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**An Acoustical Approach Toward Composition**

Skriftlig reflektion inom självständigt arbete
Till dokumentationen hör även följande inspelning:
"Constructive Interference"
"Finite Functions of infinitive sets"
"Dimension II, Destruction"
An Acoustical Approach Toward Composition
Master Thesis

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Abstract

The composition on its best is the art of dealing in between reality and pure abstraction. The music is all about sound and time. In this respect even the most traditional composers are sound artists and working with acoustical phenomena. In this self explanatory paper I try to show the ways and techniques I have been using on my compositions by summarizing and briefly introducing the different necessary research processes for each piece that I compose during the masters study. Composition could be looked as an interdisciplinary field. Much closer to science than must of other arts and yet much more subjective. I will try to explain how the music means sound and the sound means vibrations and energy in my music; and how such approach led to another step of working on perception and psychoacoustics.
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Introduction

The core of my composition interest, during past years, has been on acoustics. This led me toward a wide research on instruments and acoustical/physical behavior of the sound and the phenomena related to it, for every single piece I wrote.

With some years of experiences as player in orchestras and ensembles, and conducting different ensembles, I felt quite bored of the mainstream contemporary music. The type of music which corresponds to what I call “academic music”, most commonly in the central European countries. A mixture of noises made on instruments with quasi algorithmic systems of organizing the sounds similar to 12 tone technique. Countless amount of tasteless reproductions of Lachenmann style could be an example of what I was bored of! It was only when I found the music of late Romanian-French composer Horatiu Radulescu that I could think about a different dimension of sound-music and art that was not already occupied by mainstream academic music. Studying music of Radulescu showed me the window to a new path toward music. I started to realize “the sound” as material of music and be concern about all fascinating yet mysterious dimensions of sound as a physical entity.

The period of master education gave me the chance to gain not only technique or knowledge, but mostly a vision. An identity based on a self recognition of personal interest.

The philosophical questions about existence of music and/or art, alongside the never ending challenge for having authentic reasons to be a composer on the world in 21st century, acted as a bi-polar force to a musical self consciousness that lead me more and more toward the existence and function of sound as a substantive entity. In that aspect I could consider myself as a sonar artist, an artist who uses sound as the material of artwork.

Next step was to go beyond the sound as merely the material, and reach it within the inside. On his book “SOUND PLASMA- MUSIC OF THE FUTURE SIGN or MY D HIGH opus 19 ∞” Radulescu writes:

“meditate upon the 5040 combinations of the 7 words composing the title
Meditate upon them nearly 7 days
... SOUND... SIGN FUTURE...OF...THE OF...MUSIC THE...PLASMA OF FUTURE SIGN...
Only then start reading the following pages”

And on the first chapter under title of ENTER THE SOUND:
“The sound in itself is an endless ocean of vibrations. Although Pythagoras penetrated the secret of these waves, for millennia we made music treating the sound from its outside…”

Sound became not only the material of my music, but the music itself, the art itself, the source of inspiration and aspiration. Sound is a very alive, profound, mystical, powerful and yet flexible source of energy.

On my music, I try to have a very realistic approach toward abstract imaginations, a realistic approach to the sound as material of such imaginations. I see the sound itself as a lively source of energy, as constant vibrations and movements that are products of an action. Using the plain physics to have a broader image of abstract world one might imagine with material of sound. In a word I try to have a combination of physical facts with artistic imagination, which reaches to a rich work of art. This combination is what shapes my aesthetic and attitude on music.

I almost fully reduce the element of rhythm to time and duration in my music. In other words the actual music is processed sound(s) in the scale of time thus there is no “groove”, beat or repetitive pattern present in my music. I generally use the seconds (equal to metronome 60 bpm) as standard method for measuring the time.

Likewise I almost entirely excluded the usage of noise from my music. Most especially in case of an ornament or additional function to the sound/music; for one simple reason: it is impossible to control or estimate the noise particularly in combination with other types of sound (harmonic sounds).

In this paper I try to demonstrate and summarize the compositions that shaped my aesthetics during the period of studying master. All these compositions were a secondary chapter of a broader research on one or more acoustical topic. And finally try to show how the attention of my composition moved toward the ways in which the brain perceives/processes the sound; and effects of acoustical/physical behavior of sound on hearing and cognitive system of audiences of music in my final piece of master studies.

Being concern about the physical-and lately psychological-aspects of sound, I had to study the musical instruments I wrote for, in a more acoustical basis. I treated the instruments as tools of implementing the subjective acoustical ideas. Although in some cases the study of physical ability and acoustical property of instruments became the source of inspiration for composition.
Having studied different scientific and artistic researches that are currently available, I realized there is a lack of reliable literature and resources that could cover simultaneously the scientific and artistic aspects, at least on topics that were my interest on aesthetic and musical field. Many of current scientific papers are done by scientists or researchers with limited or no musical background and therefore actually not very useful by the composers/musicians. In fact these types of researches are not aimed to be used by music students or professionals. On the other hand most of the available researches that are done by musicians suffer from a lack of scientific justification which could explain dozens of mysterious questions related to acoustical phenomena or complex behavior of instruments. The latter types of researches are mainly done with the practical attitude to be used under limited circumstances by the musicians. Sentences similar to “for some reasons it sounds like this” or “somehow the sounding is richer in this register” are often found on such merely practical researches.
Study of vibrations on a string, a piece for string trio

Perhaps the first piece in which I directly started working with the frequencies (cycles per second) and sound, rather than musical pitches, was “Dimension III, Heterodyne Structures”.

I gained an interest on the acoustical phenomena like interference beats and summation/difference frequencies. Without having much experience on working with detailed acoustical facts, I automatically thought about some combination of instruments with the must homogeneous sound to maximize the resemblance of spectra of each sound (which would make it possible to an emphasis on the frequency of pitches), and minimize any unwanted disturbance or hindering that could happen in case of having very different spectra (different colors/timbres). For that I decided to write for the most conventional and available instruments that could be efficient as well: strings.

This became the main reason of a study on vibrations and acoustical behavior of a string and violin family in particular.

Simple acoustics of string

Seemingly there are plenty of remarkable researches and scientific papers about string instruments. The rich literature and centuries of attention and tradition have made the strings to be somehow the must studied musical instruments.

I tried to find the features of strings that could give me possibilities of creating musical events that I wanted. This needed a good comprehension of function and character of string instruments.

A vibrating string can produce a motion that is rich in harmonics. Many of the most useful features of the orchestral string instruments result from their use of bows. Compared with pizzicato (plucking the string), the bow allows the player to continuously input energy and so to maintain a note. This is important to the timbre, too: after a pluck, the high harmonics fade away quickly, leaving only the fundamental and some weak lower harmonics. Bowing maintains the rich harmonic spectrum.

The bow drives the strings with repetitive motions of “stick-slip” action. There are different properties of friction involved with every movement of bow, the force that resists against the slide cycles. With high static friction, the bow tends to stick to the string (stick) and for a while it
drags the string along with it. Moving the string creates a wave whose peak (kink) travels up and down on the string. “When the kink returns to meet the contact point, the tension in the string now acts to pull it off the bow. Under appropriate bowing conditions, it breaks free of the bow and then slides past it easily with very little friction, due to the low kinetic friction (slip). The string doesn't stop when it gets to the straight position because its momentum carries it on until eventually it stops and reverses direction. When the bow reverses direction, there is inevitably a small but usually noticeable discontinuity in the wave motion, which is a key element of articulation for string instruments”.

The picture from Music Acoustic website, shows reflections on of a travelling wave on a bowed string

Over a limited range of force applied by the player (players call this "pressure"), the cycle of stick and slip is governed by the **standing wave** in the string. When this happens the motion of the string is nearly exactly periodic, and it therefore makes a sound with an almost exactly harmonic spectrum. This means that any inharmonic effects of the string are reduced by bowing, which is not the case when the string is plucked. The periodic motion of the string includes rather sudden changes in direction, and these imply substantial power in the high harmonics. The regular action of the stick-slip action thus puts power into the high harmonics and contributes to the richness, brightness and loudness of the violin's sound.

