The search for a microtonal Flute

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The Search For A Microtonal Flute

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Declaration

I declare that this work is completely my own, that it comes from no other outside source and that no portion of this work has been previously submitted for a degree in this or any other university

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Abstract

This thesis investigates the possibility of a microtonal flute and the practicality of playing such an instrument.

Microtonality is concerned with the intervals between any two consecutive notes in a tuning system. Standard tuning is not considered microtonal, however, any other system can be. There are various tuning systems that are used throughout the world. These include Equal Tempered Tuning, Just Intonation, Chinese Pentatonic, and Javanese Slendro tuning. An instrument with the ability to change between any tuning systems would be considered fully microtonal.

In this thesis the frequencies and spectrums produced by the Boehm flute are investigated prior to investigating the 'plunger' flute and the 'sieve' flutes.

Within a given register the plunger can be considered as a fully microtonal instrument however, results from the plunger flute show that the instrument could not play the full range, and that the size of the bore greatly impeded the result.

The Sieve flutes produced a clearer sound, which was more like the Boehm flute than the Plunger flute was. However, the results show that for the two sieve flutes produced, neither of them could play in any complete tuning system. Due to the tone hole positions not matching those on the Boehm flute the instruments were unable to play in 12-ET (Equal Tempered). However, the results were not entirely unsatisfactory and with the modifications suggested for the sieve flute it is believed that a tuning system other than 12-ET would be playable.

This thesis examines some of the other possibilities that could be used to develop and subsequently produce a suitable playable microtonal flute. This thesis briefly considers how the ideas from the search for a microtonal flute could be used in the search for other microtonal woodwind instrument.

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1 Introduction.

1.1 Introduction to Microtonality

Microtonality refers to the frequencies that are played by any musical instrument when not playing the standard western musical scale based on each octave containing 12 semitones. Although there has always been microtonal music about, it is only more recently that musicians have started to use it in western music. The problem with trying to play microtonal western music is that there are not western instruments that are capable of playing the music.

Microtonality is not a new concept and there are cultures in the world where their standard tuning systems would be considered by visitors to be microtonal. In these countries the instruments have developed around their tuning system and in many ways would appear as inflexible as instruments developed for music in the western world.

To increase the use of the different tunings systems throughout the world, instruments need to be developed that are not tied to one specific tuning system. There are a few instruments in the orchestra that microtonal music is possible to be played on. The violin and its family members are such instruments. There are no fixed positions for the violinist to place their fingers to shorten the strings so other frequencies can be obtained.

1.2 Issues to be considered

There are a number of issues that need to be considered when designing a microtonal instrument based on an already developed instrument such as the flute. Any microtonal instrument would have to satisfy the following

- The timbre of the instrument would have to be as close to that of the Boehm flute for it to be considered as a flute.
- The instrument would have to be physically playable and not just one that can play all the frequencies but only when carefully set up and analysed.

1.3 Objective of thesis

This thesis investigates the possibilities of a microtonal flute and its control system for the tone hole closures. Any possible microtonal flute would have the frequencies analysed via their frequency spectrums and in comparison with the frequency spectrums of the Boehm flute.

Chapter two will review the acoustics of woodwind instruments with an emphasis on the flute and clarinet. This includes the theory for why the bore has to be shorter than would be expected to achieve the desired pitch. The developments of the flute and clarinet from the first instruments of their type to current designs are discussed, including what the important advancements have been. As the instruments have been developed, more has been discovered about the instruments and so to understand the modern instruments the historical discoveries need to be researched. The clarinet was investigated and discussed due to the difference in its structure and therefore the use it may have in designs for a microtonal flute.

Chapter three studies the various types of tuning systems and how they differ from the standard 12-ET system that modern woodwind tuning is based on. The methods to calculate the frequencies involved in each tuning system are explained and also how they can be compared to the natural tuning system of Just Intonation.

Chapter four recalls previous attempts that have been conducted into the production of microtonal instruments. As well as the flute, the clarinet and the bassoon are detailed here as although the vibrations are set up be a reed and the bores are different shapes the lessons learnt from these designs may be useful in the design of a microtonal flue. Also investigations into various methods of closing tone holes and the possible method of using software to control the closure are discussed.

Having discussed the theory and previous attempts of microtonal instruments the emphasis of the thesis from chapter five onwards will be on the practical and experimental side of creating and analysing such an instrument. This includes looking at a possible artificial blowing system, which would decrease the number of variables affecting the frequency of the sound produced. An artificial blowing system would remove the most uncontrollable variable that of the human playing the instrument.

The variables that need to be taken into consideration which alter the pitch of the instrument are investigated in chapter five. These will be discussed along with the investigation of a possible solution. Possible software for analysing the data is examined in this chapter as to its suitability to the task it would have to perform.

Before any microtonal instruments are attempted, the Boehm flute must first be understood and so chapter six examines this. The chapter details investigations into the Boehm flute, both with the key system and after the removal of the key system. Removing the key system allows for non-conventional tone hole closure patterns to be investigated to see whether the Boehm flute has any microtonal capabilities. The investigation of the Boehm flute needs to be conducted so there is suitable reference data to compare with the data from new instruments.

Having investigated the Boehm flute and the methods for analysing the data, the possible designs for microtonal flutes can be investigated. The first of these, the plunger flute, is looked at in chapter seven. The chapter discusses the design and the acoustic properties it would have that are different from the Boehm flute. After analysing the data conclusions are drawn as to its suitability as a microtonal instrument and possible improvements are suggested. The chapter also discusses the properties of the instrument that would appear to be unavoidable in assessment of the design.

Chapter eight investigates the possibility of flutes with far more tone holes than the Boehm flute, the sieve flutes. These flutes' capabilities are discussed and the instruments compared to the Boehm flute. The investigations also examine the suitability of the instruments to the quartertone scale (24-ET) however the possibility of other tunings systems being suited is discussed for further investigation.

Within chapter nine the various areas that would justify further work are discussed. These areas are split into a number of areas. Firstly the ideas for expanding on the designs investigated in this thesis are discussed. Then following from this the ideas that could be investigated next in the search for a microtonal flute are discussed. Finally the ideas that are not limited to the search for the microtonal instrument are discussed as to how they may be useful in creating and analysing future designs.

2 Woodwind Acoustics and Construction.

This chapter will look at the acoustics of woodwind instruments, including why the bore has to be shorter than would be expected to achieve the desired pitch. The history of the flute and clarinet are detailed in this chapter showing how they have developed over time and what the important advances have been. As the instruments have been developed, more has been discovered about the instruments and so to understand the modern instruments the historical discoveries need to be researched.

2.1 General Acoustical Theory

Sound propagates by compressing the molecules nearest the source, which then exerts a pressure on the next section of molecules; this compresses them and decompresses the previous section. This pattern continues throughout the medium at the speed of sound. The speed for that medium can be found from using Boyles Law if the medium is a gas. For the gas in which the sound propagates to be considered as an adiabatic system there are a number of assumptions that have to be made. The first is that there is no work done when the pressure of the gas or volume in which the gas occupies changes and the other relates to no work being done in that there is assumed to be no temperature change occurring for a change in volume or pressure. Therefore it assumes that the medium is a thermally perfect gas and the equation is:

$$v = \sqrt{\gamma R T} \qquad \text{E 2-1}$$

where T is the temperature measured in Kelvin, γ is the adiabatic index and R is the gas constant for that medium. So from this the speed of sound in air can be found for any temperature.

$$v = \sqrt{402.2T} \qquad \text{E 2-2}$$

Therefore for any one gas it can be said that the speed of sound is proportional to the temperature.

$$v \propto \sqrt{T} \qquad \text{E 2-3}$$

The frequency of the note heard depends on how quickly the molecules in the medium are compressing and decompressing, the faster they vibrate the higher the frequency. The range of frequencies a human ear can hear is 15Hz to 20 kHz, although the peripheral frequencies are the first to deteriorate in the ageing process. 1 to 4 kHz is the range that the human ear is most sensitive to and this is why one piccolo in an orchestra can be heard over every other instrument. This audible range correlates to the notes C_0 to $D\#_{10}$ as the two extremes. (C_0=16.34Hz and $D\#_{10}$=19.9kHz) where C and D# relate to the note name and $_0$ and $_{10}$ relate to the octave.

Woodwind instruments have different ways of producing the vibrations that cause the sound and three different bore types each giving rise to different characteristics. The three types of bores are open cylindrical, closed cylindrical and conical. Flutes and recorders have open cylindrical bores, clarinets have closed cylindrical bores and oboes and saxophones have conical bores. Each type of bore responds differently. To produce the vibrations oboes use double reeds, clarinets and saxophones use single reeds and the flutes and recorders produce the vibrations by the air jet from the musician hitting a 'knife edge'.

2.1.1 Acoustic Impedance

Acoustic impedance is the ratio of air pressure to airflow and is a physical property of any woodwind instrument. The instrument does not need to be played to measure its acoustic impedance, as it is independent of the flautist.

The acoustic impedance of a woodwind instrument will vary depending on how many tone holes are closed. It does not depend on what frequency the flute would be playing as with the Boehm flute the same holes are covered for many of the notes in the second octave as are in the first the acoustic impedance is the same for both registers. A register is a series of frequencies on the instrument that have similar properties, different instruments have different numbers of registers and the register breaks are in different places. There are two main ways in which a register break occurs, the first is where small tone hole (called a register hole) high up on the instrument is opened up this then creates a point of atmospheric pressure and the frequency of the note played depends on the distance from the register hole, the second method for a register break occurring is to overblow as with the flute.

As with many of the acoustical properties acoustic impedance has an electrical analogy that helps with the understanding. As

$$Acoustic\ Impedance = \frac{Pressure}{Flow}$$

then the units of acoustic impedance can be calculated as Pa.s.m^{-3}. However with musical instruments the units are more often in MPa.s.m^{-3} due to a smaller volume of air within the instrument and the pressure differences being quite large.

By measuring the acoustic impedance of an instrument the quality of the instrument can be seen as it concentrates on the physical properties of the instrument rather than the effect the musician has. Therefore it can be used as a method of finding out whether the instrument sounds poor because of the actual instrument or the musician playing it. The quality of the instrument can be split into a number of sections

- The stability of the notes
- The number of notes that can be produced with a single fingering by overblowing
- How in tune the notes produced are

Acoustic Impedance is not a static value and changes in relation to the frequency. For a bore with a single tone where the tone had only one frequency, such as a sine wave, then the acoustic impedance would be static.[1]

2.1.2 Cents

Cents are a way of measuring the differences in pitch; it is a convention that makes comparing intervals in different octaves slightly easier. The number of cents can be found using the following equation:

$$c = \left(\frac{1200}{\ln 2}\right) \times \ln r$$

Where r is the ratio of the frequency of the two notes in the interval, r can also be calculated using:

$$r = \frac{f_2}{f_1}$$

in which f_2 and f_1 are the frequencies of the two notes in the interval.

An octave comprises 1200 cents and an equal tempered semitone is 100 cents, this can be seen below.

$$\begin{aligned} c &= \left(\frac{1200}{\ln 2}\right) \times \ln 2 \\ &= 1200 cents \end{aligned}$$

the ratio between the frequencies of two notes a semitone apart is $1 : \sqrt[12]{2}$ and so $r = \sqrt[12]{2}$ and from this the number of cents can be found as

[1] Page 172-186 in [FLE91]

$$
\begin{aligned}
c &= \left(\frac{1200}{\ln 2}\right) \times \ln \sqrt[12]{2} \\
&= \left(\frac{1200}{\ln 2}\right) \times \ln\left(2^{\frac{1}{12}}\right) \\
&= \left(\frac{1200}{\ln 2}\right) \times \frac{1}{12} \ln 2 \\
&= 1200 \times \left(\frac{1}{12}\right) \\
&= 100 cents
\end{aligned}
$$

Cents make comparing two different tuning systems easier as they may not contain the same frequency at any one point. Table 2-1 shows how 12-ET can be compared to Just Intonation using cents.

12-ET			**Just Intonation**		**Comparison**
Scale Deg.	Cents	Interval	Closest Ratio	Cents	Difference in cents
0	0	Unison	1/1	0	0
1	100.00	Minor 2nd	17/16	104.96	-4.96
2	200.00	Major 2nd	9/8	203.91	-3.91
3	300.00	Minor 3rd	25/21	301.85	-1.85
4	400.00	Major 3rd	81/64	407.82	-7.82
5	500.00	Perfect 4th	4/3	498.04	+1.96
6	600.00	Augmented 4th (or) Diminished 5th	45/32 64/45	590.22 609.78	+9.78 -9.78
7	700.00	Perfect 5th	3/2	701.96	-1.96
8	800.00	Minor 6th	128/81	792.18	+7.82
9	900.00	Major 6th	42/25	889.15	+1.85
10	1000.00	Minor 7th	16/9	996.09	+3.91
11	1100.00	Major 7th	32/17	1095.05	+4.95
12	1200.00	Unison (Octave)	2/1	1200	0

Table 2-1 Comparing 12-ET to Just Intonation[2]

From this table you can see how two instruments tuning using the two different tuning systems would not sound in tune when played together even though the intervals are named the same.

2.2 The Flute.

2.2.1 Flute History

Flutes have been around for centuries in different forms and have been gradually developed and changed over time to become the instrument that we know today. There are two different types of flute: transverse flutes and duct flutes (which have also been called Whistle Flutes and Fipple Flutes). The flute we know today is a transverse flute, while the recorder is a form of duct flute. Throughout history there have been many different names for the flute and the recorder.

2 Modification of Table 12(a) (Appendix II) from [OZZ99]

For example, during Handel's time the 'recorder' was often referred to as the 'flute' and the 'flute' referred to as 'traverso' or 'German Flute'.[3]

2.2.1.1 The Flute before Boehm

All transverse flutes have the same way of producing the sound and basic structure. In this thesis the transverse flute shall be referred to as a 'flute'. The almost cylindrical pipe has evolved over time, prior to the baroque period it was cylindrical (Figure 2-1a) and then developed to have a main bore that is conical and slightly tapered (Figure 2-1b). It continued to have this structure until Theobald Boehm in the nineteenth century developed the structure used today (Figure 2-1c). The different advancements to the flute's shape can be seen in Figure 2-1. Over the time the structure of the flute has developed the key work has also developed, from having no keys to having many, but until the time of Boehm lots of forked and crossed fingerings were needed to achieve the notes required.

