The impact component of their splash is still very quiet, but the geometry of the splash is such that a bubble is generated by every splash in a very predictable manner (Pumphrey et al. 1989).[13] These bubbles are relatively uniform in size, and therefore frequency, and are very loud underwater. Small raindrops are present in almost all types of rainfall, including light drizzle, and are therefore responsible for the remarkably loud and unique underwater "sound of drizzle" heard between 13—25 kHz, the resonance frequency for these bubbles.

Table 6.2: Raindrop Bubble Acoustics

Drop Size	Diametre (mm)	Sound Source	Frequency Range (kHz)	Splash Character
Tiny	< 0.8	Silence		gentle
Small	0.8- 1.2	Loud bubble	13- 25	Gentle, with bubble every splash
Medium	1.2- 2.0	Weak impact	1- 30	Gentle, no bubbles
Large	2.0- 3.5	Impact, loud bubble	1- 35	Turbulent, irregular bubble entrainment
Very Large	> 3.5	Loud impact, loud bubbles	1- 50	Turbulent, irregular bubble entrainment, Penetrating jet

6.4 References

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