Similarly the low pressure of the bowing makes rather colorless sound with much less or weaker overtones. Combining different pressures of bowing with different speeds and different positions of bowing gives a variety of single sinusoidal-like fundamentals to much richer pitches. The result in composition could be the usage of single fundamentals (most likely flageolets) with a few Hz difference from each other in order to create very plain and clear interferences. Or considering such interferences in more complex way involving more overtones of each fundamental have simultaneous interference as well.
Pressure, position and speed

During all time of bowing, the shape of the string is two straight lines, joined by a kink that travels around the envelope shown, which is made of two parabolic segments. When the bow moves upward (up bow), the kink travels in a counter-clockwise direction. In the graphs of velocity vs time t, at the bowing point (A), an upwards moving bow starts the stick phase at time t = 0. So at t = 0, v is positive, as shown in figure b. While the string and bow move together, the kink travels to the right hand end of the string, reflects and returns. When the kink returns to A, there is a large transient force on the string (the tension on both sides of the string now has downwards components). This starts the slip phase (v < 0 in figure b) during which the kink travels to the left hand end, is reflected and returns to the bow, ready to being the stick phase again. At the midpoint of the string (B), the up and down speeds are equal (figure c).

The kink travels at a constant speed V. Let the string’s length be L. If the frequency is f so one cycle takes time 1/f. So the kink travels 2L in time 1/f so V = 2Lf. Suppose we are bowing it at a position L/n from the closer end, usually the bridge. During the stick phase, the kink travels to the far end and back, a distance D = 2L(n-1)/n. At speed V, this takes a time

D/V = 2L(n-1)/nV = (n-1)/nf.

Now the bow speed is v, so during the stick phase the bow and the string together travel a distance

A = v(n-1)/nf,

where A is the amplitude of the motion of the string at the bowing point. So, at the same bowing position, the amplitude of the motion is proportional to the bowing speed and inversely proportional to the frequency. So if you bow with greater speed, the stick
point will travel further and the amplitude will be greater. This of course makes it louder.

Varying the bowing while keeping the speed constant, results in changing only n and A in the equation above. Measuring the bowing position from the closer end of the string means that n can vary between 2 and a large number. So the amplitude at the bowing position increases from v/2f if you bow at the middle, towards v/f as you get close the bridge. However, the maximum amplitude of the string’s motion is greatest at the middle. As you move the bowing point towards the bridge, the maximum amplitude of the string increases for this reason as well.

**Bow force** is also very important because with a certain speed of bowing in a specific position, the ideal periodic movement (Helmholtz motion) could be produced only with a certain range of force. The closer to the bridge the higher the force is needed (regarded to the speed) to make an acceptable periodic movement. Further, the permitted range of force becomes narrower. With more applied force, you excite more higher harmonics.

Bowing the harmonics is even more complicated. In the higher harmonics since the nodes are multiplied the amount of kinks also multiplies. “For the second harmonic, there are two cycles of stick slip in the time that a kink takes to make one complete return trip along the string. However, there are two kinks travelling at any time, from the middle length of string”. The differences between bowing the fundamental and bowing the second harmonic are shown in a graphic on the next page (from the Music Acoustic website).

The sharp corner of the kink produces all of the harmonics, except for those that have a node at the bowing point. However, because a string has a certain stiffness, the kink is never perfectly sharp and the finite curvature limits the number of upper harmonics. Bowing with greater force (usually closer to the bridge) gives a sharper kink and therefore more high harmonics.

In addition to all said above one has to consider the numerous factors and complications concerning string functions, such as *torsional waves* or uncontrollable movements of real bowing.

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1 Equation, text and picture taken from Music Acoustics website, Joe Wolfe.
Fundamental

The amplitude at the bowing point must be half as much for the harmonics as for the fundamental.

Second harmonic

Note the symmetry of the two halves. The string has three straight-line, 120° kinks. The kinks move at the same speed as the kink of the fundamental, but because there are two of them, the cycle appears twice as quickly.
Composition

As was written before, the modes of bowing play a key role on sounding a string. Since my piece is written for string trio plus pre-recorded instruments or 12 live strings, I constantly had the possibility of having several layers of the same type of spectrum with slight different tunings that result in a net of beatings and interactions. Using combinations of bow pressures and bow positions and speeds made it possible to have numerous varieties of spectra from a single pitch.

In the study process, I noticed an interesting fraction of very high frequency in the moment of changing the direction of the bow (standing way). This frequency that is depended on the node of string in which the bow is placed, could be emphasized by accentuated bowing. I made an extensive usage of those frequencies (in different tunings) most visibly with very high pressure of bowing in *sul punticello* position. So in addition to the main sound process or sound fluid of micro intervals, I inserted these secondary data like a granulation of sound.

For this piece I asked the instruments to tune the A with 3 Hz difference from each other. The other strings were tuned with scordatura and in equal tempered system, related to the frequency of A string. A chart of all the frequencies of all strings was added to the score for this purpose.

There are three different pressures (very low, normal and very high pressure) and three different positions of bowing (sul ponticello, ordinario, sul tasto) used in this piece. However some very important information of bowing were neglected (including the speed of bowing and the modes of desired bowings). Some additional accents on the each bow change were aimed to point out to the bow’s frequency and what I called “phase shifting bow” in later pieces.

Having intervals of 3Hz would result 3 beats per second (listen to audio) between two adjacent instruments (i.e first viola and second viola). While following the same ratio, there are constantly different amounts of beatings between different instruments. For example first and third violas have 6 interference beats and first and fourth violas have 9; the combination of each two sets of beatings creates a different result. Having the whole 12 instruments playing the same pitch itself results in complicated and constantly shifting net of different beats and interactions.

Additionally I used the staggering fraction of high frequency produced by beating the string with a metallic triangle beater on different places. The resultant sound has a weak fundamental and stronger higher harmonics, as well as sounding of the open (or damped) string.
The multiphonics on strings were not directly used on this piece; nevertheless I noticed them during the study process and used them in later pieces. There are several ways of producing mutiphonics on a single string.

By carefully positioning the bow and a lightly touching finger on the string, the string spectrum can be conditioned to provide narrow bands of pronounced energy. This leaves the impression of multiple complex tones with the normal (Helmholtz) fundamental as the lowest pitch. The phenomenon is seen to be caused by two additional signal loops, one on each side of the finger, which through the repeating slip pattern get phase locked to the full loop of the fundamental.

The key of a multiphonic sound is the node in which the bow inputs the force on string, and very precise and adequate speed/pressure of bowing. Thus it is predictable to have a good number of multiphonics while altering the speed, pressure and position of bowing though in a less controlled fashion.

**Notation**

This piece is written in two scores, one for a live string trio, and the other for 9 other strings which could be recorded and played-back during the performance, or could be performed with live musicians in the concert.

In case of a trio performance, every musician has to have a MIDI switch pedal in order to trigger the relevant recorded material, and a headphone to hear the click track in some parts. The sound of recorded instruments, with some exceptions, comes out from the speaker behind the same musician; and it’s usually a sound file compound of three lines of the same instrument (in different tunings). The places where the musicians should press the pedal are indicated in the score with a “Bang” sign.

Extract from first page of performance score from “Dimension III, Heterodyne Structures” shows a Bang command underneath the cello part.
Most of the properties of notation I used in this piece were developed during my previous pieces ("Dimension I, Construction on Time" and "Stain violin solo version"), and later they became substantial on my further pieces as well.

The score and parts are written whether with traditional notation, grid notation or a combination between both ways. The score is transposed; the notation merely shows the place of putting the fingers, but not the sounding. In fact I’ve used a kind of tablature instead of notation. In most places a grid indicates the place in which the fingers should touch the string(s) in order to produce a very high flageolet sound. The same grid, sometimes in combination with the traditional 5 lines staff, may indicate the different places where the beater should beat the string(s).

All the barlines are written merely to simplify the performance. The music must be flow and there must not be any impulse in the music. Also there is not strong beat or off-beat in bar.

Basically all the straight lines _________ are the continuous or lasting of a pitch, sound or a pattern.

All the unheaded notes are repeats of the previous note or pitch (the same), or changing the bow while continuing last pitch. Mostly they have been used in combination with lines. In this case an additional note with bracket above the passage indicates the duration.

Extract from “Dimension III, Heterodyne Structures” first viola (live) part. The durations are given on the top of lines.

Curved lines are used for different purposes. A curve line with very small dents may indicates a vibrato, while bigger dents may show the fluctuations on sound or extension of a pitch (slight glissando). A combination of a curved line with both small tents and big tents also may be used as a guide for doing glissandos. In this case the highest point and the lowest point of glissando is indicated.
A combination of different curved lines demonstrating different functions.

I’ve used some different clefs in combination with grids, in order to write the special sounds/pitches in this piece. The function and structure of these symbols (clefs) are rather simple. All of them are compounded 4 vertical lines which indicate the strings and one or two more signs which may indicate bridge, (edge of) fingerboard or tail of instrument.

(‿) : Bridge
(⟩) : Fingerboard (the edge of fingerboard)

Above each grid or staff the number of string(s), which should be used, are written. (I) is first/highest string and (IV) is fourth/lowest string on each instrument.
Visualization of the sounding of A₄ played by the whole ensemble. Using the sine waves and SPEAR software.