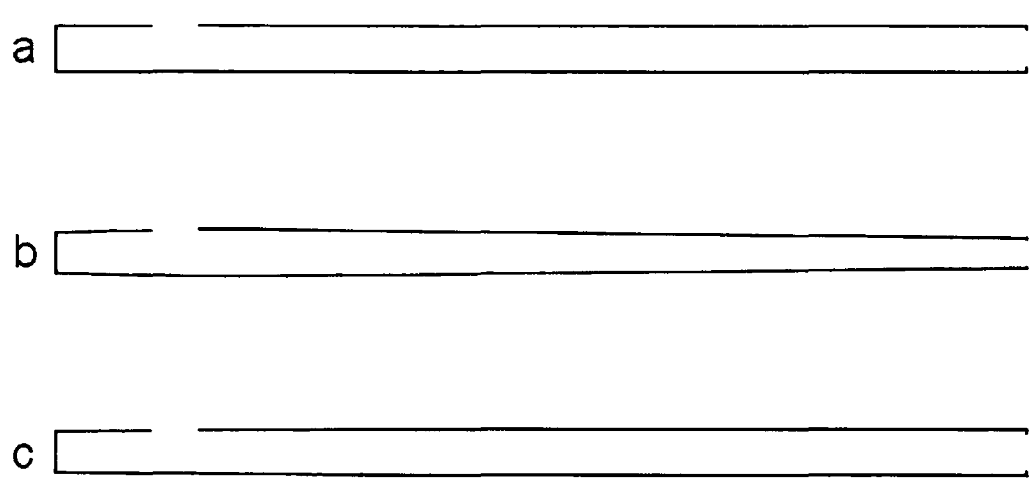

Figure 2-1 The development of the Flute's structure

2.2.1.2 Boehm's work on the flute

Boehm made a lot of improvements and changes to the flute. As well as the key system that he developed, he also made improvements to the shape of the flute, particularly the embouchure hole and headjoint. Boehm spent much time looking at the effects of the tone holes and where they should be placed and what size they should be. Through this work the flute developed into the instrument known today.

Boehm was a flautist as well as a flute maker and when he started making his flutes he was making them for his personal use. Boehm made his first flute at the age of sixteen in 1810. From then until 1818 he made instruments in his goldsmith's shop based on other people's

[3] Page 2 in [BAT79]

designs with his modifications. In 1828 Boehm opened up a flute factory and started work on his first flute with 'posts' to improve the key structure. By 1832 Boehm had redesigned the key structure yet further and implemented his new system with ring keys on a wooden flute. However, Boehm did not make any flutes between 1833 and 1846, but in 1847 he produced his first metal flute with the ring key system, which is known today as the Boehm system. This flute won the top prize at both the London World Exposition in 1851 and the Paris World Exposition in 1855. While designing his key structure Boehm also recalculated where the tone-holes should be, and how large they should be to allow all notes within the tuning system to be played.

Boehm changed the shape of the embouchure hole to the rounded rectangle that is used today, the rectangular hole gave a longer 'knife-edge' than an oval or round hole. The straight side of the embouchure hole meant that when the instrument was played a stronger tone was produced when compared with an oval hole: as there were more molecules that could be excited to produce the sound.

When Boehm first implemented his key system it was on a flute with a conical bore. Boehm still worked on improvements to the structure of the flute and by 1871 Boehm had redesigned the structure to include a cylindrical bore with a parabolic head-joint rather than a conical bore.

Boehm introduced the silver flute to flautists and ever since then they have become the most popular flute. Boehm had found that there were a number of factors connected with the material that affected the timbre of the instrument and how long a single note can be held. Metal instruments tend to be lighter than wooden instruments due to the volume of material that is needed to make them. Wooden instruments need thick bore walls, whilst metal instruments can have very thin walls. Even though the metal would probably have a higher density, due to the much larger volume required with the wooden instrument, the wooden instrument would be the heavier. The lighter the instrument the easier it is to hold a single note and less effort is required to play for the same bore length. Boehm found that the brittleness and hardness of the instrument made a difference in the timbre. When looking at the silver flute's advantages Boehm found that they were easy to play to produce a sound, but blowing too hard often occurred producing a harsh sound, as opposed to the best tone qualities that lend themselves to large rooms. Although they were easy to play, the flautist needed to have a strong embouchure to produce the best sound, which required much practice. Wooden flutes on the other hand were suited to people's embouchure before they have had extensive practice. The wooden flute was popular in Germany as it tended to suit their music style. Further on in his career, Boehm recommended a flute with a wooden head joint and silver bore as the best combination of materials to suit the needs of most people and to produce the best overall tone. Boehm had been making instruments out of the two materials throughout his career, through this was never taken in to account by the other makers of the time.

2.2.1.3 The Flute after Boehm

The flute has not changed its key system or structure since Boehm. A modern Boehm flute can be seen in Figure 2-2.

Figure 2-2 The Boehm Flute

After Boehm made his first silver flute, the trend for the flute material changed from wood to metal. Recently many of the best flautists in the world have been using wooden flutes or wooden head joints more and more, believing that the tone of the instrument is more pleasant. This can be related to Boehm's findings, when he stated that a flute with a wooden head-joint and a silver bore would produce the best tone.[4] However, Coltman's experiments in 1971[5] would suggest that this is not the case: he found that there was no noticeable difference measurable by the human ear between the different materials. Coltman showed that blindfolded flautists couldn't tell the difference between the different materials, when either using a plastic head joint on bores of copper, silver and grenadilla wood. Coltman was looking at the material of the bore whilst Boehm had looked at the instrument as a whole, and had found that a combination of material was best.

2.2.2 Flute Acoustics

The flute is an open cylindrical bored instrument. Each end of the instrument is at atmospheric pressure, as they are both open to the air. Even though the player's mouth partly covers the embouchure hole, the majority of it is still open to the atmosphere; therefore the embouchure hole behaves as an open end.

The pressure wave created within the instrument is caused by the vibration of the air particles. Where there is an open end the air particle can move to their maximum displacement, this creates an anti-node, as can be seen in Figure 2-3 Displacement wave for the fundamental frequency wave in a flute. A node is a point of zero displacement in a wave and an anti-node a point of maximum displacement. As a sound wave is a pressure wave the relationship between a displacement wave and a pressure wave needs to be explained as only the pressure wave will be referred to from now. At a node as there is zero displacement the pressure would be at its maximum where as at a anti-node as there is maximum displacement of the air particles the pressure would be equal to the atmospheric pressure.

[4] Page 56 in [BOE64]

[5] [COL71] and [COL73]

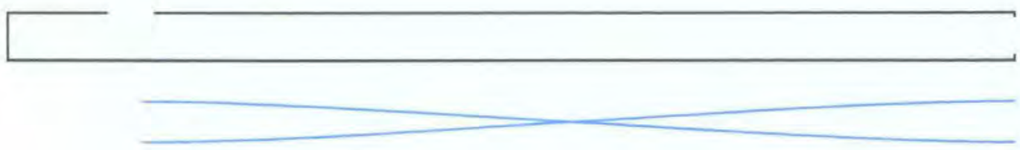

Figure 2-3 Displacement wave for the fundamental frequency wave in a flute

As both ends of the instrument are at atmospheric pressure there must always be a point of constant pressure of the standing wave there and so the fundamental wave must have a wavelength of twice the length of the instrument. This can be seen in Figure 2-4 along with the wavelength changes that occur when tone holes are opened up and the point at which atmospheric pressure first occurs changes.

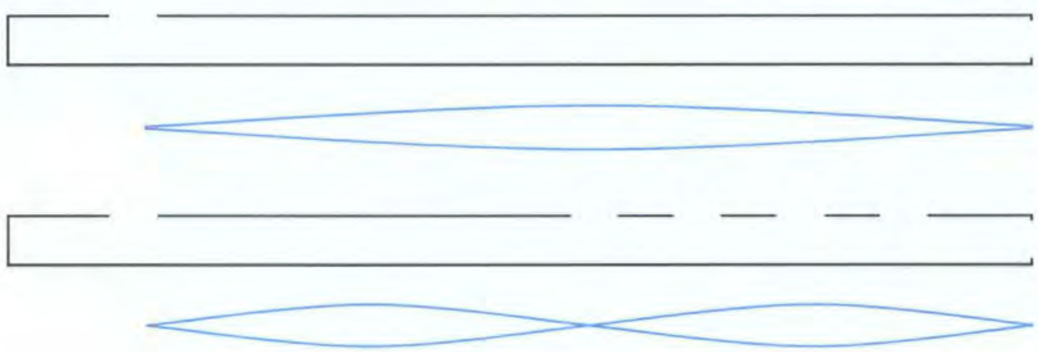

Figure 2-4 Fundamental waves on a flute

The established wave can also be called a standing wave because it produces points of constant atmospheric pressure and points of maximum and minimum pressure, which occur at constant positions.

2.2.2.1 End Effects on a flute

With any standing wave, end effects will occur if the diameter of the bore is small. The end effects result in the wavelength of the wave being longer than the bore of the instrument. Therefore when working out the frequency of the note being played, they need to be taken into consideration. This length is known as the acoustical length of the instrument. For an open-cylindrical bore end effects occur at both ends. For the flute, when all the tone holes are closed, such as in Figure 2-5, the end effects are Δl_T and Δl_E. The wavelength can be compared to a substitution tube which is a tube that is closed at both ends; it has no acoustical practicality, as the sound wave would never be able to escape to be heard, however is it therefore the same length as half the wavelength and does not involve any end effects.

Figure 2-5 A flute with its actual length and its acoustical length

The end effect at the end of the tube, Δl_T, can be found using the equation:

$$\Delta l_T = 0.3 * d_1 \qquad \text{E 2-9}$$

where d_1 is the diameter of the bore at the end of the flute.
The end effect at the embouchure end is slightly more complicated: it can be found using:

$$\Delta l_T = \frac{S_0}{S_E} * L_E \qquad \text{E 2-10}$$

where S_0 is the surface area of the bore at the embouchure hole, S_E is the surface area of the embouchure hole and L_E is the length of the embouchure hole.

For a Boosey and Hawkes Regent flute the end effects are as follows:[6]

$$\Delta l_T = 0.3 * 19$$
$$\Delta l_T = 5.7mm \qquad \text{E 2-11}$$

and

$$\Delta l_T = \frac{241}{88} * 12$$
$$\Delta l_T = 32.987 \qquad \text{E 2-12}$$
$$\Delta l_T = 33.0mm(3sf)$$

[6] [NED69]

When one or more tone holes are opened the end effect at the embouchure hole does not change, but at the tone hole it is different to when the flute has all its tone holes closed. Figure 2-6 illustrates this.

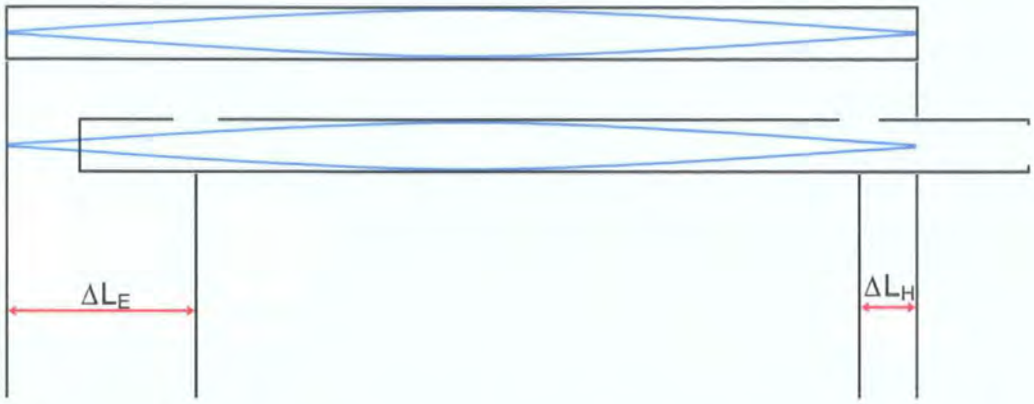

Figure 2-6 Flute's acoustical length a tone hole open.

Boehm investigated the placement of tone holes and through this found the end effects for the Boehm flute.[7] Much of Boehm's investigations would have been by trial and error until the formula for calculating the end effects was found. The end effect at the tone hole depends on what height the key pad is above an open tone hole.

Playing a flute with all its tone holes closed, and playing a flute type instrument of identical length and embouchure but with just a plain tube, will not sound the same note. The actual flute will sound flatter than the flute with the plain tube: this is because the actual flute has a larger internal volume. This is due to all the tone holes that are closed, as each one does not create a smooth bore: they actually create a small cavity in the side of the tube, and these cavities all add up to flatten the instrument. This can be compensated by making the length of the flute slightly shorter. This problem occurs more with metal flutes than wooden flutes: with wooden flutes the cavity is very small whereas with metal flutes a 'chimney' is built up from the bore, for the key pad to rest on and this increases the cavity volume.[8]

2.2.2.2 Multiphonics

A mulitphonic occurs when two or more notes are played at the same time. They appear because when looking at the frequency spectrum, there are two or more strong frequencies that are not harmonics of each other.

[7]Page 34 in [BOE64]

[8] Page 62 in [NED69]

Although multiphonics are possible on the flute, woodwind instruments with reeds also produce them. Benade investigated into multiphonics on the clarinet and the oboe to a greater extent.[9] Benade discusses how the sound of the instrument when playing pure tones will influence its ability to play multiphonics. Instruments that produce a bright, harsh sound will normally produce multiphonics easier. However with all instruments just slight changes in the performer's embouchure can result in a pure tone being produced rather than a multiphonic.

The multiphonic sound is also not particularly sustainable, as the oscillations within the instrument do not help to keep the strength of the standing wave and therefore the sound, whilst with a pure tone the oscillations and the standing wave will keep its strength as long as there the initial oscillations caused by the musician.

As multiphonics are played there are more individual tones that can be heard other than the main tones. These extra tones are formed from various relations that occur between the main tones. This principle is heterodyne and appears in all the sounds produced not just the multiphonics.

A possible multiphonic on the Boehm flute can be played using the fingering in Figure 2-7, where it will play C_5 and F#$_5$. The frequency spectrum can be seen in Figure 2-8.

Figure 2-7 Fingering for Flute Multiphonic C_5 and F#$_5$

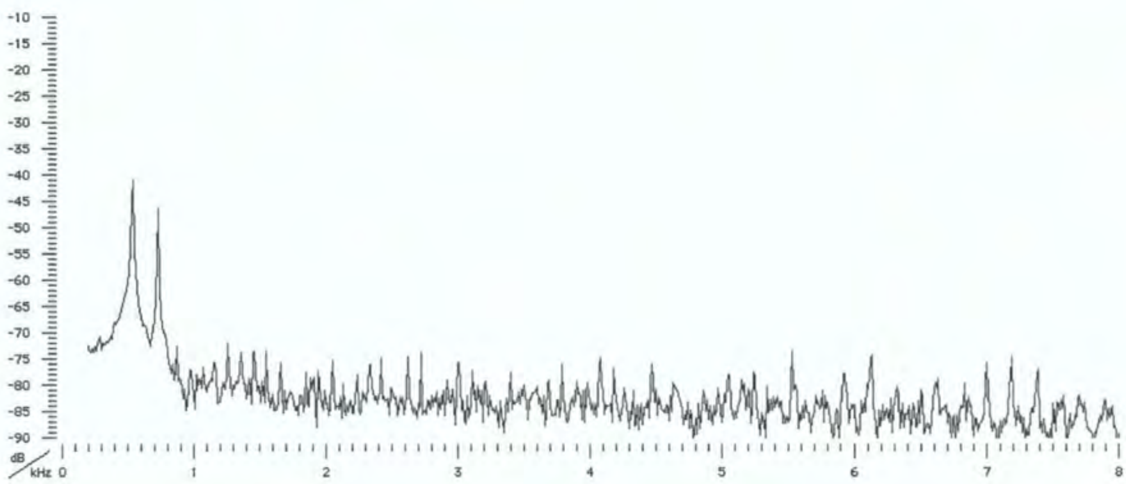

Figure 2-8 The spectrum of a Multiphonic (C_5 and F#$_5$) on the flute[10]

[9] Pages 559 to 567 in [BEN90]

[10] Flute Multiphonic C_5 and F#$_5$ from [UNSW05]

As can be seen in the spectrum there are two strong frequencies which are not harmonics of each other.