Sine wave reproduction of a section of the piece
Representation of the same section in the score. At left is the recording score and the right side is the performance score.

Checking the frequencies of middle section of the piece. Time domain is not proportional.
Study of vibrations on 2-dimensional membrane: a piece for 12 timpani

Following a rather long study on acoustics of percussion instruments, I made an attempt to write the same music/aesthetic I’ve been working on for a less studied and yet widely used ensemble in contemporary music era: percussions.

It certainly is a challenge to compose music whose core is in precise interaction of frequencies and acoustical behavior of sound waves, for a hardly controllable percussion instrument. However what in my opinion is the extreme and almost careless use of percussions in new music was inviting enough to try different function of percussion ensemble.

The initial idea was to compose a piece for 12 timpanis-4 musicians. I planned to tune the timpanis following a ratio of 6Hz difference from each other, with exception of the lowest and highest timpanis that had to act as two extreme ends of an imaginary spectrum. Therefore it would be possible to have a complex combination of different beatings between small frequency changes, while having a descending ratio of intervals from lowest to the highest timpani. Beside the frequency of fundamentals, I wanted to have a number of overtones on each timpani; so the function and amount of beatings would be varied in different overtones while using the chance of having other sets of pitches and transitions in sound.

A brief note on acoustic of timpani

A membrane can be thought of as a two-dimensional string, in that its restoring force is due to tension applied from the edge and could be tuned by changing the tension. Figure below shows the four modes of vibration on a circular membrane. In the first mode (the fundamental) the entire membrane moves in the same direction, although the center has the greatest amplitude. In other modes, there are one or more nodal diameters or nodal circles that act as boundaries or pivot lines. Those nodes are the places where could produce different overtones of the membrane (and the air inside the kettle) by enticing with different methods or materials.

Modes of vibration in a 2-dimensional membrane. Picture from The Science of Percussion Instruments, T. Rossing.
A major difference between vibrations in a string and in a membrane is that the frequencies of modes in a string are harmonics of fundamental, while in a two-dimensional membrane they are not. Another difference is that in membranes nodal lines (circles and diameters) replace nodal points of string. In practical sense that gives possibility to find the nodes within a circle in a right radius of the drum head.

Although the frequencies of modes of vibrations in a normal membrane are not harmonic, a carefully tuned and well made modern timpani can produce a clear sense of pitch in fundamental plus more than three overtones. The reasons are that (1) the membrane vibrates in a “sea of air”, and the mass of air lowers the frequency of lower vibrations. (2) The air enclosed by kettle has resonances of its own that interact with the modes of membrane with similar mode. (3) The stiffness of membrane raises the frequency of higher overtones. The two latter are mostly responsible for fine tuning of the membrane.

Further discussions concerning the vibrations of the air enclosed by kettle and its effects on tuning and raising the frequency of overtones are excluded from this article.

**Experiment**

Regarded to the studies of different modes of vibration and finding harmonic nodes, I executed a series of experiments on different modern timpanis, with different drum heads and different mallets. The aim of experiments was to find the best way for precisely tuning the timpanis with the intervals of a few frequencies (Hz) from each other; as well as making an established method for making several different overtones (flageolets) on timpani. (listen to the audio example)

The result was that timpanis with plastic (fiberglass) drumhead are the best choice for very precise tuning due to a strong fundamental. It was possible to derive at least 4 distinctive overtones on plastic skins while on natural skins second or third overtones were barely achievable and untrustworthy. To the favor of plastic skins it should be mention that most actions and movements (moving hand or objects) on the timpani could be done quietly and easily with minimum of unwanted disturb.

As it’s shown in the picture the sound spectrum varies according to the place of beating on timpani. The presence and loudness of higher partials respectively is highly depended on various factors. Other factors such as the envelope of sound (attack or accent of a stroke) and loudness of
stroke are important in presence of stronger or weaker overtones. However in percussions, the material and hardness of a mallet/beater plays a crucial role in the spectrum of sound and therefore the possibility of having a clearer pitch and/or different overtones.

![Sound spectra from a 65-cm kettle drum tuned to E3 (165Hz)](image)

(a) approximately 0.03 s after striking in normal point
(b) approximately 1 s later
(c) approximately 0.03 s after striking at the center
(d) approximately 1 s later

After trying numerous different mallets and beaters, I found a type of xylophone’s hard felt mallet to be most suitable for deriving multiple overtones. The privileges of this mallets including making a relatively soft attack, the ability of hitting the drum in a very specific node and visible presence of high overtones and strong fundamental made it a perfect choice for my piece. Also because of the felt it was possible to damp precise nodes and silently move the mallets on the skin which was needed to get some specific type of overtones in my piece.

![Example mallet](image)

Similar to the beating, the methods of producing different overtones on timpani highly affects the sounding of overtones. From very clear single pitched overtones to different sets of multiphonics on a membrane are achievable by different ways of damping the skin in certain nodes. I introduced four methods of damping the skin, each with a different sounding result. The time
relation between the act of damping and the actual stroke (damp after, before or together with beating) also has a role on the resultant sound.

**Composition**

The final result of study process was used in the composition of “Constructive Interference” in the following ways:

1- The sound is being produced on timpanis simply with beating on them or ringing the skin with help of *superballs*. Damping (=touching) different places/nodes on timpani-positions- alters the sound (frequency) with stimulating other possible overtones on skin and bowl of the timpani; or changing the active length and modes of vibrations on the skin. The way of damping the skin, alongside to its place, somehow affects the frequency and quality of sounds. There are different methods and materials used for damping such as using: finger, palm, beater or bowl.

2- The skin of each timpani should be measured and 4 nodes (points) be marked, so the player can easily find the proper place of overtones during the performance. The skin should be marked on the ratios of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$ and $1/5$. Each one of these nodes will be called a *position*.

3- There are four different ways of damping the skin and thus making different combinations of overtones: damp with tip of finger, with palm of a hand, with thenar or with the beater. Also the moment of damping the skin makes a different on resulting sound: either the damping sign is before or together with the strike or the damping is done after the beat (D.A.B).
4- Each player needs to have 2 superballs, 8 balls for the whole ensemble. The material, size, speed and angle of moving the superballs affect the sounding results and should be taken into account. In this piece two different functions of superballs are used which are making a steady fundamental (or overtone in case of prepared timpani) pitch of timpani, and/or making a very high pitch of scratching the balls on the skin. Respectively the different speeds and pressure of movements were used to indicate the dynamic and sounding of superballs.

In addition to notes above there are 12 bowls, preferably metallic singing (Tibetan) bowls, needed in order to prepare the timpanis in certain places. The size of bowls should be proportional to that of timpani; also the weight of them must be heavy enough to avoid making any extra vibration or beating on the skin of timpani. However the pitches (tuning) of the bowls are not important.
Notation

Apart from this piece I started a way of notation which remained in all the other pieces I wrote during the master studies. The basic to notate the sounds and time durations directly, therefore rhythm is reduced into merely different durations of sound (and no sound) that is the target of my music.

The system used for notating the musical events during this piece, is like a code system containing time process and the actions. In fact it must be considered as a tablature rather than notation.

As a basic rule, the time process is on horizontal axis ($x$) and the actions in vertical axis ($y$). Based on this rule, each page has divided into 30 squares in $x$ axis (horizontal), and each square last one second. Thus the duration of each page is 30 seconds. For facilitating the faster movements, every square itself has subdivided into 4 equal portions (in horizontal axis) which might be considered as 16th notes.

There are 3 different levels of intensity and thickness on the division lines: light, medium and heavy.

Heavy lines are used to show the beginning of music/time line (in $x$), as well as dividing each page into 6 equal portions that could be considered as bars. Therefore the first beat/second (beginning) of each bar is with heavy line.

There is a heavy line at the very ending of each page also. This line should be ignored and it’s merely to show the end. It has no value on time, and in the best condition it must be considered as equivalent of first line in the next page.

Medium lines in $x$ axis represent every second. With the conjunction of medium lines in $y$, they form squares.

Light lines are the subdivision of every second, into four portions. In other words, if we consider every 6 seconds as a bar, therefore the medium lines are main beats and the light lines are 16th notes inside each beat.
A semicircle and the number inside, indicates which timpani to be played on, as well as showing the places of action on that timpani.

Every five seconds a heavy line, could be considered as barline. [this line is the first beat and should be played]

A heavy line separates the active area for each player and each instrument. [instruments from each other]

The medium thick line (in y-axis) in the middle shows the center of timpani, the light ones below, respectively show the 4 positions that are marked on the skin of timpani.

Picture taken from legends of “Constructive Interference” describing the notation system.
Study of vibrations of air in a closed cylindrical tube/acoustic behavior of clarinet

I started the piece for four clarinets when I was already in the middle of composing a larger piece (Dimension II). The idea was to develop the clarinet section of the larger piece and make a whole piece of music out of it. In fact the main function of this piece is very similar to the clarinet section of Dimension II, though the structure and time process is completely different.

Among all the wind instruments clarinet has the fantastic possibility of controlling the air flow so carefully that could resemble a sinusoidal wave almost perfectly. The peculiar spectrum and acoustic impedance of clarinet gives it the unique ability to completely eliminate the overtones and play an almost pure fundamental pitch, especially in the low register. The reason of course lies on the acoustics of instrument.

Clarinet is a closed cylindrical tube which is why only the odd harmonics are presented on the spectrum of a pitch, most likely in the Chalumeau register. These characters of clarinet convinced me that it is the best medium to convey the type of acoustical imagination/experience that I am interested in my music.

Studying acoustics and mechanic of clarinet also gave me much inspiration for new possibilities in composing the piece. For example the acoustical impedance of the clarinet body in different pitches/registers was a good reason on choosing different pitches and pitch progression. Before explaining the composition of the piece, it is useful to introduce the physic/acoustic of clarinet particularly the sections which inspired my piece or were used on my composition.

How the woodwinds work

Woodwind instruments work with a long, thin column of air. The lowest note is played with all the tone holes closed, when the column is longest. The column is shortened by opening up holes successively, starting from the open end. At the other end there is something that controls air flow: an air jet for the flute family and cane reeds for other woodwinds.

A sound wave can travel down the tube, reflect at one end and come back. It can then reflect at the other end and start over again. For a note in the lowest register of the flute, the round trip constitutes one cycle of the vibration. In the lowest register of
clarinets, two round trips are required. In woodwind instruments, the effective length is changed by opening and closing finger-holes or keyholes along the side. This is the way pitch is changed within the same register of the instrument: all holes closed gives the lowest note, and opening the holes successively from the bottom end gives a chromatic scale.

Changing the effective length of the pipe is not the only way of changing pitch, however: on any wind instrument, you can usually play more than one note with the same fingering (The use of simple and cross-fingerings to change the length of the standing wave is not discussed in this paper).

**A glimpse to acoustic of clarinet**

The source of power input of the instrument is the flow of air that the player provides. With a pressure greater than the atmospheric pressure, this flow is a source of continuous rather than vibratory power. Sound is produced by an oscillating motion or air flow (like AC electricity). In the clarinet, the reed acts like an oscillating valve (technically, a control oscillator).

Due to the importance of understanding the acoustic and function of clarinets, and their direct impact on my composition, the following pages are entirely quoted from the Music Acoustic website, from University of New South Wales.

The reed, in cooperation with the resonances in the air in the instrument, produces an oscillating component of both flow and pressure. Once the air in the clarinet is vibrating, some of the energy is radiated as sound out of the bell and any open holes. A much greater amount of energy is lost as a sort of friction (viscous loss) with the wall. In a sustained note, this energy is replaced by energy put in by the player. The column of air in the clarinet vibrates much more easily at some frequencies than the others (i.e. it resonates at certain frequencies). These resonances largely determine the playing frequency and thus the pitch, and the player in effect chooses the desired resonances by suitable combinations of keys.

The reed is springy and can bend. In fact it can oscillate like a spring on its own. This character of the reed is what makes the “squeak” on the sound of clarinet. “Normally, the reed's vibration is controlled by resonances of the air in the clarinet. But it's also
true that the reed vibration controls the air flow into the clarinet; the two are interconnected”.

Let's imagine steady flow with no vibration, and how it depends on the difference in pressure between the player's mouth and the mouthpiece. If you increase this pressure difference, more air should flow through the narrow gap left between the tip of the reed and the tip of the mouthpiece. However, as the pressure gets large enough to bend the reed, it acts on the thin end of the reed and tends to push it upwards as to close the aperture through which the air is entering. If you blow hard enough, it closes completely, and the flow goes to zero.

![Flow-pressure diagram](Music Acoustic Website)

The player provides a flow of air at pressure above atmospheric: this is the source of energy, but it is (more or less) steady. What converts steady power (DC) into acoustic power (AC) is the reed. The first part of the graph (and the dashed line) represents a resistance: flow proportional to pressure difference. Just like its electrical analogue, an acoustic resistor loses power. The operating regime is the downward sloping part of the curve. The operating regime is the downward sloping part of the curve. This is why there is both a minimum and maximum pressure (for any given reed) that will play a note. Blow too softly and you get air noise (left side of the graph), blow too hard and it closes up (where the graph meets the axis on the right).

This diagram allows us to explain something about how the timbre changes when we go from playing softly to loudly. For small variation in pressure and small acoustic flow, the relation between the two is approximately linear, as shown in the diagram below at left. A nearly linear relation gives rise to nearly sinusoidal vibration, which means that, even if the fundamental in the sound spectrum is strong, the higher harmonics are weak.
As we play more loudly, we increase the pressure (which moves the operating point to the right) and we also increase the range of pressure. This means that the (larger) section of the curve we use is no longer approximately linear. This produces an asymmetric oscillation. It is no longer a sine wave, so its spectrum has more higher harmonics. (Centre diagram.)

When we blow even harder, the valve closes for part of the part of the cycle when the pressure in the mouthpiece is low due to the standing wave inside the instrument. So the flow is zero for part of the cycle. The resultant waveform is 'clipped' on one side (diagram at right), and contains even more high harmonics. Adding more harmonics makes the sound louder as well, because the higher harmonics fall in the frequency range where our hearing is most sensitive.
The frequency equals the wave speed divided by the wavelength, so this longest wave corresponds to the lowest note on the instrument. It’s possible to play other notes by overblowing—by changing your embouchure and changing the blowing pressure. These other notes correspond to the shorter wavelength standing waves that are possible, subject to the condition that the sound pressure be zero at the bell and a maximum in the mouthpiece.

**Closed pipe (clarinet).** The blue curve in the top right diagram (next page) has only quarter of a cycle of a sine wave, so the longest sine wave that fits into the closed pipe is four times as long as the pipe. Therefore a clarinet can produce a wavelength that is about four times as long as a clarinet, which is about $4L = 2.4$ m. This gives a frequency of $c/4L = 140$ Hz—a one octave lower than the flute. Now the lowest note on a clarinet is either the D or the C# below middle C. We can also fit in a wave if the length of the pipe is three quarters of the wavelength, i.e. if wavelength is one third that of the fundamental and the frequency is three times that of the fundamental. But we cannot fit in a wave with half or a quarter the fundamental wavelength (twice or four times the frequency). So the second register of the clarinet is a musical twelfth above the first.
The clarinet is not completely closed by the reed: a small, varying aperture is left, even when the player pushes the reed towards the mouthpiece. However, this average area is much less than the cross section of the clarinet so the reflection of the acoustic wave is almost complete, and the acoustic flow is very small, in spite of the large acoustic pressure produced by the vibrating reed. High pressure, low flow: it is a high value of acoustic impedance.

The predominant presence of odd harmonics in the lowest or chalumeau register gives this register its characteristic 'hollow' timbre. From about E₄ up to A#₄, the even harmonics become more important. Once the speaker key is used, the systematic difference between odd and even harmonics almost disappears, and the timbre becomes bright and clear. The register that uses only the speaker key as a register is called the clarino register. The altissimo register uses the hole for the left index finger as a register hole as well.

**Composition**

There are much more to discuss about clarinet acoustics which couldn’t be fit into this essay. Topics such as the effect of register holes and tone holes, cross fingerings, cut-off frequencies and the frequency response and acoustic impedance of clarinet that each made an influence in my compositions and applying sounds on clarinet.

The piece, “Finite Functions of infinitive sets”, is written for two clarinets in A and two in Bb. Each clarinet should be tuned with 3 Hz interval difference from the adjacent one.

Probably the most visible usage of acoustical characters of clarinet in this piece (and next pieces) are the teeth notes. Putting the teeth on the reed makes the vibrations of the reed dominate that of clarinet’s body, so the result is very high frequencies of stable and/or unstable reed sounds.

Using the teeth notes with in several slightly detuned instruments make an instant production of summation frequencies. The reason is because of the energy on rather high unstable frequencies (in the most sensitive register of our hearing) that visibly interfere with each other and create obvious and loud summation frequencies.