2.2.2.3 Production of the sound

The sound is produced on the flute by an air-jet being directed at the far edge of the embouchure hole away from the flautist's mouth: see Figure 2-9. This air jet is then split by the 'knife edge' and some of the air escapes, but the rest is directed into the flute where it creates a displacement wave. This wave's frequency is what determines what note is played and the flute's length determines the fundamental frequency. A different angle and speed of air jet creates a different harmonic of the displacement wave (over blowing or lipping up) allowing higher octaves to be played with the same fingering.[11]

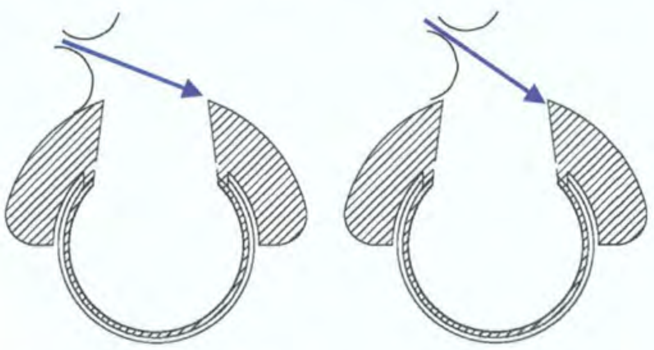

Figure 2-9 Lipping up and down.

Each note that is played is made up of many frequencies which are harmonics of the fundamental and occasionally some sub-harmonics (notes that are lower than the fundamental) The power of these harmonics alters with the volume of the note being played, this means that the one note played on the same instrument at different volumes has a different characteristics for each volume. This can be seen in Figure 2-10 and Figure 2-11, which shows the sound spectrum for C_4 played on a flute with a B foot at different volumes.

[11] Pages 117-118 in [BOE64]

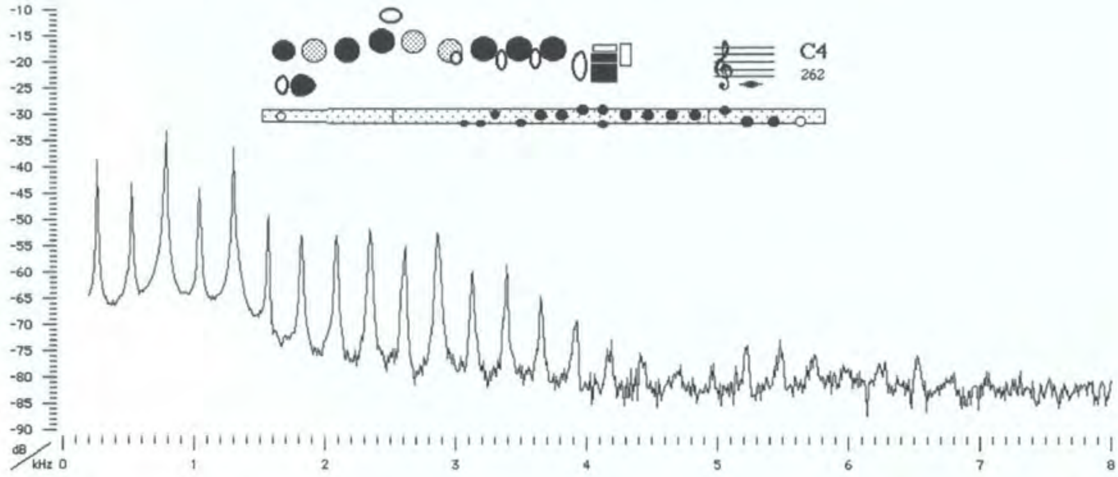

Figure 2-10 The Sound Spectrum for C_4 being played forte on a flute.[12]

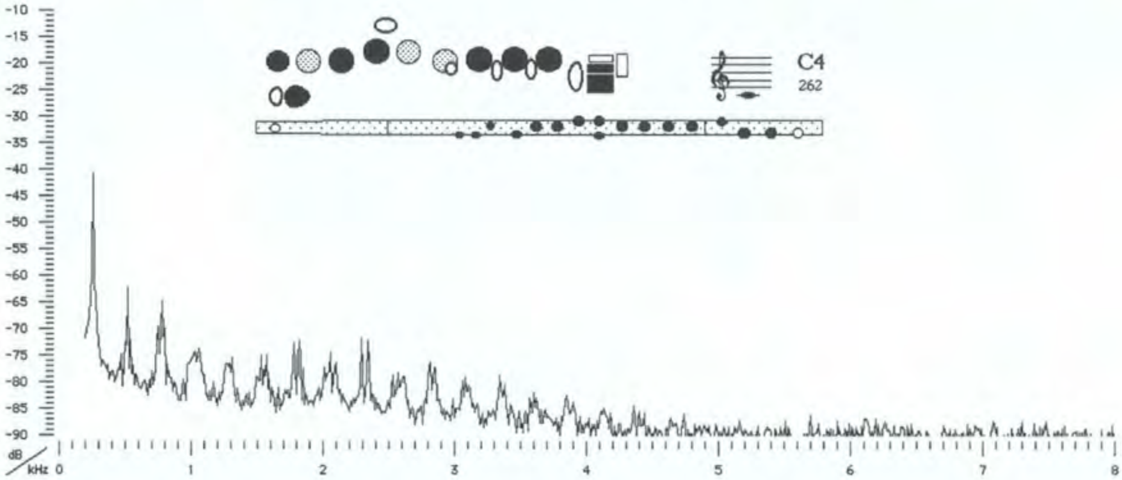

Figure 2-11 The Sound Spectrum for C_4 being played pianissimo on a flute.[13]

As Figure 2-10 and Figure 2-11 show, the power of the fundamental frequency is the same for all volumes, it is the power in the harmonics, which are increased when playing at a higher volume, and decreased at a lower volume. A quieter note therefore has less powerful harmonics and so the fundamental has a substantial strength compared to them, this means that the waveform for a quiet note is the nearest to sinusoidal it can be.

Occasionally notes contain sub-harmonics as well as harmonics, but when this occurs it is very difficult for the human ear to pick them out. For example sub-harmonics occur when playing E_6 (1320Hz) on the flute, however the sub-harmonics contain approximately 0.01% of the power of the fundamental frequency.[14] Another reason why they are difficult for the human ear to pick out is because E_6 occurs in the range that the human ear is most sensitive to (1 kHz- 3 kHz) and

[12] Flute C_4 from [UNSW05]

[13] Flute C_4 from [UNSW05]

[14] [DIMT05] and Flute E_6 from [UNSW05]

therefore that makes it difficult to pick out other frequencies within the spectrum as the frequency of E_6 would be very prominent.

2.2.3 Flute Construction

Flutes can be made from a whole array of materials from wood to metal. In the past they have even been made from glass, ivory and porcelain. In first part of the 19th century Claude Laurent was known to have made flutes out of crystal and glass.[15] Metal was not used until Boehm made his first hard silver alloy flute in 1847. Since then the material trend has changed from the traditional material being wood to the majority of flutes being made from an array of metals. It is common for flutes to be made from silver; this has to be a hard silver alloy because pure silver is too soft to use. Beginners' flutes are made from nickel silver, which is an alloy of copper, nickel and zinc. As the flautist improves they will move up to a silver plated flute, which is a nickel silver flute that has then been silver-plated. The next quality of flute is a solid silver flute, which is what the majority of professional flautists use. Some may have a gold plated flute or even a 14-carat solid gold head-joint. There are a few flutes that are platinum plated but, as Coltman found,[16] there is no detectable audible difference between the materials of the bore, so the use of the precious metals would appear to only be for decorative value.

The most important part of the flute's construction and structure is the head-joint as it is the part of the flute that greatly affects the tonal quality and the tuning of the instrument. There are two important factors, firstly the size and shape of the embouchure hole and secondly the position of the stopper and hence the size of the cavity between the embouchure hole and the stopper. With the embouchure hole there are a number of factors that can have a large difference to the tonal quality and response of the instrument. These include very slight variations to the embouchure plate's curvature, edge sharpness and the angle at which the embouchure is under cut. Figure 2-12 shows a cut-through section of a flute's head-joint. All these factors affect the flute's acoustic impedance, however, it still has to be remembered that the intonation of the flute also greatly depends on the performer, the air stream they produce and its strength and the embouchure they produce with their mouth.

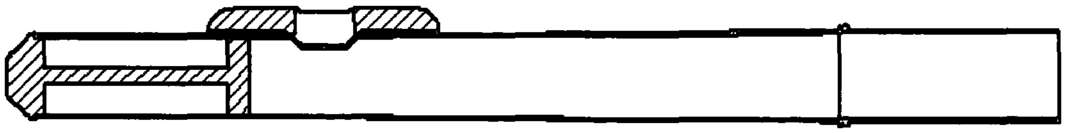

Figure 2-12 Section through a flute head joint

[15] Page 209-210 in [BAT79]

[16] [COL71] and [COL73]

2.3 The Clarinet

The clarinet is probably the most flexible woodwind instrument, with a range of nearly four octaves and a full dynamic range of *ppp* to *fff*. The clarinet's range of notes can be split in to three sections, the chalumeau register, the clarinet register and the altissimo register. Modern clarinets can play in all three registers with equal quality. The tonal quality also can vary greatly from a mellow soft sound to a harsh trumpet sound, allowing the instrument to blend in to the type of group that its playing in. Clarinets can be used to play classical music, in the traditional orchestra but are versatile enough to be involved in the jazz scene and can be played alongside trumpets and saxophones. The sound of the instrument can be changed by using different strength reeds, mouthpieces and ligatures. The versatility of the clarinet can be heard in the first few bars of George Gershwin's '*Rhapsody in Blue*' with the very famous glissando over nearly three octaves, to a piece such as the second movement of Weber's '*Grand Duo Concertant*' where the subtleties in tone can be easily heard in the first few bars from the tempo and phasing. These can be seen in Figure 2-13 figures and Figure 2-14 below.

Figure 2-13 Gershwin's '*Rhapsody in Blue*'

Figure 2-14 Weber's '*Grand Duo Concertant*'

Jazz clarinettists tend to use softer reeds and more relaxed ligatures. Their embouchure is also much more relaxed. These factors help the clarinettist to 'bend' the notes and for something like the glissando in '*Rhapsody in Blue*' where the embouchure is very important.[17]

2.3.1 Clarinet's History

The clarinet has developed in different countries is slightly different ways, unlike the flute which uses the same key-system throughout the majority of the world. The clarinet has developed into using three main key-systems throughout the world, of which the most predominately used in German countries is the Oehler system and the Albert system is used in the USA. The German system and French system are the two most popular systems. The German system tends only to be used in German speaking countries whereas the French system, which didn't come into existence until 1839, is the system that most people are familiar with. The French system tends to be called the Boehm system but it is only based on how Boehm came up with the key system

[17] From BBC Radio 4 Front row programme 10th Feb 2004

for the flute. In 1839 Hyacinthe E Klose put a proposal to Louis-August Buffet about using the idea of Boehm's method of ring-keys on the clarinet. Buffet built a prototype instrument and was awarded with a medal at the Paris Exhibition the same year. This prototype's key system has only changed slightly since 1839 and is commonly known as the Boehm system but this is a bit of a misnomer as the key structure was only based on one of Boehm's ideas.

2.3.1.1 The Chalumeau and early Clarinets.

Johann Christophe Denner (1655-1707) is attributed to the invention of the clarinet that has some similarities to the chalumeau, which was already around at the time. Denner's instrument had two keys, and when overblown it's harmonics could be played. It was this register that was the best. The chalumeau at this time also had two keys, but the position of the tone holes and the bore sizes were different between the two instruments. The chalumeau played well in the lower register (now known as the 'chalumeau register', below written A_4 which can be seen in Figure 2-15) and did not play above that whereas the clarinet that Denner introduced had a good overblown register (now known as the 'clarinet register', written B_4 to C_6 which can be seen in Figure 2-16) but the fundamentals were poor.

Figure 2-15 The Chalumeau Register

Figure 2-16 Clarinet Register

There are few examples of the chalumeau left and even those remaining are reconstructions and therefore the actual sound of the chalumeau is bit of a mystery. It is thought that the chalumeau was shorter than the clarinet of today and that the most keys it had was two keys above the other tone holes that were opposite each other meaning that it would not be able to be overblown to get the higher registers.[18]

The composers of the time often wrote music for both the chalumeau and the clarinet, which reiterates the fact that each one had different preferred ranges. Over time clarinettists found that they could play notes higher than the clarinet register (the 'altissimo register' above written C_6, which can be seen in Figure 2-17) if they experimented with different fingerings. Denner's family also constructed clarinets and chalumeaux. The chalumeau had a different tonal quality to the clarinet, which enabled it to survive for sometime with the clarinet before it became redundant. Over time the clarinet improved its sound in all three of its registers making the chalumeau more and more redundant.

[18] Pages 16-20 in [BRY76]

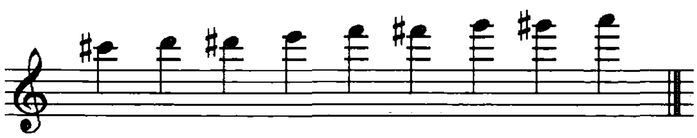

Figure 2-17 The Altissimo Register

Since the clarinet was invented it has developed from its original form to what we know today. The shapes of the clarinet and the internal bore have not changed but the key structure has.

The clarinet developed from having three keys in about 1760 to having five keys in about 1780, so by the time Mozart wrote his *Clarinet Concerto* in 1790 the clarinet had developed quite a way from Denner's clarinet. Also Mozart wrote the clarinet concerto for the basset clarinet, which has a larger range as it can play lower notes down to a low written C (C_3), as can be seen in Figure 2-18.

Figure 2-18 The Basset Clarinet's extra range

Before the introduction of many keys on the clarinet, it was only able to play single diatonic scales and so was unable to play pieces in any key. Clarinets were therefore made in many different sizes to allow different keys to be played. Today clarinets are still made in different sizes, however, the B-flat clarinet is most widely used with the A clarinet being used to make fingerings easier, and the other sizes used in special occasions. The E-flat clarinet is used in pieces that require a clarinet to play very high, above the range of a standard clarinet.

Ivan Muller (1786-1854) worked on the design of the clarinet and in 1812 took an instrument with thirteen keys to the Paris conservatoire. This instrument included the work Muller had done into the finer detail around the tone holes. Muller cut the tone holes so that they were slightly receded and also changed the material that the pads were made of. Originally they were made from felt but Muller changed them to be wool covered in gut or leather in a cup shaped key: this change reduced the amount of leakage from the tone holes and therefore increased the quality of the sound produced. Today the wool has been replaced by felt again but the leather has been kept to keep the seal in the higher quality instruments and for the others a type of paper is used.

2.3.1.2 Oehler and Albert Systems

Alongside the key system that Buffet introduced, known as the Klose or French system, there was the inventor of the saxophone, Adolphe Sax, who also worked with Eugene Albert, one of his pupils, in developing the Clarinet, who produced a key system that was based on Muller's work. The system introduced by Eugene Albert was developed further by by Oskar Oehler (1858-1936) into the German system (also known as the Oehler system) that is still used today.