The other special sound in this piece was the usage of multiphonics. A two-note multiphonic requires the superposition of two standing waves (whose frequencies, which are not in harmonic
ratios, determine the pitches). Usually, this is achieved by opening one (usually small) tone hole in a series of closed tone holes. The wave travelling downstream from the reed is partially reflected at the open tone hole, which makes one standing wave. The rest of the energy in the incident wave continues down the bore, until it reaches the first in a series of open tone holes. Here it is reflected to make the second standing wave.

For this situation to apply, the frequencies of the notes have to be such that the effect of the inertia of the air in the open tone hole is large enough to allow some transmission past the hole, but small enough to produce some reflection. For low-pitched notes, the tone hole is usually small.

It is important to bear in mind that multiphonics have more than one pitch, therefore they require more pressure of air and air flow. That makes it impossible to play multiphonics constantly or for a very long time.

I tried to find the most standard multiphonics in different categories. Those with beatings in themselves and those without beatings. Next step was to choose the multiphonics with very small or micro intervals from each other (either in fundamental or in higher harmonics). Combining all these with different tunings of instruments and in both A and Bb clarinet (which have different frequency response on the same pitches) gave a chance to create a rather unique and peculiar combination of sound.

Bisbigliandi were used as additional synthesis to a sound flow. The function of bisbigliando is to play the same pitch (same note name rather than frequency) with different fingerings in a way similar to a trill. I used different speeds of this “color trills” for each new pitch. The result was a constant fluctuating sounds in very closed frequency range. In other words I used the bisbigliandi as the secondary source of interference on the texture of frequencies.

**Notation**

Notation of this piece was very similar to that of previous piece and more or less became the established method of writing the sound for my music (at least in this volume of related pieces). I could successfully invite the musicians to look at the flow of sound in a different way than the traditional music writing, and that could be achieved only by the type of notation.
I had already realized that the traditional way of notating the music which has been used for a couple of centuries is not capable to convey my musical thoughts.

The first problem with traditional notation is that it is a clavier based type of notation. There are only the established solid steps up and down, suitable for writing pitches that are easily performed by a clavier instrument. While my music is not based on pitches or such large interval gaps. I have been thinking of sound as vibrations and cycles, therefore the concepts of pitch or musical steps are almost irrelevant.

I tried to reduce all the disturbing elements from my notation (such as rhythmical complexity) and invite the musicians to directly see and feel the sound.

Another malfunction of traditional notation is about dynamics and intensities. Firstly the very limited signs of “f” and “p” and their combinations are not enough to demonstrate the sound level that is desired for such detailed acoustical interactions. Secondly there is not distinction between different aspects of loudness in the classical notation.

In other words it’s not clear what aspect of sound is covered by dynamic sounds. While for a music which is based on sound waves the difference between “sound pressure level”, “amplitude and magnitude”, “intensity” or “power/force” are crucial and determinent.

Sadly until now I was not able to find a sufficient equivalent for dynamic ranges. Nevertheless I tried to achieve and cover all the different aspects of loudness with my notation. My aim was to make the musicians to notice the small details on magnitude of lines or intensity and interpret them in their playing. Surprisingly the musicians found this way of notating the music very practical and comprehensive, for the special type of sound that I was claiming through the music.

The main difference in notation of this piece with the timpani piece (Constructive Interference) was that I reduced even more lines and used only a middle line as an 8th note (instead of 4 lines for each 16th note). However in places were precise timing was needed, I made additional precise marks/durations on top (or below) main line to make it clearer for the musicians (look at example at page 37).

Similarly, the music is written on measured papers. The horizontal axis of the paper indicates the time process; the vertical axis could be ignored. There are lines with 3 different intensity in the horizontal axis: heavy line, medium and light line. Each medium line contains a square and represents one second of music; the square is divided in two by a light line. This light line could
is subdividing a second and could be considered as an eight note. The thickest line could be considered as a bar line; in this case each bar contains 6 seconds or 6 beats.

The music starts directly on the first thick line. Respectively all the lines are active, except the very last line of each page, which is representing the first line of the next page. Therefore the last thickest line of every page should be ignored.

The small bow sign under the new notes indicate the normal slur note, and means the new pitch should be played as continuous to the previous one, without any disruption.

The small bow at the end of each page indicates the continuity of the sound throw the next page without disruption (tie note).

The beams of the notes are generally omitted. Only the note head shows the new information of frequency (pitch) and timing (rhythm).

The rhythmical property of the sound could be noticed proportionally to the place where the note heads are written. However a more precise indication of rhythm is given under the main line. In all the other cases the place of each note or action regard to the box could be considered proportional. For example a note half way after the middle line of one second could be interpreted as one sixteen note.

In the section “decomposite thought” another clef was used. This clef shows the extension of the movements. The player should play pitches within this extension, with regard to the place of drawn line in micro interval scale.
Finite Functions of infinitive sets, first page. Note at the rhythm indication under the lines on second and third bar.

Example of notating the multiphonics
Clef used to show playing between the given range of pitches

Notating of bisbigliandi in a tutti section

Since the notation of my next pieces are very similar to this piece, I will exclude discussions about the notation for the next pieces. Sections from the score are added in the appendix.
Standing waves and multiphonics on wound string: dimension II

“Dimension II, Destruction” was a long term project in which I used all the knowledge and techniques that I gained during the previous pieces of master studies. In fact this piece is a summary and development of all those pieces. Now looking back at time, I see that I wrote the other pieces as a sort of study for composing this piece as a final of a chapter.

The piece is written for sextet plus pre-recorded instruments, or 18 live musicians. The ensemble is:

4Flutes (1+3)
4Clarinets (1+3) 2 clarinets in A, 2 clarinets in Bb
Piano + 2 crotales
Percussion (4 crotales + playing inside piano)
4Violins (1+3)
4Celllos (1+3)

Similar to the other pieces, I started composing this piece with studying on the acoustic of instruments I was going to write for, in order to have an understanding of ways to write my desired type of music.

I had had extensive studies on string and percussion instruments and clarinets. As well as good experiences with other woodwinds and plucked strings. The main thing to grasp in this piece was acoustic of piano.

But before that a very short note on flutes and how inspired by acoustic of flutes, I became interested on whistle tones.

Flute and the minima peaks

The basic acoustic function of flute is somehow similar to that of clarinet. With the main difference that flute works with the minima peaks of acoustic impedance spectrum.

The flutist blows a rapid jet of air across the embouchure hole. The pressure inside the player's mouth is above atmospheric. The work done to accelerate the air in this jet is the source of power input to the instrument. The player provides power continuously. In the flute, the air jet, in cooperation with the resonances in the air in the instrument, produces an oscillating component of the flow.
The jet of air from the player's lips travels across the embouchure-hole opening and strikes against the sharp further edge of the hole. If such a jet is disturbed, then a wave-like displacement travels along it and deflects it so that it may blow either into or out of the embouchure hole. The speed of this displacement wave on the jet is just about half the air-speed of the jet itself (which is typically in the range 20 to 60 metres per second, depending on the air pressure in the player's mouth). The origin of the disturbance of the jet is the sound vibration in the flute tube, which causes air to flow into and out of the embouchure hole. If the jet speed is carefully matched to the frequency of the note being played, then the jet will flow into and out of the embouchure hole at its further edge in just the right phase to reinforce the sound and cause the flute to produce a sustained note. To play a high note, the travel time of waves on the jet must be reduced to match the higher frequency, and this is done by increasing the blowing pressure (which increases the jet speed) and moving the lips forward to shorten the distance along the jet to the edge of the embouchure hole.

The pipe is open to the air at the ends resulting that the total pressure at the ends must be approximately atmospheric pressure. In other words, the acoustic pressure (the variation in pressure due to sound waves) is zero. These points are called pressure nodes, and they effectively lie past the end of the tube by a small distance (about 0.6 times the radius, as shown: this distance is called the end correction).

Pressure nodes and antinodes. Music Acoustic website.

The wave shown above is the longest standing wave that can satisfy this condition of zero pressure at either end. In the figure below, we see that it has a wavelength twice as long as the
The frequency $f$ equals the wave speed $v$ divided by the wavelength $\lambda$, so this longest wave corresponds to the lowest note on the instrument.

\[ f = \frac{v}{\lambda} \]

Proportion of the wavelength to the frequency and distribution of harmonics in flutes. Picture from Music Acoustic website.

The air jet has its own natural frequency that depends on the speed and length of the jet. To oversimplify somewhat, the flute normally plays at the strongest bore resonance that is near the natural frequency of the jet. Register holes are used to weaken the lower resonance or resonances and thus make one of the higher resonances the strongest.