The Oehler System is much more complicated than the Klose system but is still in widespread use especially around Germany. For instance, a clarinettist auditioning for one of the clarinet parts in a German orchestra would have to play a German clarinet: if they play a Boehm-system clarinet, they are not allowed into the orchestra, and it is not possible for a clarinettist to just swap to the other fingering system with out having previously learnt it.[19] The German clarinet has twelfth's that are more in-tune than the Boehm twelfth's, as Oehler's objective was to improve the tone quality and the pitch of the instrument rather than the ease of play. There are 22 keys and 5 ring keys and there are more cross fingerings than in the Boehm system. There is also more sliding from one key to another rather than using the other hand as in the case of the Boehm system clarinet. This is evident in looking at an image of an Oehler system clarinet where the key system for the lower joint can be seen, such as in Figure 2-19[20] and compared to the lower joint of the Boehm system clarinet in Figure 2-20.

Figure 2-19 Lower Joint of Oehler System Clarinet

Figure 2-20 Lower Joint of Boehm System Clarinet

The full Oehler system can be seen in Figure 2-21.[21] The Oehler system clarinets did not use the same clamping ligature as the Boehm system. They used a wrapped string ligature, but the ligature used in the Boehm system has now started being used in the Oehler system. The Oehler system clarinets are thought to be better for orchestral and ensemble work as they have a throaty sound which is more robust.[22]

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[19] [OSB03]

[20] [EBA05]

[21] [EBA05]

[22] [OSB03]

Figure 2-21 Oehler System Clarinet

There are still clarinets produced today that use the Albert system but the term "Albert system" really related to any simple system clarinet. The term came about after a Chicago firm started calling any simple system clarinet an Albert System Clarinet. There are many different key systems that are called Albert systems that have various numbers of keys. This key system is not widely used through out the world but does tend to be popular with jazz musicians especially in the USA. An Albert system clarinet can be seen in Figure 2-22[23] and when comparing it to Figure 2-21 it can be seen how the Oehler system clarinet developed from the earlier Albert system clarinet with the keys on the lower joint. With both the Oehler system clarinet and Albert system clarinet the lever keys on the lower joint do not have an alternative lever on the other side of the instrument.

Figure 2-22 Albert System Clarinet

2.3.1.3 Boehm System

The Boehm system reduced the number of forked fingerings that had been used in the past, making the instrument easier to play and improving the sound of the notes, the forked fingerings from before sounded poor. The work that Muller had done was also taken into account by Buffet and Klose. The appearance of the clarinet was also improved on the Buffet-Klose instrument; the raised bosses that in previous clarinets the keys had pivoted on were removed because the new key system did not require them. So there were many improvements to the clarinet by Buffet and Klose: these improvements were aesthetic, technical, musical and acoustical, so all the areas of the clarinet were improved with this instrument. The Buffet-Klose clarinet was patented in 1844. This instrument had the same number of keys, tone holes and ring keys as the modern clarinet of today as it hasn't changed much in the intervening time. The main change is that the modern French clarinet has eleven needle springs rather than the original four and it has smaller tone holes. A modern Boehm system clarinet can be seen in

[23] [EBA05a]

Figure 2-23. Various instrument makers have attempted to make improvements to the Boehm system but they have never really caught on. The original Boehm system clarinets designed by Buffet and Klose had intonation problems with playing twelfths in-tune, but this has been overcome with time and improved construction methods.

Figure 2-23 Boehm System Clarinet

2.3.2 Clarinet Acoustics

The clarinet is an instrument with a closed cylindrical bore: this is because the mouthpiece end of the clarinet is not open to the atmosphere when being played. The pressure at the bell of the clarinet is the same as atmospheric pressure due to it being open to the atmosphere, whereas the pressure at the mouthpiece is variable depending on the pressure of air supplied by the clarinettist and the air particles cannot move so a node is produced. The clarinettist can never supply air at atmospheric pressure unless they stopped blowing, in which case, the clarinet would stop producing any sound. Therefore, there must be a point of maximum pressure difference at the mouthpiece, and this can be seen in Figure 2-24. A typical value for the air pressure provided by the clarinettist at the mouthpiece is 3kPa.[24]

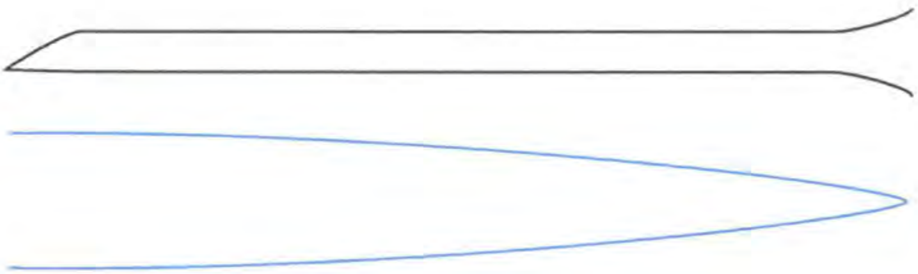

Figure 2-24 Fundamental wave in the clarinet

From knowing that there has to be a point of maximum pressure difference at the mouthpiece and a point of atmospheric pressure at the bell, the longest standing wave to be formed in the instrument can be found to be four times the length of the bore plus the end effects that will occur. This is the lowest fundamental frequency playable on the clarinet and as can be seen in Figure 2-25 and is an octave lower than the lowest note obtainable on an instrument with an

[24] Page Clarinet Acoustics on [UNSW05]

open cylindrical bore of the same length. In Figure 2-25 the clarinet has been simplified by removing the bell and the shape of the mouthpiece. Closed cylindrical bores are useful when you want much lower notes without the bore being too long, which would happen if you used an open cylindrical bore.

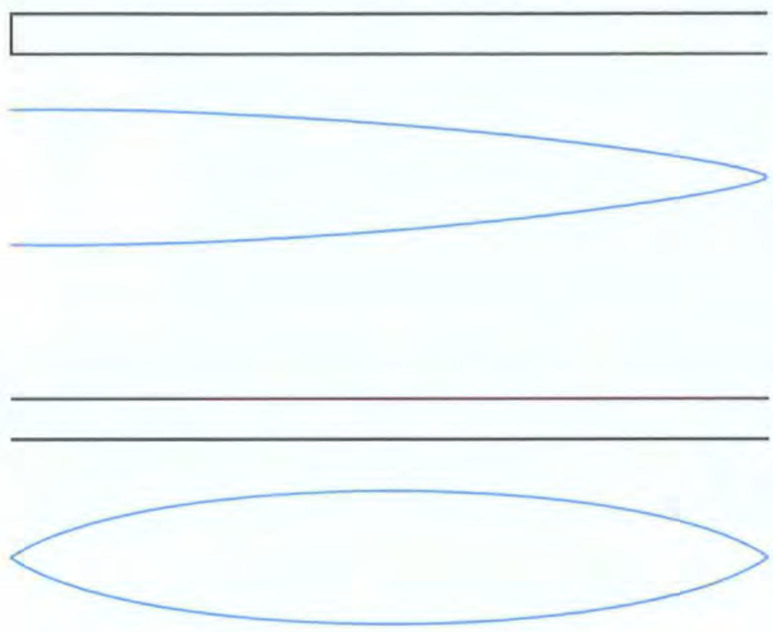

Figure 2-25 Fundamental Waves within the two types of bore

Tone holes are opened or closed to change the note played. These work the same as they do on the flute by shortening the fundamental standing wave so as to produce a higher frequency sound. The length of the new fundamental must take into account the end effects that occur at each tone-hole.

2.3.2.1 Overblowing

When a clarinet is overblown the note that occurs is a twelfth above the first note played. This happens because only the odd harmonics from the fundamental can occur, due to the closed cylindrical bore. This also means that the clarinet cannot use the same key system and fingering system that the flute uses, as the flute overblows at an octave. The clarinet therefore has to have enough keys and tone holes to be able to play the seven extra notes that are required, between the octave and the twelfth, to enable the full scale to be played.

The twelfth that is produced when the clarinet is overblown is not a perfect twelfth, as would be expected, but slightly flat. It is also the case that all the harmonics that can be produced by over blowing are slightly flat compared to the previous note that was played. In turn this means that the higher harmonics can be flat by a substantial amount compared to the fundamental. This flattening of the note occurs due to the reaction of the reed under the higher pressures required to over blow and the end effects that occur at the bell. At higher pressures the reed deforms differently from at lower pressures causing the notes to be flat.

As the harmonics are slightly flat from overblowing, this method cannot be the general method for changing from one register to another. Instead using register holes does this. These are holes high up on the instrument that do not alter what the fundamental frequency would be with out the register hole, but just disrupt the fundament frequency and so the next harmonic becomes the most prominent. There are two register holes that are used on the clarinet, the first is used for B_4 to C_6 and the second in conjunction with the first is used for $C\#_6$ and above.

The spectrum of the clarinet varies greatly with volume and pitch. The power in the harmonics change in different proportions as the instrument is played louder. Therefore it is not possible to make the instrument louder by increasing the power by a single factor without making the instrument sound strange. So by increasing the power when using electronics to change the volume, this would make the timbre be incorrect when compared to the natural sound of clarinet playing that note at that volume. Figure 2-26 and Figure 2-27 show the spectrums of E_3 being played at two volumes, *pp* and *f*, on the clarinet, these illustrate how the spectrums vary with volume. When the clarinet is playing E_3 *pp* the harmonics are very weak in comparison to the fundamental and so the waveform for that note is the nearest to sinusoidal that is possible.

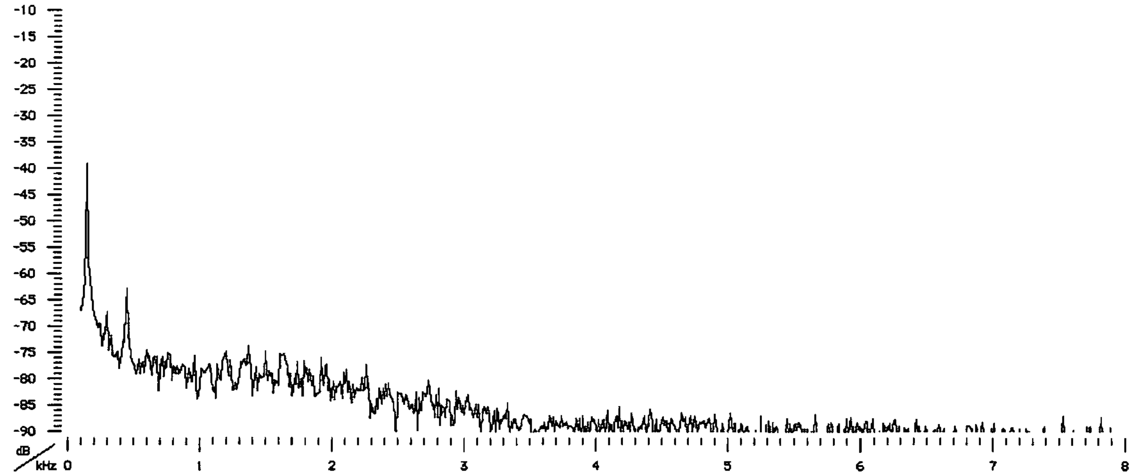

Figure 2-26 E_3 played piano[25]

[25] Clarinet E_3 of [UNSW05]

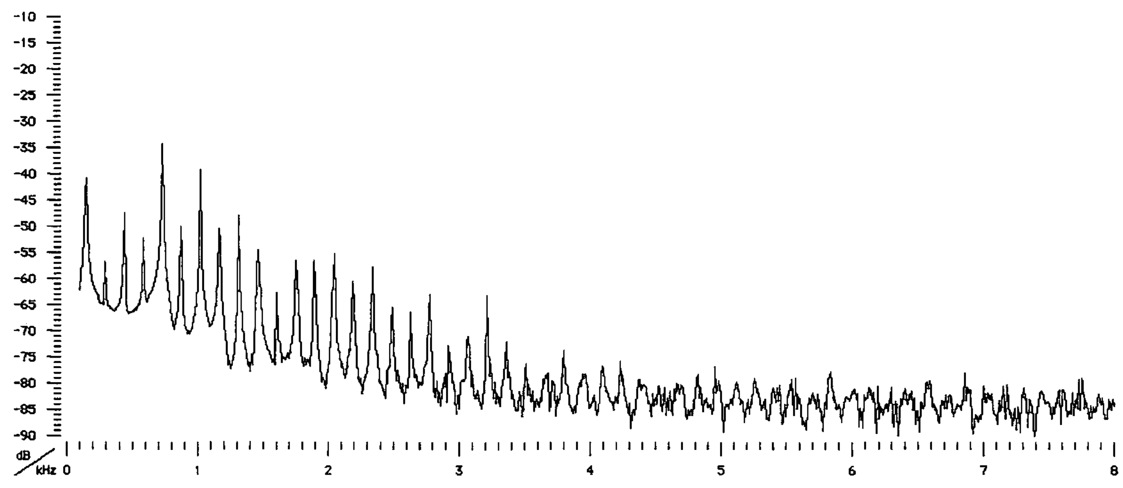

Figure 2-27 E_3 played forte

Figure 2-27, Figure 2-28, Figure 2-29, Figure 2-29 and Figure 2-30 show the spectrums for each instance a clarinet can play an E (E_3, E_4, E_5 & E_6) [26] (all at *f*). From these you can see that to change the pitch the respective powers of the harmonics change in their proportion compared to the fundamental. This is due to the difference in timbre that occurs in the different registers. E_3 and E_4 have many of the same features, such as the much weaker even harmonics; this is due to them both being in the chalumeau register. As the clarinet plays up through the higher registers the even harmonics are able to become more prominent, as can be seen with E_5 (in the clarinet register) and by the time E_6 (in the altissimo register) is reached the even harmonics have increased in power, so as the full harmonics series to appear in the spectrum for the note.