It's worth adding that the flute is not entirely open at the embouchure: the hole across which the player blows is smaller than the cross section of the pipe. This narrowing does have an acoustic effect. Nevertheless, it is sufficiently open that large oscillating flows of air can enter and leave the pipe with very little pressure difference from atmospheric. Low pressure, high flow: this boundary condition is a low value of acoustic impedance.

Due to the effects of low pressure air flow, it is possible to derive the higher partials of a fundamental with very controlled flow of air. “Whistle tones” are easy to be played over a long time, due to the low pressure of jet.

I used a combination of whistle tones from different fundamentals and in different tunings. Result in a cloud of high and very soft harmonic movements of sound.

There are much more to discuss about acoustic of flutes which can’t be fit to this essay. For further discussions concerning flutes look at: [http://www.phys.unsw.edu.au/music/flute/](http://www.phys.unsw.edu.au/music/flute/)
Piano

The main challenge on this piece was to write for piano. After studying and experimenting on acoustics of piano, I decided to use only one string of piano and play simultaneously on different overtones of it.

The D\textsubscript{1} string has the best acoustical character for my piece, for several reasons. First of all the ease of playing and having a single string would make it possible to play on it on either sides. Due to the thickness and mass of string there is always a certain amount of inharmonicity which could make an interesting result for disturbing and interfering of its overtones with the high frequencies of other instruments in the ensemble.

I asked two musicians to play on the either sides of this string. So each one of them would strike the string (with different material) and create different types of traveling and standing waves alongside the string. Having simultaneous different modes of waves and vibrations, that couldn’t be controlled very easily.

The figure (right) shows the interaction of two waves, with equal frequency and magnitude, represented as a time sequence travelling in opposite directions: blue to the right, green to the left. The red line is their sum: the red wave is what happens when the two travelling waves add together (superpose is the technical term), time increases from top to bottom. You could think of it as representing a series of photographs of the waves, taken very quickly. The red wave is what we would actually see in such photographs.

Suppose that the right hand limit is an immovable wall. The wave is inverted on reflection so, in each "photograph", the blue plus green adds up to zero on the right hand boundary. The reflected (green) wave has the same frequency and amplitude but is travelling in the opposite direction.
At the fixed end they add to give no motion - zero displacement: after all it is this condition of immobility which causes the inverted reflection. But if you look at the red line (the sum of the two waves) you'll see that there are other points where the string never moves! They occur half a wavelength apart. These motionless points are called **nodes** of the vibration, and they play an important role in nearly all of the instrument families. Halfway between the nodes are **antinodes**: points of maximum motion. But note that these peaks are not travelling along the string: the combination of two waves travelling in opposite directions produces a **standing wave**.

Note the positions (nodes) where the two travelling waves always cancel out, and the others (antinodes) where they add to give an oscillation with maximum amplitude. You could think of this diagram as a representation (not to scale) of the fifth harmonic on a string whose length is the width of the diagram.

**Composition**

I imagined the beatings on both sides of string by the two musicians, would create a second “fake” standing wave which would result in unexpected acoustical behavior. However there is always a danger that the two waves would cancel out each other (this could only happen until a limit in reality).

I noticed different nodes of vibrations on the string of piano. Some main nodes that would result in relatively strong single-pitched overtones. And the nodes between them that would result in different multiphonics.

Obviously the modes of holding or damping the string as well as their timing related to the strike, alters the sounding result of the harmonics. There are some behaviors of piano string that are quite different than other string instruments.

Torsional waves and movements of piano string are pretty strong. I realized that holding the string with two fingers, induce the torsional movement and create a very clear single pitch most especially in the main nodes. Damping with the tip of finger however is more suitable for different types of multiphonics.

Another phenomena that I used on the piano part was what I called “double harmonics”. Similar to artificial harmonics on violins, double harmonics are working with touching two different nodes of a piano string simultaneously. This could be done on the two different sides of string
with two musicians, or by one musician on one side of string. For example damping the $4^{th}$ and $3^{rd}$ harmonics together would result on $12^{th}$ harmonic partial.

**Preparation and notation marks**

The string has to be marked on the ratios/nodes of $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{5}$ and $\frac{1}{6}$ on both sides of the string resulting on harmonic partials of $2^{nd}$, $3^{rd}$, $4^{th}$, $5^{th}$, and $6^{th}$.

![Diagram of pianist and percussionist](image)

The pianist should keep the key depressed as long as the line continues, in order to let the other musician play on the string. The pedal should be used only on the last 20 seconds of the piece.

$\triangle$: damp the strings with the tip of fingers i.e index finger. In case of double harmonics, one node with tip of thumb and the other tip of index finger.

$\square$: hold the string on the given place with thumb and index finger; therefore the torsional movement of string will be affected and the result is a clearer overtone with a stronger single pitch.

M: multiphonics on piano string. Damp the string in between the main nodes and the result will be a combination of several harmonics anyway!

DH: double harmonics (artificial harmonics). Make higher harmonic partials with damping more than one node at the same time, similar to what is known as artificial harmonics on string instruments. i.e

DAP: damp the string slightly after beating or pressing the key. The sign is replaces sometimes with $\gg$ or simply shown by dotted lines that the damping occurs after the beat.

$\hat{\diamond}$: scratching the string with the triangle beater. Regarded to the angle of the line and the additional signs (look at the bowing signs on string section) it could be done slowly or quickly, with light or heavy pressure. Most desired sounds are very slow (speed) and heavy (pressure) of rubbing the string in a way that the sound of dents of string will be noticeable one after the other,
resulting a spectrum with emphasize on lower partials; and very fast and light movements creating rather high sounds which are variable based on the speed of rubbing action.

- beat the string either with pressing the key (hammer) or with the triangle beater on the given place. The pianist always play with the key and the percussionist always with the beater.

Occasionally the precise indication of desired partials is given when it’s needed; otherwise an approximation of the harmonic behavior of the string has been meant.

The piano score is written for an imagined concert tuning piano A=440/1 (D1≈ 36.70 Hz). However different conventional tunings won’t make a problem.

The size of concert piano is indifferent; the bigger pianos make it harder to play while the smaller ones have more inharmonicity on the wounded D string.

**Tuning system**

Having 16 instruments with different potentials and yet very capable for precise tuning, I tried to make a system of tuning which could cover a wide range of close frequencies. Considering the limits of each instrument and the differences on different pitches and different octaves, I ended up with a chart of having intervals of 1Hz difference (in A₄) between the whole ensemble.

That would result differently in different sections, and also in different octaves. For example flutes were tuned with 2Hz differences and the clarinets with 3Hz differences; however the combination of both groups should have summed up a variety of frequencies with 1Hz difference with possibly no unison in both groups.

Also in section where flutes had a solo the result would be different with solo sections of clarinets. This principle was used in the whole ensemble. The important thing is when the difference of tunings between A₄ in clarinet is 3Hz; the difference of A₃ on same instruments will be 1.5Hz and similar to higher octaves the amount would be double. This had to be regarded specially for tuning the lower strings of violins and cellos. Therefore in order to somehow distributing all frequencies in a desired ratio (i.e 1Hz in the 4th octave or 0.5Hz in lower octaves) the ratio of tunings could have been different on different strings of an instrument. For example if the E string needed to be tuned with 3Hz difference, the D string might have to be tuned in 0.5Hz intervals. So in connection with the wind instruments the result would have been a concrete system of frequencies with specific/desired difference.
The table below shows the frequencies of tuning the whole ensemble. Note that the higher or lower pitches on each instrument would increase/decrease the ratio of differences and therefore the amount and quality of interference beats.