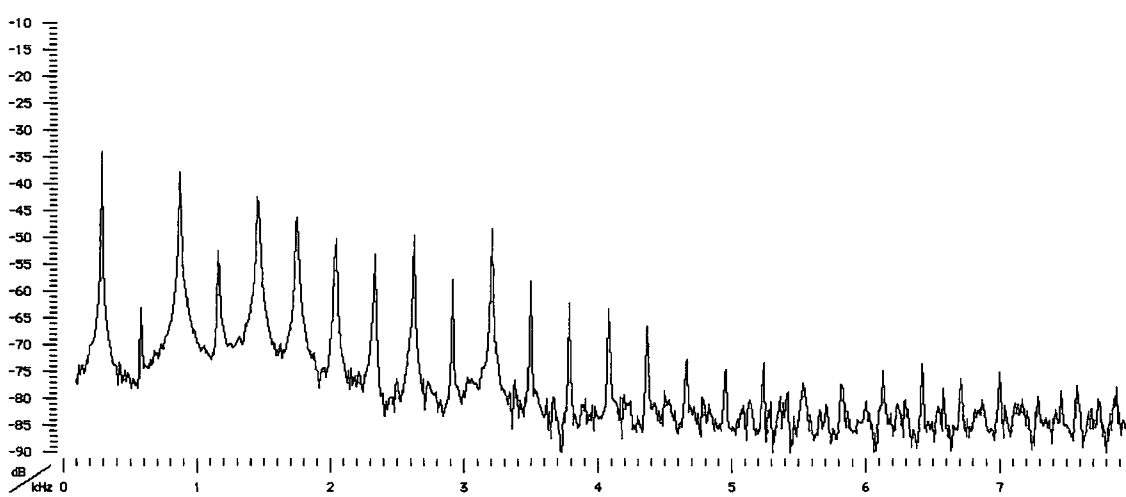

Figure 2-28 E_4 played forte

[26] Clarinet E_3, E_4, E_5, E_6 from [UNSW05]

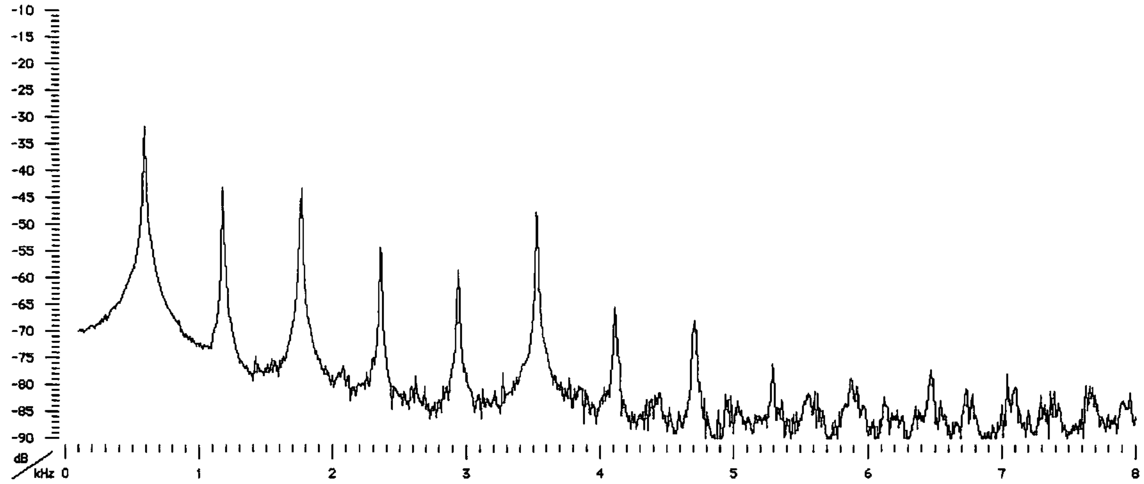

Figure 2-29 E_5 played forte

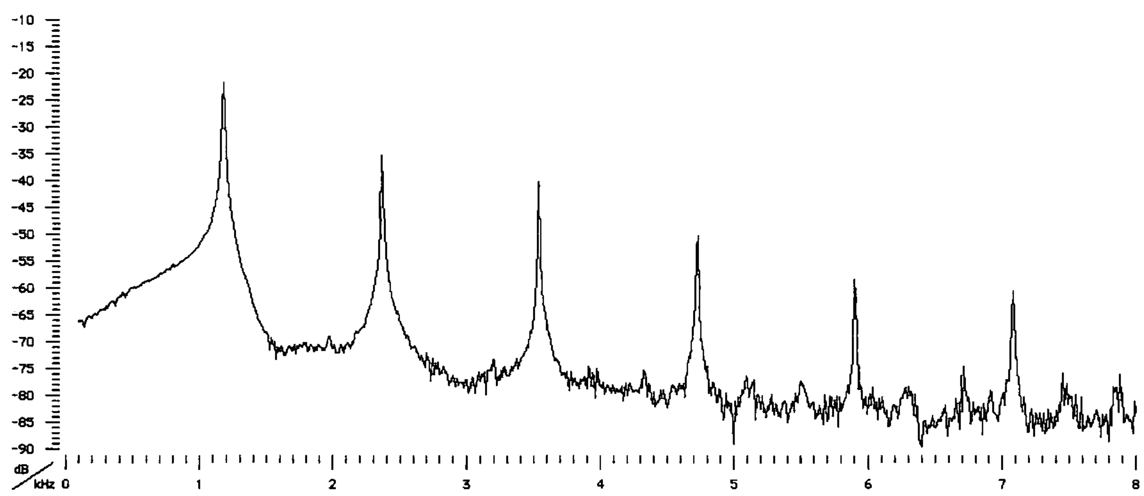

Figure 2-30 E_6 played forte

2.3.2.2 The Reed

The original vibrations within the clarinet are produced by the reed, which converts the steady airflow from the clarinettist into an oscillating displacement wave. This is done by the reed vibrating in the airflow so as to open and close the gap that the air can travel through into the instrument. The displacement wave would then produce the pressure wave for the sound.

The reed also controls the volume of the instrument by the pressure and the amount of airflow produced by the clarinettist. A higher pressure from the clarinettist makes the reed vibrate further, therefore producing a larger oscillation, which in turn makes the clarinet produce a louder sound. However, if the pressure is too high the reed will just close against the mouthpiece not letting any air through to the instrument and if the pressure is too low the reed will not vibrate due to there not being enough force to move the reed, and so no sound would be produced as the air going into the instrument would not be vibrating.

The reed has a natural frequency that it will resonate at; this frequency is much higher than the clarinet can play and when the reed oscillates at its natural frequency it produces a squeak. For the reed to be controlled to avoid producing a squeak, some damping has to be introduced which is effected by the lower lip of the clarinettist. The damping has to be controlled so that the oscillations of the reed correspond to the resonance of the clarinet bore for the note that is required and therefore the standing wave required producing the sound. The reed must resonate at the same frequency as the note requires otherwise no sound is produced.

2.3.3 Clarinet Construction

The factors that define a clarinet are the shape of its cylindrical bore and the relationship between the tone holes and the length of the instrument, the bore is the resonator, and the mouthpiece with the reed, which is the generator of the vibrations. These aspects combined make the instrument produce that typical clarinet sound and so make it what it is.

Clarinets can be made from a whole variety of materials from wood, plastic, ebonite and can even be made from glass or metal, but each material creates a different sound. Even though they are made from different materials and may actually look very different from each other they are still clarinets, they still have the vital factors that make them a clarinet. A metal clarinet is still a clarinet even though to the eye of someone who isn't that familiar with clarinets they may think that it is a saxophone, purely because it is metal, but it is the shape of the bore and the position on the key work determine that it is a clarinet. Clarinets have a cylindrical bore, which does not vary greatly in diameter from the mouthpiece to the start of the bell.

The clarinet is constructed by making the bore of the instrument out of either plastic or wood and then attaching the key work to it. The clarinet has a number of sections, normally five: mouthpiece, barrel, upper joint, lower joint, and bell, but it can come in four where the upper and lower joints are one piece. The wood that is used most often in the clarinets is Grenadilla wood from South America, which is then dyed black to disguise the subtle reddish tinge that is found in it. Subsequently Grenadilla wood is often mistaken for Ebony because of the use of dye.

When a clarinettist first takes up the instrument they are likely to start playing on a plastic or ebonite clarinet. Over time as they improve they are likely to move on to a wooden clarinet and then stay with wood for the rest of the time that they play the clarinet. Metal clarinets are only likely to be used for specific types of music, such as jazz, so therefore only specialist clarinettists would use them. One of the factors that make wooden clarinets more popular is that once the clarinettist has warmed the instrument up, the clarinet will stay at that temperature for far longer and will not overheat. The temperature of the clarinet effects it's tuning. In an orchestra it is found that at the start of a rehearsal there is not a great deal of point in tuning. Only after the instruments are warm is it time to tune. The musicians tune up when the instruments have reached their steady temperature, otherwise the musicians would have to tune up twice and as the first piece was being played would get more and more out of tune with the orchestra rather than hopefully getting more and more in tune with the rest of the orchestra.

2.3.3.1 The Mouthpiece

The mouthpiece of the clarinet has also changed over time, from when the clarinet was played with the reed on the upper side of the mouthpiece. The mouthpiece was made out of the same wood that the rest of the instrument was constructed from to the more resilient materials such as ebonite (a hard rubber type material) and throughout the 20^{th} century this was almost universal, now however plastics are also used. The contours of the top of the mouthpiece only started to appear in the 20^{th} century, before then it would just have been flat. For many years after the French changed to playing with the reed on the lower side of the mouthpiece the Germans still had the reed on the upper-side of the mouthpiece.

The slight changes in shape of the facing of the mouthpiece make some large differences to the sound of the instrument and what strength reeds work best with it. And so when buying a clarinet mouthpiece today there is a large range to choose from. Each one suits a different style of music or a different individual depending on their embouchure. The length and angle of the facing of the mouthpiece are the two principle factors and it is a case of balancing the one against the other to find the most suitable mouthpiece for the use required.

2.4 Conclusion

This chapter has shown how the flute and clarinet have developed over time, with the small changes Boehm made to the shape of the flute's head joint staying along with the other advancements that Boehm introduced. The method of sound production has been shown for the two instruments and the factors that affect the frequency detailed, therefore, allowing any microtonal designs to take them into account. The acoustics of the instruments have been shown with which harmonics are to be expected in the spectrum for the different registers of each instrument. The chapter has also discussed the general acoustics for the different instruments. Acoustic Impedance has been looked at showing how it has a use for testing the quality of an instrument without human inference.

3 Tuning Systems.

Having shown the capabilities of modern woodwind instruments, the reasons for requiring a microtonal instrument can be considered. This chapter studies the various types of tuning systems and how they differ from the standard 12-ET system that modern woodwind tuning is based on. The chapter investigates how to calculate the frequencies involved in each tuning system and also how they can be compared to the natural tuning system of Just Intonation.

3.1 Introduction to tuning systems.

There are various tuning systems that are used throughout the world, of which Equal Tempered Tuning and Just Intonation Tuning are the two most common types. Equal Tempered and Just Intonation repeat at the octave. Other examples that also repeat at the octave are Meantone, Well-Tempered and Chinese Pentatonic. Javanese Slendro repeats as well but the point at which is repeats is greater than the 1200 cents of an octave. Meantone tuning, Well-Tempered tuning and Equal Tempered tuning all developed from Pythagorean tuning. There are also tuning systems that do not repeat at the octave.

Although there are many similarities between 12-ET (12 division Equal Tempered tuning) and 12-JI (12 division Just Intonation tuning) the tuning system that the western world has become accustomed to is 12-ET. Since the early 1800s when Equal Tempered tuning was introduced composers have been basing their music in it. Consequentially becoming the most dominant tuning system in the Western World and so sub-sequentially as music has mainly been based on 12-ET so have the instruments that have be developed. Although as many instruments allow the musician to control the intonation of the instrument and so are not tuned to strict 12-ET. Japanese instruments designed to play in 12-ET are however strictly tuned in 12-ET.

As the instruments that have been developed have been based on 12-ET and also the music composed a vicious cycle of music and instruments has been produced and from this the western world has used other tuning systems less until recently when there has been an increase in interest of other tuning systems.

Other areas of the world do not have a dominant tuning system like 12-ET is in the western world and so use different tuning systems. These tuning systems give the music a distinctive sound, for example Chinese Pentatonic music.

3.2 *Just Intonation Tuning*

Just Intonation (JI) uses ratios to work out the intervals and the intervals that are produced are tuned so that they do not beat. This gives rise to the alternative names for Just Intonation, Pure Intonation, as the intervals are so pure and Natural Tuning. Having intervals based on ratios is fine for single intervals. However, when there is a series of intervals based on ratios, the first and final notes of the series may beat, as they are not tuned pure with each other. Two such instances of this are called commas, see section 3.5 Commas. The ratios can be found by looking at the intervals between the notes in the harmonic series. For example the difference between the first and second notes is an octave and the frequency of the 2nd note is twice that of the fundamental frequency, therefore the ratio for an octave is 2:1. If the harmonic series is studied to find an interval of a perfect fourth and the ratio worked out by comparing the two frequencies to the fundamental frequency, as can be seen between the 3rd and 4th is a fourth, therefore the two frequencies compared to the fundamental (f) are

$$f_{3rd} = 3f$$

$$f_{4th} = 4f$$

so the ratio for a fourth is

$$4f:3f \quad = \quad 4:3$$

All frequencies for Just Intonation can be found in the same way. Table 3-1 shows the frequencies and ratios for a Just Intonation scale with 12 notes in each octave (12-JI).

Note Name	Interval	Ratio	Frequency
A	Unison	1/1	220.00
A#	Minor 2nd	16/15	234.67
B	Major 2nd	9/8	247.50
C	Minor 3rd	6/5	264.00
C#	Major 3rd	5/4	275.00
D	Perfect 4th	4/3	293.33
D#	Augmented 4th/ Dimished 5th	45/32	309.38
E	Perfect 5th	3/2	330.00
F	Minor 6th	8/5	352.00
F#	Major 6th	5/3	366.67
G	Minor 7th	16/9	391.11
G#	Major 7th	15/8	412.50
A	Octave	2/1	440.00

Table 3-1 Frequencies and ratios of Just Intonation

The majority of the ratios required for the various intervals in 12-JI can be derived from relatively low down in the harmonic series with the exception of a dimished 5th which uses the 5th and 6th octaves. When looking at the ratios in other Just Intonation tuning systems the harmonics involved in these ratios can get very high such as 128:81 (Pythagorean Major 6th). The ratios can be put in to categories of 3-Limit, 5-Limit, 7-limit, 11-Limit and 13-Limit & above. Each category corresponds to the highest factor in the ratio, such as the ratio for a 5th , 3:2, comes in the 3-Limit category where as the ratios for a major 7th , 15:8, comes in the 5-Limit category because the highest factor in 15 is 5. The ratios that fall in the 11-limit and above categories can be termed extended Just Intonation.[27]

3.3 Equal Tempered Tuning

Equal Tempered Tuning systems use ratios to work out the frequency of the notes on a logarithmic scale. They repeat at the octave and have *n* number of steps between notes to get from one octave to the next. Western music conventionally used 12-ET (12 Equal Tempered) where there are twelve steps between the octaves. The frequency of the notes is worked out using ratios. So the ratio between one note and the next (a semitone apart) is

$$1:\sqrt[12]{2} \qquad \text{E 3-4}$$

The ratio between one octave and the next is

$$1:2$$

This enables the frequencies of notes using other Equal Tempered tuning systems to be calculated, using the same method. So if *n* is the number of divisions within one octave then

$$1:\sqrt[n]{2} \qquad \text{E 3-5}$$

is the ratio of the frequencies between two adjacent notes. This enables the general formula for working out the frequencies to be:

$$\sqrt[n]{2} \times f_m = f_{m+1} \qquad \text{E 3-6}$$

[27] [OZZ98] page 29 - 30

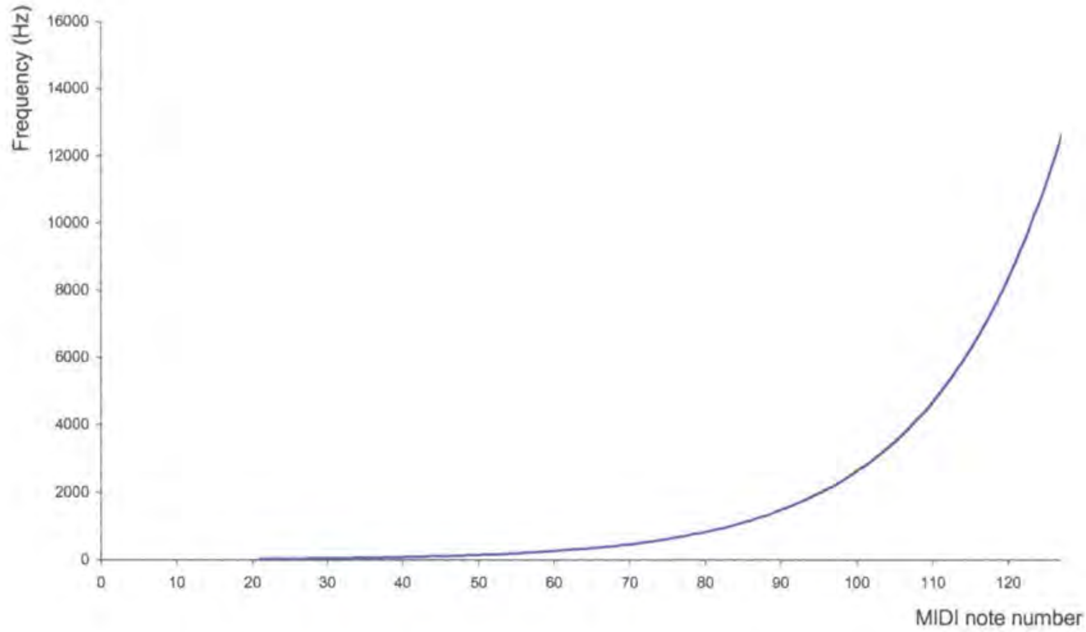

Figure 3-1 Frequencies of 12 Equal-Tempered Tuning

Figure 3-1 shows the how the frequency increases exponentially as the notes get higher, the graph is using 12-ET.