<table>
<thead>
<tr>
<th>Flutes:</th>
<th>Clarinets:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 440 Hz</td>
<td>1. 448 Hz (Bb)</td>
</tr>
<tr>
<td>2. 442 Hz</td>
<td>2. 445 Hz (Bb)</td>
</tr>
<tr>
<td>3. 444 Hz</td>
<td>3. 442 Hz (A)</td>
</tr>
<tr>
<td>4. 446 Hz</td>
<td>4. 439 Hz (A)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Violins:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I. 652 Hz</td>
<td>I. 653.5 Hz</td>
</tr>
<tr>
<td>II. 433 Hz</td>
<td>II. 435 Hz</td>
</tr>
<tr>
<td>III. 265 Hz</td>
<td>III. 267 Hz</td>
</tr>
<tr>
<td>IV. 190.5 Hz</td>
<td>IV. 192 Hz</td>
</tr>
<tr>
<td>I. 655 Hz</td>
<td>II. 438 Hz</td>
</tr>
<tr>
<td>II. 441 Hz</td>
<td>III. 269 Hz</td>
</tr>
<tr>
<td>III. 271 Hz</td>
<td>IV. 193.5 Hz</td>
</tr>
<tr>
<td>IV. 195 Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cellos:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I. 221.5 Hz</td>
<td>I. 220 Hz</td>
</tr>
<tr>
<td>II. 148 Hz</td>
<td>II. 146.5 Hz</td>
</tr>
<tr>
<td>III. 97 Hz</td>
<td>III. 95 Hz</td>
</tr>
<tr>
<td>IV. 66 Hz</td>
<td>IV. 64 Hz</td>
</tr>
<tr>
<td>I. 218.5 Hz</td>
<td>II. 145 Hz</td>
</tr>
<tr>
<td>II. 143.5 Hz</td>
<td>III. 93 Hz</td>
</tr>
<tr>
<td>III. 91 Hz</td>
<td>IV. 62 Hz</td>
</tr>
<tr>
<td>IV. 60 Hz</td>
<td></td>
</tr>
</tbody>
</table>

Table of all frequencies used for tuning in “Dimension II, Destruction”
Conclusion

Interactions and interferences of sound waves

Looking back to the compositions I worked on, I can see a distinguishable motif. A line that was developed and progressed to the last and most recent pieces.

My aim in composition had been to gain a balance between imagination and reality, science and art. I tried to know the material of music as best as the science allows us. However being an artist, one can “feel” the lacks that science could present.

There are always considerable percentages of error. The acoustical reality never works precisely as science describes. In the point of view of an observer/artist, what physics does is: modeling the reality of a phenomenon based on the data and material from mathematics. And here is the gap; there are no proofs that such calculations should be authentic.

Even if it would be possible to completely measure and calculate all the aspects of real sound with all the possible errors or unexpected results, which involves infinite amount of data/calculation and infinite memory to restore/process those data, it won’t be a task for an artist to do! However such attempt would be similar to create a “perfect system”, something that cannot exist, at least theoretically.

I have been trying to consider the reality while imagining the acoustic experience (music). It is not possible to “hear” the music I’m writing beforehand. I can’t hear the intervals of 1Hz on my mind. The only I could do is to “imagine” the sound. And the rest is a matter of experience and knowledge that how surprised you would be to see the reality of such acoustical imaginations.

I have used acoustical phenomena such as interference beats and difference/summation frequencies frequently in my music. As a basis for understanding of acoustics, especially on those phenomena, one has to know that the perception and also production of such features is highly depended on numerous other factors.

First of all, sound waves radiate in all directions. The frequency (what gives the impression of pitch) is the amount of cycle periods a wave makes in one second. Since the wave is emitting in all directions, the further the sound travels the wider the periods become. That means the amount of cycles in a second then will be lower, which gives the impression that the frequency (pitch) is changed due to distance.
However there are plenty of other factors that alter the sound. The wave radiations are not isotropic. There are always reflections of waves due to the walls or objects in a hall. The other key facts concerning wave transmission are not discussed here.

So the first thing a composer/sound artist has to know is that no two people in the audience will hear the same thing. That is why all the calculations and considerations of composing are merely approximation.

In other word my music is an attempt to approximately realize the pure work of acoustical-abstract imagination, to the reality of audible sounds.

**Perception, interpretation and hearing: first step on psychoacoustics**

The very last piece of music in my master studies could be considered as a new chapter in my musical career. “Acoustical Modelings” was written almost together with DimensionII, Destruction. Both pieces have much resemblance in the sounding and similar acoustical properties.

However *Acoustical Modelings* was aimed to cover a different aspect of sound/music. After many pieces dealing directly with the acoustic and actual physical facts, now I tried to be concern about perception and hearing of those sounds.

If in previous piece there were real/visible interferences on frequencies which would make a summation frequency, in recent piece I attempt to build such experiences inside the brain of listeners rather than the actual phenomena. The target of this composition is based on psychoacoustics.

There are many places where the sounding of piece is not about what is written in the score or what the instruments are playing, but about how those sounds would be heard with our hearing system. For example I used some very quite bass notes underneath of a dense section of loud and high frequencies. Obviously the bass notes won’t be heard but they aimed to be perceived. The bass notes in this example suppose to build up a “fake” spectrum for those very high frequencies. So if one (most likely several) of those high frequencies coincide with the frequencies of overtones from the bass note, then we would perceive those sounds in a different way.
Seemingly this is a new field of study and not so many researches related to psychoacoustics have been done yet (at least in this kind of function). The ability of listening and processing the sound is different on different people.

I attempted to put a number of “tricks” for the ear and brain in this piece, and am quite excited to see how the result will be. The piece start with a very long section of tremolos on crotales, then the other instruments enter on very high frequencies as well. This introduction takes almost 8 minutes, with no change break. The amount of energy on the high frequencies is considerable, however it won’t be damaging. This beginning is like a study on what sounds the brain and ears tend to notice in a very long seemingly stable but with unnoticeable shifts on intensity of different frequencies.

The time process of this piece also is some kind of a study on the perception of time. It starts with very long motionless yet quite annoying high sound (for about 8 minutes). What comes after is getting more and more stretched. In a balanced situation, after listening to an intro of 10 minutes, you would expect at least 30 minutes of music. While I tried to manipulate this concept by stretching the music slowly with an increasing ratio (similar to logarithmic).

It’s worth to mention that I generally avoid the discussion about emotions or intuition from my music, because I consider them as personal aspects of composition. However making a balance between intuition (emotion) and structure (intellect) is the perfect situation for my music. Choosing subtitles such as prelude, postlude or coda, or using some other elements from romantic music (for example an spectral rendering/pitch-progression form a short theme of Wagner’s Tristan Und Isolde in my piece Dimension II) could be suggesting to some more personal aspects of music that are not necessarily important for the audience.¹

The gentle transition from acoustics to psychoacoustics could be a promising end for the education. Luckily at the end of my study, I realized there are too many things to learn and research both in acoustics and psychoacoustics.

¹ The titles I chose for different sections of my pieces. In “dimension II, Destruction” the title of sections are: Prelude, Synthesis, Coda, Postlude. In the prelude section I used a spectral rendering from Wagner’s theme on Tristan und Isolde’s prelude as a pitch progression. Similarly in “Acoustical Modelings” sections are titled: Cochlear Response, Inner Rendering, Outer Rendering, Postlude. The usage of terminology of romantic era such as postlude and prelude is itself considered as a suggestion to the emotional impacts beyond or alongside to the acoustical experience of sound/music.
Bibliography


Livingston, Guy. *Horatiu Radulescu*, interview. 2007


**Appendix**

Some sections of the scores and complete recordings of these pieces are added to the thesis:

- Constructive Interference
- Finite Functions of infinitive sets
- Dimension II, Destruction
- Acoustical Modelings (only score)
FINITE FUNCTIONS

Of infinitive sets

For four clarinets

Arash Yazdani
Dis-equilibrium Inharmonicity (Artificial Function)
DIMENSION II

For Sextet plus pre-recording
Or 18 live musicians

Arash Yazdani
General Notes:

This piece is written for the Estonian ensemble for new music “Ensemble U:” consisted of six musicians; flute, clarinet, violin, cello, piano and percussions.

Except piano and percussion, all other instruments are multiplied by 4, shaping a group of four lines for each instrument with first instrument as the main line. These lines could all be performed with live musicians (18 musicians), or be recorded and played back on the concert.

The piece could be performed with or without click-track or conductor. In any case the proportion of time process is stable during the whole piece.

Each page contains 29 seconds of time process represented in 29 cells, and divided by heavy barlines into four bars of 6 seconds plus one bar of 5 seconds (the very last bar of each page has 5 seconds music while the first four bars have 6 seconds).

All the lines indicate the duration of an earlier given pitch. The lines without indications are repetition of the last given pitch. It is crucial to notice where the lines stop and start again.

All the barlines are merely in order to ease the playing and reading.

It is desirable to perform the piece with the click of 55 per beat, instead of a second.

The whole piece should be performed **without any vibrato!**

The ensemble is:

4Flutes (1+3)  
4Clarinets (1+3) 2 clarinets in A, 2 clarinets in Bb  
Piano + 2 crotales  
Percussion (4 crotales + playing inside piano)  
4Violins (1+3)  
4Cellos (1+3)

The quarter tones used in the piece should be as close to a precise forth portion of a whole tone as possible. However a little lower or higher than quarter tone is allowed on winds if all the instruments of a section play the similar pitch.