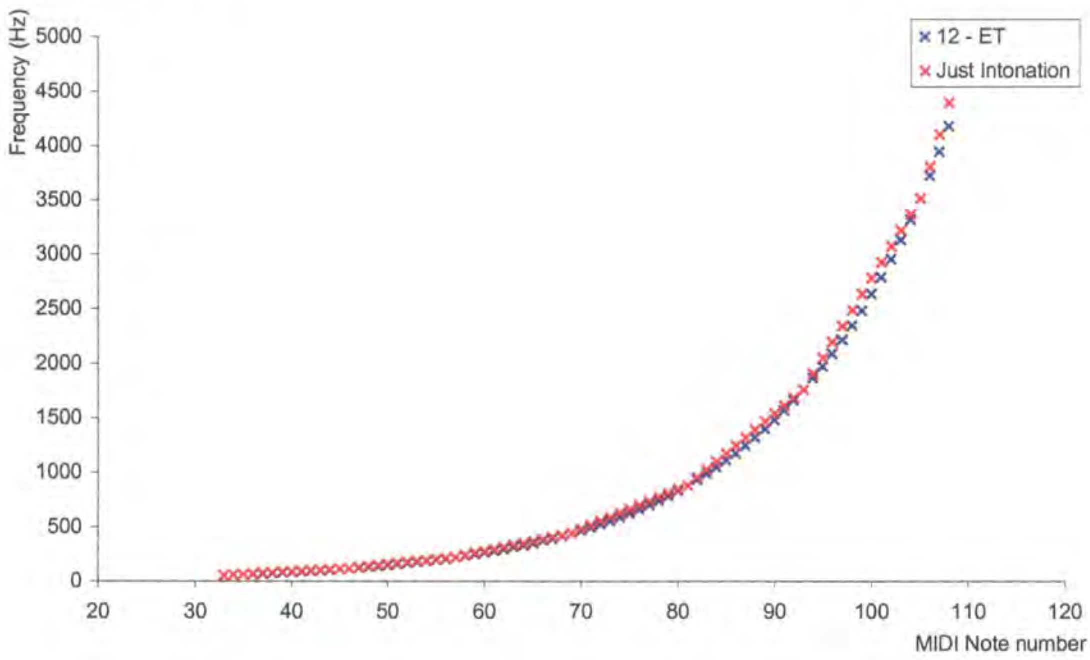

Figure 3-2 Comparison of the frequencies in 12-ET and 12JI

Figure 3-2 compared 12-ET to 12-JI, and shows how they are the same frequencies at the octaves but vary between them.

3.3.1 Scale Systems based on 12-ET

There are many scales that can be produced from the notes that are used in 12-ET tuning. The most common of these are the major and minor scales and their respective arpeggios.

3.3.1.1 Modes

The Major and Minor scales come from two of the seven modes that exist, each one is made up of a different pattern of tones and semitones. Table 3-2 shows the seven modes and what the semi-tone patterns are for each one.

Mode Name	Semi-tone Pattern	Mode Notation	Same As
Ionian	2212221	mC	Major Scale
Dorian	2122212	mD	
Phrygian	1222122	mE	
Lydian	2221221	mF	
Mixolydian	2212212	mG	
Aeolian	2122122	mA	Minor Scale
Lorian	1221222	mB	

Table 3-2 Mode Semitone Patterns

For all modes there is a specific notation that is followed as is seen above, m denotes the fact that it is a mode and the other letter denotes the note of the C Major scale it could start on. The notation of a mode in a different key, for example an Ionian mode starting on E, is notated as mC^+3, where the ^+3 denotes that there is a transposition of mC up 3 semitones, (+ is up and – is down).

3.3.1.2 Major and Minor Scales and Arpeggios

The Major scale is the Ionian mode and there are by transposition twelve different scales that can be formed using the same pattern of semi-tones and tones. Each Major scale also has its respective arpeggio, which consists of the first, third and fifth notes of the scale producing the semi-tone pattern of 435 plus two more major arpeggios starting on the four and fifth notes of the scale (the subdominant and dominant). These can be seen in Table 3-3 for C major.

C Major	C	D	E	F	G	A	B	C
C Major Arpeggio	C		E		G			C
Subdominant (F Major) Arpeggio	C			F		A		C
Dominant (G Major) Arpeggio		D			G		B	

Table 3-3 C Major Scale and Arpeggio Notes

Each Major scale has a relative natural Minor scale where both scales include the same notes. The note that the Minor scale starts on can be found as the third note of the Major scale, and the Major scale starts on the sixth note of the minor scale.

The natural Minor scale is the same as the Aeolian mode and once again there are twelve different scales and their respective arpeggios. The Minor scale has two different types; the harmonic minor and the melodic minor, both of which include accidentals. Table 3-4 shows how the different minor scales vary from each other using A minor (the relative minor of C major). The semi-tone pattern of the minor arpeggio is 345.

Natural A Minor (same as Melodic descending)	A	B	C	D	E	F	G	A
Harmonic A Minor	A	B	C	D	E	F	G#	A
Melodic A Minor (ascending)	A	B	C	D	E	F#	G#	A
A Minor Arpeggio	A		C		E			A

Table 3-4 A Minor Scales and Arpeggio Notes

3.4 Other Tuning Systems

3.4.1 Pentatonic

The most commonly used pentatonic scale can be formed by removing the fourth and seventh notes from the major scale from 12-ET, producing the semi-tone pattern of 22323 and also the Pentatonic Blues scale can be formed from 12-ET with a semi-tone pattern of 32223.

3.4.1.1 Chinese Pentatonic

The Chinese Pentatonic scale uses a series of perfect 5ths (using Just Intonation) to calculate the notes to be included in the scale. So the notes of the Chinese Pentatonic include the notes F C G D A, in Western Notation, when using F as the starting point, which when rearranged produce the scale F G A C D as can be seen in Figure 3-3.

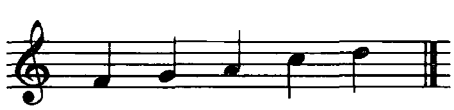

Figure 3-3 Chinese Pentatonic Scale

However, the Chinese do not use the same naming system that we have and the notes within the Chinese Pentatonic are Gong Zhi Shang Yu Jue which can be found using the following mathematics.[28]

They're found by adding a third of the wavelength to the first note to get the second and then removing a third of the new wavelength to get the third note, this process is then repeated until all the 5 wavelengths have been found.

[28] [NUS05]

$$Gong = \lambda$$

$$Zhi = \frac{4}{3}\lambda$$

$$Sang = \left(\frac{4}{3} \times \frac{2}{3}\right)\lambda$$

$$= \frac{8}{9}\lambda$$

$$Yu = \left(\frac{4}{3} \times \frac{2}{3} \times \frac{4}{3}\right)\lambda$$

$$= \frac{32}{27}\lambda$$

$$Jue = \left(\frac{4}{3} \times \frac{2}{3} \times \frac{4}{3} \times \frac{2}{3}\right)\lambda$$

$$= \frac{64}{81}\lambda$$

Which when rearranged into the lowest to highest comes out as zhi, yu, gong, shang, jue and the frequencies become:

$$f_{Gong} = \frac{c}{\lambda}$$

$$f_{Zhi} = \frac{3}{4} f_{Gong}$$

$$f_{Shangi} = \frac{9}{8} f_{Gong}$$

$$f_{Yu} = \frac{27}{32} f_{Gong}$$

$$f_{Jue} = \frac{81}{64} f_{Gong}$$

and when rearranged they can be found as:

$$f_{Zhi} = \frac{c}{\lambda_{Zhi}}$$

$$f_{Yu} = \frac{8}{9} f_{Zhi}$$

$$f_{Gong} = \frac{4}{3} f_{Zhi}$$

$$f_{Shang} = \frac{3}{2} f_{Zhi}$$

$$f_{Jue} = \frac{16}{27} f_{Zhi}$$

If using a basis of the frequency of Zhi to be 330Hz then the other notes will be as follows

Yu 371.25Hz

Gong 440Hz

Shang 495Hz

Jue 556.875Hz

These can then be looked at in terms of cents (in relation to Zhi), which enables the frequencies to be calculated no matter what the first frequency was. It also allows the scale to be compared to other tuning systems that may not use the same frequency as their basis for calculating the rest of the notes. These can be seen in Table 3-5.

Chinese Pentatonic			Just Intonation		
Scale Deg.	Cents	Interval	Closest Ratio	Cents	Interval
0	0	Zhi	1/1	0	Unison
1	203.91	Yu	9/8	203.91	Just 2nd
2	498.04	Gong	4/3	498.045	Just Perfect 4th
3	701.96	Shang	3/2	701.955	Just perfect 5th
4	905.87	Jue	27/16	905.87	Pythagorean Major 6th

Table 3-5 Comparison of Chinese pentatonic to Just Intonation[29]

Chinese Pentatonic music traditionally does not have any harmony. However, there are hybrids of Chinese and Western music, which do use harmony. The types of instruments used in Chinese pentatonic music are different to the western instruments due to the features of the tuning system. The voice plays a large part in their music and other instruments include various types of gongs and chimes, as well as having their own family of string instruments and wind instruments. The string instruments include the Zheng, which is a zither with thirteen to seventeen strings and some lute type instruments. Within the wind instruments, there is a mouth organ that is made from a number of bamboo pipes called a Sheng.[30]

3.4.1.2 Javanese Slendro

Javanese Slendro tuning systems have five notes within each octave, which are spaced approximately equally. One such scale is the Gamelan kodok ngorek where the starting frequency is 270Hz and therefore this has a ratio of 1/1 and the other five notes can be found from 227.965 cents, 449.275 cents, 697.675 cents, 952.259 cents and finally 1196.79 cents which make the octave flat by 3.21cents.[31] Although 3.21 cents may not seem much it means that as the pitch increases the frequency gap between the Slendro octave and an octave of 1200 cents. Table 3-6 shows the comparisonof the Javanese Slendro tuning system to Just Intonation.

[29] Modified from [OZZ98]

[30] [UWM05]

[31] [*01]

Javanese Slendro		Just Intonation			Comparison
Scale Deg.	Cents	Interval	Closest Ratio	Cents	Difference in cents
0	0	Unison	1/1	0	0
1	227.965	Septimal 2nd	8/7	231.17	-3.205
2	449.275	"Supermajor" 3rd	9/7	435.08	+14.195
3	697.675	Just Perfect 5th	3/2	701.955	-4.27
4	952.259	Harmonic minor 7th	7/4	968.83	-16.571
5	1196.79	Unison (Octave)	2/1	1200	-3.21

Table 3-6 Comparison of Javanese Slendro to Just Intonation[32]

There are a large number of different tuning systems from around Java and Bali that each have their own individual sound.

3.4.2 Pythagorean

Pythagorean tuning creates mainly pure fifths and pure octaves with one 'wolf fifth' for every eleven pure fifths. Pythagorean tuning is calculated using pure fifths starting on C and so the following notes are calculated

C G D A E B F# C# G# D# A# F C

The final C is not a pure fifth above F and so this is the 'wolf fifth'. Also if the method was repeated going down the notes, the frequencies for C# and D♭ would not be the same, which would not be what was expected. Different keys sound different and when started on an F these cause a problem, as this is the 'wolf fifth' and also closely related to the key of C. Pythagorean tuning developed into other tuning systems which are more widely used today.

3.4.3 Meantone

Meantone tempering developed from Pythagorean tuning. Meantone tempering creates as many pure octaves and pure major triads as is possible. This therefore creates several wolf tones and also many keys are unplayable in meantone tuning due to the fact that many major thirds and fifths are slightly changed (tempered) to produce a near as possible pure major triads.

Equal Tempered tuning was derived from Meantone Tempering and the 12-ET system can be said to be a specific kind of Meantone Tempering, as it follows the same principles with trying to contain as many pure octave and pure major triads as possible.

[32] Modified from [OZZ98]

3.4.4 Well Tempered

Well-tempered tuning systems do not have any wolf tones and consequently any key can be played. Due to the fact that each key whether major or minor sounds unique. The key of C contains pure triad; whereas the keys that are unrelated to C have more and more impure triads. This means that as each key was unique music would be written for a specific key for the sound of that key. Whereas with equal tempering, the mood of the piece is dictated more by whether its major or minor key, rather than the starting note of the key.

Well-tempered tuning was popular in the eighteenth century and composers such as Bach composed music for instruments such as the Well-Tempered Klavier.[33] Meantone tuning and Well-Tempered tuning can also have variation in the number of divisions in each octave as Just Intonation and Equal Tempered tuning have. Well-tempered tuning is more complicated than Meantone tuning or Pythagorean tuning.

3.5 Commas

These are the same differences in pitch, which occur when examining the difference between Just Intonation (Pure Tuning) and Equal Tempered tuning. When commas occur it is detrimental to the music and so it is fundamentally important that they are avoided. There are two commas that can occur, the first is the Syntonic comma and the second is the Pythagorean comma.[34] Commas are calculated in cents, which enables them to be translated easily to start at any pitch.

3.5.1 Syntonic Comma

This comes about when looking at the difference that occurs with four perfect fifths minus a just major third and 2 octaves. When using Just Intonation the (just) perfect fifth is 701.96 cents, the (just) major third is 386.31 cents and 1 octave is 1200 cents. The value of the comma is found by

$$\begin{aligned} 4 \times justperfectfifths - justmajorthird &= 4 \times 701.96 - 386.31 \\ &= 2421.53 \end{aligned}$$

$$\begin{aligned} 2 \times octaves &= 2 \times 1200 \\ &= 2400 \end{aligned}$$

The Syntonic comma is the difference between them

$$2421.53 - 2400 = 21.53$$

[33] [LOY99]

[34] Page 172 in [CAM97]

so therefore the Syntonic comma is 21.53 cents.

When using Equal Tempered a perfect fifth in ET is 700 cents, a major third is 400 cents and an octave is 1200 cents, so the same method reveals that the comma 'vanishes' with Equal Tempered tuning.

$$\begin{aligned} 4\times perfectfifths - majorthird &= 4\times 700 - 400 \\ &= 2400 \end{aligned}$$ E 3-12

which is the same as the number of cents for two octaves.

3.5.2 Pythagorean Comma

This occurs with the difference between a circle of perfect fifths (twelve perfect fifths) and seven octaves. The circle of perfect fifths using Just Intonation does not close as shown below in Figure 3-4, which also compares the circle of perfect fifths in Just Intonation with the same in Equal Tempered tuning.

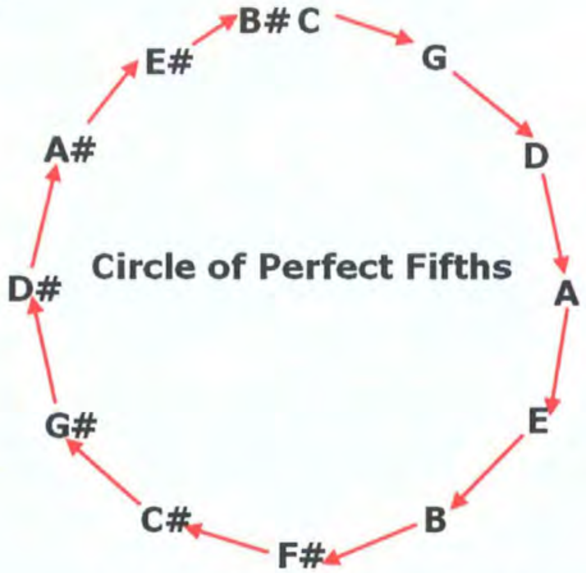

Figure 3-4 Circle of Perfect fifths

The Pythagorean comma can be found using a similar method as was used to fid the Syntonic comma.

$$\begin{aligned} 12\times Justperfectfifth &= 12\times 701.96 \\ &= 8423.51 \end{aligned}$$ E 3-13

$$\begin{aligned} 7\times Octave &= 7\times 1200 \\ &= 8400 \end{aligned}$$ E 3-14

The difference between the two values is the Pythagorean comma

$$8423.51 - 8400 = 23.51$$

therefore showing that the Pythagorean comma is 23.51cents.

3.6 Inherent Problems with current instruments

Many instruments have slight peculiarities in their tuning, the clarinet has a tendency to be flat in the lowest region of its range (below C_4) and sharp in the higher regions (above C_6), this can avoided by the clarinettist when adjusting their embouchure to counteract the effect and therefore producing an in tune note. With the flute the fine-tuning is controlled by the embouchure of the flautist and so the flautist has to listen very carefully to get the instrument in tune and the end-stop in the flute must be in exactly the correct position for the overblown note to be in tune with the fundamental.

When a piano is tuned the tuner will deliberately tune the higher notes slightly sharp and the lowest notes slightly flat.[35] The piano tuner will tune the middle section of the instruments range to be tuned for equal tempered tuning and then the extremities are tuned using octaves from the previously tuned section. When tuning the octaves the piano tuner is listening out for any beating and then tuning the instrument so that the correct amount of beating occurs for each note. Once the instrument has been fully tuned middle C (C_4) will be in tune whereas the highest C (C_8) could be as much as 30 cents sharper than what would be expected.

3.7 Conclusion

As has been seen in this chapter there are numerous tuning systems. Each tuning system will produce its own distinctive sound. The methods used to calculate the frequencies have been shown and compared to Just Intonation. A few of the systems when compared to Just Intonation have notes that correspond exactly, whereas others have only the starting note corresponding.

[35] Pages 322-323 in [BEN90]

4 Previous Research.

Having discussed the various tuning systems that exist, it follows that previous attempts at western microtonal instruments should be investigated. In this chapter these attempts are examined. As well as the direct microtonal research there have been investigations into the closure of the tone holes by alternative methods and using software to control the closures. These are also discussed within this chapter.

There have been many attempts at constructing microtonal instruments and investigating microtonality and how musicians could use it more. Although there has been more interest into microtonality in recent years, there were also attempts at the turn of the twentieth century. Only some of the many attempts to produce a microtonal instrument have been successful. These attempts have varied from complete reworking of the holes and key-systems to just adding to the already proven Boehm flute.

Most investigations previously undertaken into microtonal instruments have concentrated on the design of an instrument for a specific tuning system. The majority of the time this has been for quartertone music, 24-ET or 24-JI.

4.1 Quartertone Instruments

4.1.1 Flutes

4.1.1.1 Redesigned flutes

The most successful quartertone flute is the Osten-Brannen Kingma flute; this is the only commercially available quartertone flute.[36] The key system is an extension of the Boehm system with extra tone holes to increase the number of notes played and also with half keys. A half key is where there are two keys on top of each other and the lower part is able to be closed, leaving the outer one open to produce a tone hole that is smaller than the fully open one. This can be seen in Figure 4-1. The recorder uses a similar method for $C\#_4$ and $D\#_4$ with one of the two small holes closed, see Figure 4-2.

[36] Page 69 in [OZZ98]

Figure 4-1 Closing half a tone hole

Figure 4-2 Half tone holes on the recorder

Although there has only been one commercially successful quartertone flute there have been a number of investigations into the quartertone flute.

4.1.1.2 Additions to the flute

IRCAM[37] has researched designs for microtonal instruments for many years. One possible method for the flute that was designed used 'branched tubes'.[38] These were tubes that were attached to the head joint of a flute. When playing any of the notes in 12-ET the tubes would remain closed. However, when trying to play quartertones the branched tubes would be opened, via a key operated by the spare thumb. Opening the branched tubes would allow the air to pass down them, therefore lengthening the bore. Consequently due to the lengthening of the bore the pitch of the note is flattened. As different notes require different lengths to be added to them to

[37] Institut de Recherche et Coordination Acoustique/Musique

[38] [CAU03] and page 71 in [OZZ98]

flatten them by a quartertone, the branched tubes would have to have allowed for this. They attached it to the head joint, which could be removed and replaced with a conventional head joint when required.

Robert Dick has designed a "Glissando head joint" where the lip plate and embouchure hole slides up and down the head joint therefore changing the frequency that the instrument produces. When the embouchure hole is positioned nearest the keys the instrument will behave like a traditional Boehm flute. The slider mechanism on the head joint will flatten the note being played as the embouchure hole moves towards the other end of the head joint. The maximum amount that the notes can be flattened by varies from note to note, due to the percentage change in the bore length varying. The smallest amount a note can be flattened by is whilst playing B_3 (this requires a flute with a B foot), which can be flattened by a major second. The largest amount a note can be flattened by is a major third and this happens when playing C_5.[39]

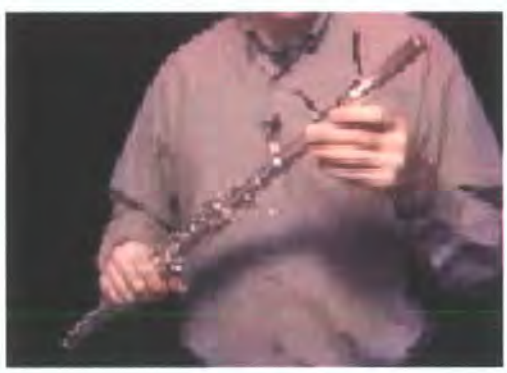

Figure 4-3 The Glissando Headjoint[40]

As can be seen in Figure 4-3 the head joint has two "wings", one on either side of the lip plate. These are there for the flautist's cheeks to sit in so that the slider action of the glissando head joint can take place, by the wings holding the lip plate in the correct position to play and the flautists hands moving the main bore of the instrument up and down.

The "Glissando head joint" fits on to a standard Boehm flute and so is interchangeable with a standard head joint should the flautist require.

4.1.2 Clarinets

4.1.2.1 Redesigned Clarinets

In the first half of the twentieth century there were a number of quartertone clarinets made. One company 'Kohlert' made three; the first was designed by Dr. Richard H. Stein in circa. 1906 to 1912, then two were commissioned by Alois Hába in 1924 and 1931.[41] There is very little

[39] [BRA05] and [DIC05]

[40] [DIC05]

[41] Page 69 in [OZZ98]

information about these quartertone instruments. What is known is that the first instrument made by Kohlert had extra keys for the quartertones when compared with the standard Bb clarinet.

In 1933 Fritz Schüller patented a double-bored quartertone clarinet.[42] The one bore was tuned to standard Bb and the other bore was tuned a quartertone flatter. This meant that the second bore had to be longer. The clarinet had a switch valve, which enabled the chosen bore to have the air stream. The two bores merged into one bell, having split from one barrel near the mouthpiece. The keys on the instrument worked both bores simultaneously and it can only be presumed that as it was developed in Germany, that the key system that worked both bores at the same time was the Oehler system. The image of the instrument in Figure 4-4 looks similar to the Oehler system in the system; see Figure 4-5, with the style of the lever keys. As can be seen from Figure 4-4 this instrument would be very cumbersome to play.

Figure 4-4 Double-bored Quartertone Clarinet[43]

Figure 4-5 Oehler System Clarinet[44]

4.1.2.2 Additions

IRCAM in Paris have done research into producing a device that can be attached to a clarinet that will allow it to then play quartertones.[45] The one design involved adding a piston onto the mouthpiece of the instrument which was then activated mechanically by a brake cable attached to a foot pedal and the piston. The idea for this device was that when the foot pedal was in its normal position the piston plate would be flat against the side of the mouthpiece. This would

[42] Page 70 in [OZZ98]

[43] [*02]

[44] [EBA05]

[45] [IRC03]

make the clarinet mouthpiece seem like a normal mouthpiece and therefore the clarinet would sound normal for the fingering being played.

Yet without altering the fingering or the clarinettist's embouchure the pitch of the note can then be changed. This is done by pressing on the foot pedal, through which the brake cable retracts the piston producing a space inside the piston which fills with air. This space is then part of the volume of air that flows through the clarinet and because of the where the extra volume is it lowers the frequency of the note being played. This is because the volume in the piston acts like extending the main body of the instrument. The pitch of the note being played is flattened by a quartertone.

There are some problems associated with this design.

- When the piston is retracted to produce the chamber of air in the piston the timbre of the instrument would be altered. The chamber of air makes the sound produced a more breathy sound that isn't as clear. This would mean that half the notes would have one timbre and the other half would have a different timbre. Having alternating timbres is not desirable. An instrument may have different timbres for different registers and for the way the instrument is being played e.g. a clarinet playing some jazz requires a different sound to a clarinet playing some Mozart. Throughout each register the timbre would be expected to be the same.

- The time it takes for the foot pedal to be fully pressed and the piston to move may create problems if it wasn't quick enough. Also when the foot pedal is released the piston has to respond. Would this create a noticeable glissando between the two notes?

- The piston appears to only have two different positions within the actuation method, closed and open. This would be if the foot pedal were very difficult to control, for example if the pedal was like a pedal on a piano. As each note requires a different amount of extra length to flatten its pitch by a quartertone, then a set volume of air in the piston would flatten some notes by less than a quartertone, and some by more than a quartertone.

4.2 Logical Woodwind

There have been three investigations into logical woodwind by Professor Gils Brindley, Edwin Norbeck and Howard McGill. Each of them investigated a different instrument: Brindley a Bassoon, Norbeck a flute and McGill a clarinet.

4.2.1 Bassoon

Professor Brindley designed a logical bassoon in 1967, which enabled the same fingering to be used for each octave with one key designated to selecting which octave.[46] The instrument was designed to simplify the Bassoon's complicated key structure to make it easier to play without changing the instrument's timbre. An electric circuit replaced the complicated key work, which was in between the keys and the holes. As the musician pressed a key down the logic circuit would work out which keys were being pressed and then convert the combination in to the correct holes being closed. The holes were closed by solenoids.

Although the logical bassoon was successful, as it simplified the fingering, but still sounded like a standard bassoon, it has never been adopted by anyone other than Professor Brindley himself. The reason for this, is connected with the difficulties that manifest when playing the standard bassoon, which Professor Brindley was trying to eliminate. These difficulties can be over come in time with practise on the bassoon.

4.2.2 Flute

In 1973 Edwin Norbeck conducted investigations into a 'computer assisted flute' and produced an instrument that had a logical fingering.[47] A combination of three fingers selected which note was to be played, and then the other fingers selected the octave, and whether the note was sharp or flat. The computer was used to programme which holes closed with each finger combination. Norbeck's instrument had the holes being closed by solenoids connected to a computer.

4.2.3 Clarinet

In 1992 Howard McGill investigated logical woodwind and constructed a logical key system for the clarinet, where the hole closures were solenoids and these were linked to a computer.[48] The computer could then be programmed for the logic required. The logical clarinet worked in a similar way to the logical bassoon in that the holes closed depended on the computer working out the logic from the combination of keys that were pressed. Having the clarinet linked to a computer rather than having fixed logic enables the logic to be reprogrammed differently if required.

To simplify the logic for the investigation some of the tone holes on the instrument were blocked up. This produced a diatonic instrument that in the chalumeau register would play in the key of Bb major and when overblown would play in the key of F major.

46 Page 65 in [OZZ98]

47 Page 66 in [OZZ98]

48 Page 66 in [OZZ98]

4.2.4 Conclusions

Norbeck and McGill both used computers to control which holes were being closed by the solenoids for that particular finger combination, which enabled the hole combination to be changed by reprogramming the computer to a different logic. Brindley had used a logic circuit which was fixed in one logic pattern, making the instrument fixed into which holes closed when the pads were pressed.

Logical instruments, if developed further, may help combat the challenges faced when providing hole combinations for microtonal instruments and may also improve the speed at which the instruments can be played. There are two ways that the speed of the instruments can be affected.

- The first is that the key system is simpler and therefore the fingering is as well, making it easier to change from one combination to another. There are no levers that have to be swapped between; each finger only has one key that it presses, stopping the need for any extra movement.

- The closure of the holes will happen as fast as the computer and solenoids will allow. This would tend to be faster than the musician playing the notes, as the musician with the logical key system would only have to touch a sensor pad to close the corresponding holes. This contrasts with any current woodwind instrument where there maybe any one of three ways closing the tone holes. There could also be a direct closure of the tone hole by the musician's finger, a finger pressing on a key pad which covers the hole or there could be a lever system attached to the key pad which is too far away for the musician to reach. All of these three ways take different amounts of time to close the holes and introducing the computer would even the time out.

Having a key system in which the hole closures are controlled by a computer allows all logical woodwind instruments to have the sensor pad system and fingering pattern independent of whether the instrument was an open cylindrical bored instrument, a closed cylindrical bored instrument or a conical bored instrument. This would allow the clarinet, a closed cylindrical bore, to have a fingering pattern that repeats at the octave rather than the twelfth.

This would enable easier movement from one instrument to another, allowing the musician to concentrate on the main difference between the instruments, mainly how the air is made to resonate, whether it be a single reed as with the clarinet and saxophone, a double reed as with the oboe and bassoon or by the angle at which the air jet hits a knife-edge to set up the oscillations.

Also the logical woodwind instruments would allow for a clarinet (a B♭ instrument) to play the correctly sounding notes for a piece of music written for the flute (a C instrument) without having to transpose. The transposition could be just done by changing the programme controlling the hole closures on the clarinet.