(♯): one quarter sharp.
(𝄪): three quarter sharp.
Notation:

The music is written on measured papers. The horizontal axis of the paper indicates the time process; the vertical axis depended on instrument, could be used as a basis for domains of action or frequency (pitch). There are lines with 3 different intensity in the horizontal axis: heavy line, medium and light line. Each medium line contains a square and represents one second of music; the square is divided in two by a light line. This light line is subdividing a second and could be considered as an eight note. The thickest line could be considered as a bar line; in this case each page has 4 bars of 6 seconds or 6 beats plus one bar (last bar) of 5 seconds/beats.

The music starts directly on the first thick line. Respectively all the lines are active, except the very last line of each page, which is representing the first line of the next page. Therefore the last thickest line of every page should be ignored.

The small bow (slur) sign under the new notes indicate the normal slur note, and means the new pitch should be played as continuous to the previous one, without any disruption.

The small bow at the end of each page indicates the continuity of the sound throw the next page without disruption (tie note).

The beams of the notes are generally omitted. Only the note head shows the new information of frequency (pitch) and timing (rhythm).

The rhythmical property of the sound could be noticed proportionally to the place where the note heads are written. However a more precise indication of rhythm is given under the main line. In all the other cases the place of each note or action regard to the box could be considered proportional. For example a note half way after the middle line of one second could be interpreted as one sixteen note.

The music starts directly on the first second. The lines show the duration of each pitch. So the sound continues until the line goes on and stops directly when it stops (similar to real-time notation). The very last line of each page should be ignored, and is the same as the first line of the next page.

The small bowed line under the notes means playing as a slur note (in continuous of previous note).

All the tunings should be done with a regard to the number of beatings per second between 2 adjacent instruments. For example to tune the first flute 440 Hz with the second flute 442 Hz the player should notice 2 beats per second while playing the middle A (A4). Or first flute (440Hz) and the first clarinet (448) musicians should hear 8 beats per second while playing the A4 together.

Flutes:

\( \tilde{\phi} \) : Whistle Tone. Gently blowing through the mouthpiece to produce thepartials up to the 16\(^{th}\) from the given fundamental note. In many places the player should change the fundamental fingerings while performing the whistle tones already. The rhythm and intervals where the player can breathe or have pause is indicated on the grid; as well as the frequency domain.

Norm: normal playing pitches.
The information of bowings could be consisted of two or more different features of bowing including speed, pressure/intensity, place of bowing modes of bowing etc. \( \text{\textbullet} \)

Different positions of bowings are corresponding with the spectral features of the sound of string and have the utmost importance.

M.S.P: Molto sul ponticelo.

S.P: Sul ponticelo.

Ord: Ordinario.

S.T: Sul tasto.

M.T: Molto (sul) tasto.

\( / \quad / \) : Phase shifting bow. Change the bow with a little click on the moment of changing, bow in between two imaginary walls. The resultant sound should be a different emphasis on the spectrum shape of sound on each phase of bowing (up and down).

\( \text{\textbullet} \quad \text{\textbullet} \) : Legato bowing; change the bow smoothly, without any click or change of spectrum shape.

\( \uparrow \) : Very light pressure of bowing (pressure of bow on string).

\( \downarrow \) : Very high pressure of bowing (pressure of bow on string).

\( \text{\textbullet} \) : Normal pressure of bowing.

\( \rightarrow \rightarrow \) : Fast speed of bowing.

\( \rightarrow \rightarrow \rightarrow \) : Slow speed of bowing.

\( \rightarrow \) : Normal speed of bowing.

\( \text{\textbullet} \text{\textbullet} \) : Bowing on 2 strings simultaneously.

\( \rightarrow \) : Bowing on only one string.

\( \circ \) : Change between two (or more) different sets of harmonics on two (or more) different strings. In any case try to follow and imitate the grids for the relative highness and lowness of the pitches (i.e the higher partials are notated in a higher place on the grid).

The sharpness and shape of the grid lines aims to suggest different ways of playing the partials. For example quick and messy changes of the notes or playing them for a longer time and smoothly change to the other note (higher or lower).

The indications of strings are given via Roman number.
The indications of harmonic partials are given by numbers. The fundamental partial is 1\textsuperscript{st} harmonic, and the second partial is 2\textsuperscript{nd} harmonic and so on. In order to give an imagination of the whereabouts of harmonics, a table with loose indication of the partials to pitches is added as an appendix to the score. However the concept of pitch has no meaning in such tiny intervals of different frequencies.

It is most convenient to play all the high overtones of strings with only one finger. Using the finger nail with a slight pressure makes it easier to achieve the high overtones, especially on the lower strings.

A clef that shows the relative position of finger on string is used in most places. The more precise indication of frequency/pitch is given by the harmonic number of desired partials.
# Table of all frequencies for tuning:

**Flutes:**

1. 440 Hz  
2. 442 Hz  
3. 444 Hz  
4. 446 Hz

**Clarinets:**

1. 448 Hz (Bb)  
2. 445 Hz (Bb)  
3. 442 Hz (A)  
4. 439 Hz (A)

**Violins:**

1) I. 652 Hz  
   II. 433 Hz  
   III. 265 Hz  
   IV. 190.5 Hz  
2) I. 653.5 Hz  
   II. 435 Hz  
   III. 267 Hz  
   IV. 192 Hz  
3) I. 655 Hz  
   II. 438 Hz  
   III. 269 Hz  
   IV. 193.5 Hz  
4) I. 656.5 Hz  
   II. 441 Hz  
   III. 271 Hz  
   IV. 195 Hz

**Cellos:**

1) I. 221.5 Hz  
   II. 148 Hz  
   III. 97 Hz  
   IV. 66 Hz  
2) I. 220 Hz  
   II. 146.5 Hz  
   III. 95 Hz  
   IV. 64 Hz  
3) I. 218.5 Hz  
   II. 145 Hz  
   III. 93 Hz  
   IV. 62 Hz  
4) I. 217 Hz  
   II. 143.5 Hz  
   III. 91 Hz  
   IV. 60 Hz
ACOUSTICAL MODELINGS

For 15 musicians

Arash Yazdani
General Notes:

This piece is written for the Ensemble Phoenix Basel.

The proportion of time process is stable during the whole piece.

Each page contents 30 seconds of time process represented in 30 cells, and divided by heavy barlines into five bars of 6 seconds.

All the lines indicate the duration of an earlier given pitch. The lines without indications are repetition of the last given pitch. It is crucial to notice where the lines stop and start again.

All the barlines are merely used in order to ease the playing and reading.

It is desirable to perform the piece with the speed of 55 bps, instead of a second.

The whole piece should be performed without any vibrato!

The ensemble is:

Flute
Oboe
Clarinet in Bb
Double Horn in F (simultaneously using Bb valve as well)
Trumpet in C (simultaneously using Bb valve as well)
Trombone
Piano + 2 crotales
2Percussions (each plays 4 crotales + playing inside piano)
2Violins
Viola
Cellos
Double Bass

The quarter tones used in the piece should be as close to a precise forth portion of a whole tone as possible. However a little lower or higher than quarter tone is allowed on winds if all the instruments of a section play the similar pitch.

( ): one quarter sharp.

( ): three quarter sharp.
On the first section there is a clef used to indicate playing within a major second interval. The player should follow the grid and play in quarter tones between the given extend. Play legato and breathe on given places. Avoid any glissando as much as possible.

**Reeds:**

: Teeth on the reed!

Norm: Normal playing, after bisbigliando or reed sounds.

Bsbg : Bisbigliando, should be played like fluctuations on the sound, the speed of bisbigliandi is given where appears.

**Piano/Percussion:**

Two musicians will be playing simultaneously on the either sides of the same string, D1 of the normal grand piano (the lowest D on piano) whose door has been removed for the ease of playing. The string has to be marked on the ratios/nodes of ½, ⅓, ⅓, 1/5 and 1/6 on both sides of the string resulting on harmonic partials of 2nd, 3rd, 4th, 5th, and 6th.

The score is not written based on conventional pianistic techniques and it is more convenient to be performed by two percussionists. However in this text the player who is playing on the keyboard side is referred to as pianist and the musician who plays on the back side of piano is called percussionist.

Both musicians share the middle of string (2nd partial) on their playing range, and the two opposite direction of string. The pianist also needs to play on the short portion of the string between the hammer and tuning pin

Two sets of bow hairs have to be placed on D1 and A0 strings. A third player is needed to do the bowings on these two strings. Bowings start on the center of string (first node/2nd harmonic). Different speeds and ways of bowing is asked by the musician (look at the string sections for signs of bowing speed), as well as movements of bow toward different nodes. The freedom of these movements is depended on the brand and model of piano, however in this piece the player should bow on the upper side of string, from the center to the holding pins.