4.3 Alternative Hole Closure Methods

With the logical woodwind instruments, solenoids were used to close the holes. These do their job, however, they are cumbersome and so other hole closure methods have been studied as possibilities. In *21st Century Orchestral Instruments* Patrick Ozzard-Low discusses three mechanisms to close the tone holes.[49] As a tone hole decreases in size the pitch produced by the instrument decreases: an example of this is the recorder. To play D_4 the right hand little finger is not covering any hole. However when $C\#_4$ is played one of the two smaller holes that the little finger can cover is covered, creating the effect of the tone hole being smaller. The three methods discussed were

- 'Concentric pad' where a tone hole would have two pads covering it, the first having a hole of the centre that the second pad would cover. This method would allow part of the hole to be covered leaving the centre still open. This can be seen in Figure 4-6.

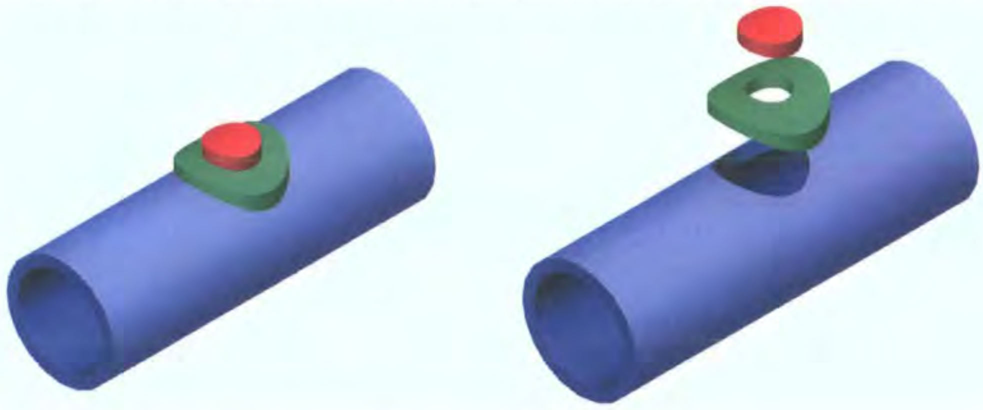

Figure 4-6 Concentric hole closure

- 'Crescent shaped sliding covers' where the hole would be closed from one side. To produce the extra pitch the sliding cover would only cover part of the tone hole. This can be seen in Figure 4-7.

[49] Pages 71-72 in [OZZ98]

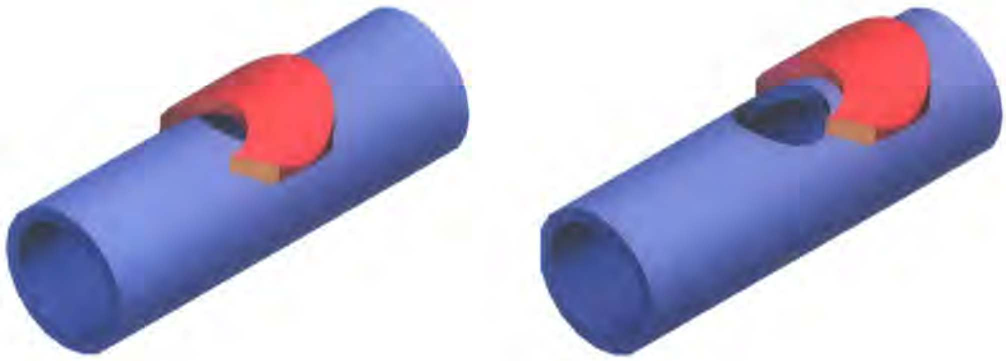

Figure 4-7 Crescent shaped hole closure

- 'Iris diaphragms' would work in a similar way to the crescent shaped sliding cover except that the smaller hole could be in the centre of the fully open tone hole, where as for the sliding cover the smaller hole would be off to one side of the larger hole.

4.4 Telescopic instruments

In the 1960s a flute was designed which involved a telescopic action. The 'Vermeulen flute' had two cylindrical tubes one inside the other which altered the pitch of the instrument by varying the length of the bore.[50]

Bart Hopkin designed a mechanism for changing the instrument's bore length without many moving parts.[51] The bore that he designed had a split all the way up the one side, which could be closed by a flexible strip. In an untouched position the strip would leave the slit open, reducing the length of the bore. To close the slit which would lengthen the bore the flexible strip just had to be pressed against the bore at the desired position. When the strip was pressed down the entire strip above that point also closed against the bore. This enables glissandos as the strip is smoothed along the instrument. In addition sudden changes in length could be made by pressing down at another point on the strip and lifting up from the first position. The flexible strip was made of a magnetic material so that there were no leaks up from the end point of the bore where the strip was being pressed down.

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[50] Page 72 in [OZZ98]

[51] Page 73 in [OZZ98]

4.5 Conclusion

As can be seen in this chapter there have been a number of attempts at microtonal woodwind instruments however only one has become commercial, the Osten-Brannen flute. It has been shown how the other ideas had a good grounding in theory but in practice did not achieve the desired effect. Control systems for tone hole closures were briefly discussed where the keys pressed and the pads over the tone holes are not connected by a mechanism, but, were controlled by some logic functions.

5 Preliminary Investigations

The previous chapters have discussed the theory and previous attempts to create microtonal instruments. From this point forwards in the thesis the emphasis will be on the practical and experimental side of creating such an instrument.

However, before any construction can take place the other variables that may alter the pitch of the instrument need to be taken into consideration. These will be discussed in this chapter together with the investigation of a possible solution. In addition the chapter compares some software available on the Internet for analysing the data collected. From this the most suitable application is discussed.

5.1 Computer Software for Analysis of Data

With all the data that would be produced through the various experiments a suitable method of analysing the data needed to be found. All the data produced by recording the sounds produced would be in a wave format and from this, without any changes, only the time taken to play the sound and the volume at which it sounded can be seen. This does not give the relevant information needed. The information that is required for the comparisons would be seen in the frequency spectrum and therefore a suitable program to calculate the Fast Fourier Transform (FFT) is needed. Three different pieces of software were compared to find the most suitable for the task required. Of these three applications there were two that were freeware, Audacity and Spectrogram and then there was one shareware application, Goldwave.

There were a number of aspects that were compared to gauge which application was the most suitable. These were

- Ease of recording
- Overall presentation
- General ease of use, including navigation to find the function required
- Ability to analyse new data and previous saved wave files
- Ability to save wave files for later analysis
- Ability to produce clear analysis of data via a spectrum
- Ability to produce suitable graphs for inclusion in this thesis
- Problems with the software

- Extra advantages

5.1.1 Spectrogram

This application was very quick to run, as it does not need installation on the computer. This is explained when actually using the software, as it is very simple compared to others in that it only produces the FFT once the wave file has been imported.

Recording the sound directly into the software can be done. However the software will record for a pre-instructed time unless stopped. This means that if the recording should take longer than was originally estimated then the program would have stopped recording before it was required. Having to set the time to record for is suitable if it is known how long that particular experiment is going to take. If the recording takes less time that the pre-instructed time then this does not pose a problem as the recording can just be stopped.

To import a previously recorded wave file there are two methods that can be used, one method is by analysing the file as its being played which happens in real time (scan file), or the other method which is faster just analyses the file without playing it (analyse file).

Once the wave has either been recorded or imported the spectrum of the wave can be investigated. Figure 5-1 show as screen shot of Spectrogram at this point.

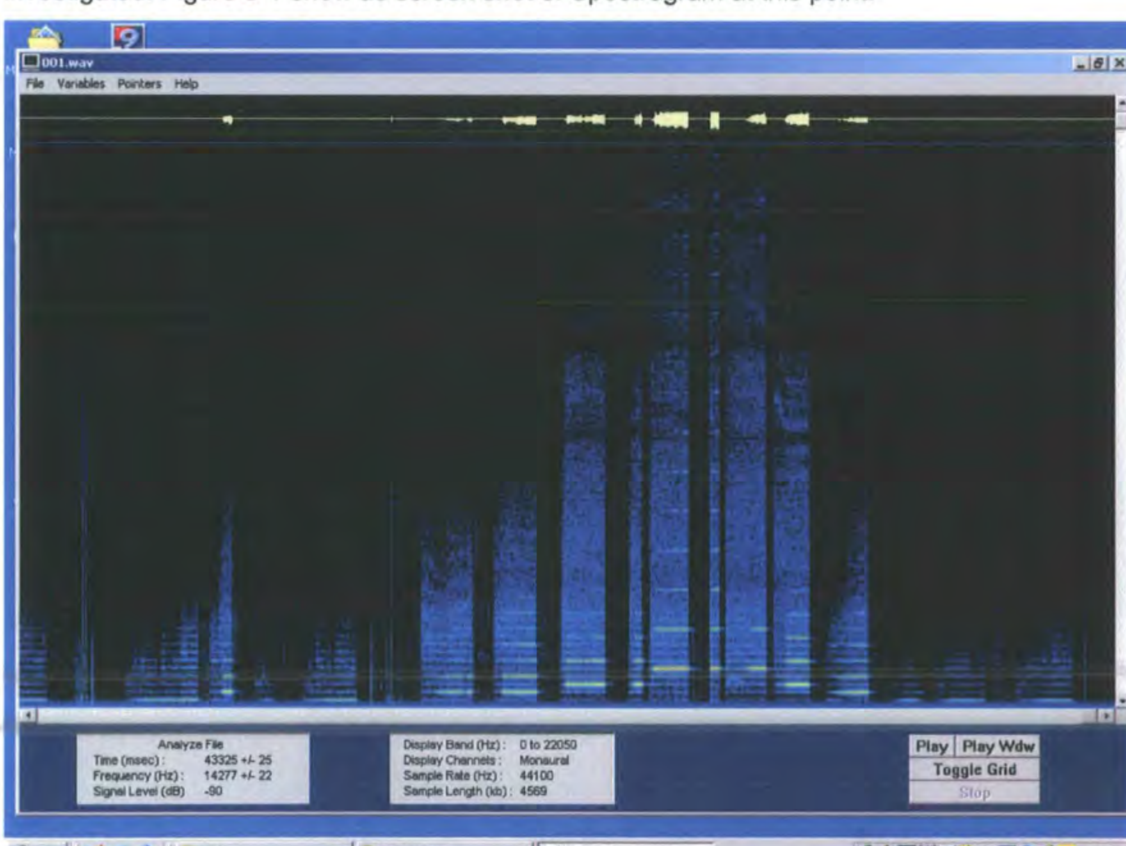

Figure 5-1 Screenshot of spectrogram with a wavefile

As can be seen the wave appears at the top of the window and the large part of the window is taken up by the spectrum. For the spectrum the frequency ranges from 0Hz at the lower end up to 22kHz at the higher end. The colour relates to how strong the signal at that frequency at time is. This view of the spectrum allows for a visual inspection of how much noise there is when the instrument is producing no sound. Ideally there should be no noise and so the spectrum should appear the same as the background. Where there is white noise it would appear as a block of a constant colour, such as it does when there is no wave being analysed. The screenshot shows a 50 second period of time and this can be reduced to one second but no further. This means that at all points the wave form at the top of the window will always appear as a block, so the actual wave structure can never to seen.

To produce a single frequency spectrum the point in time required is clicked on and a window is opened up with the variables that can be changed. The frequency spectrum produced will produce a window as can be seen in the screenshot in Figure 5-2.

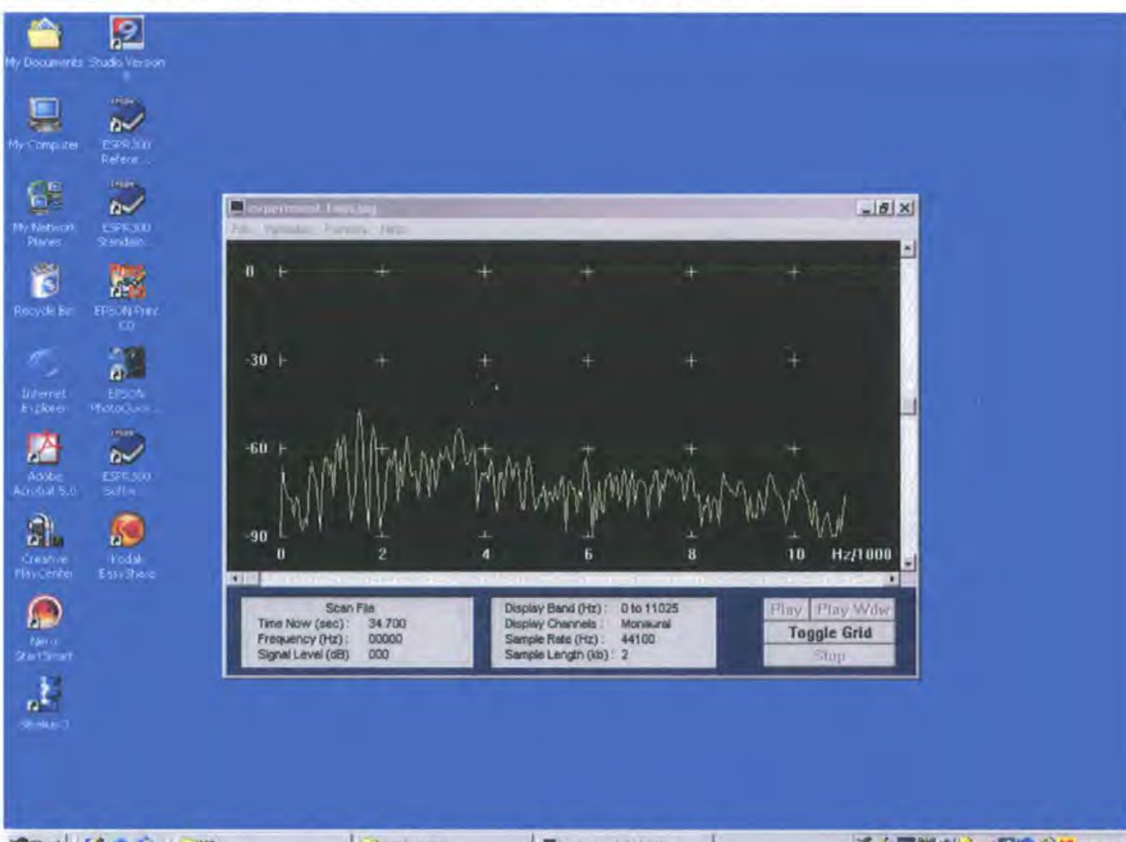

Figure 5-2 Screenshot of Frequency spectrum within spectrogram

The window has a fixed size and so the detail seen in the spectrum is limited. Also the scale cannot be altered and so there are only markers every 2kHz and on the level axis every 30dB. This means that it is not easy to see whether there are harmonics as there is only one set of numbers to go on. It is fine if the fundamental frequency is 2kHz, as the harmonics will appear at the markers.

The application is simple to use and the functions that it performs are easily found however the presentation of the data is relatively poor for detailed analysis.

5.1.2 Goldwave

To record into the Goldwave application a new wave file has to be opened first with a chosen length. This means that like Spectrogram the length of the sound to be recorded needs to be known.

Once the wave file is open recording into it is easy. The control buttons in the device controls window are set out the same as on any music player. The recording will start from where the cursor has selected. So recording into the second half of a file is possible without altering the first half. Once a sound has been recorded it can be recorded over if the record button is pressed again. The waveform will appear as in Figure 5-3 showing a screenshot of Goldwave.

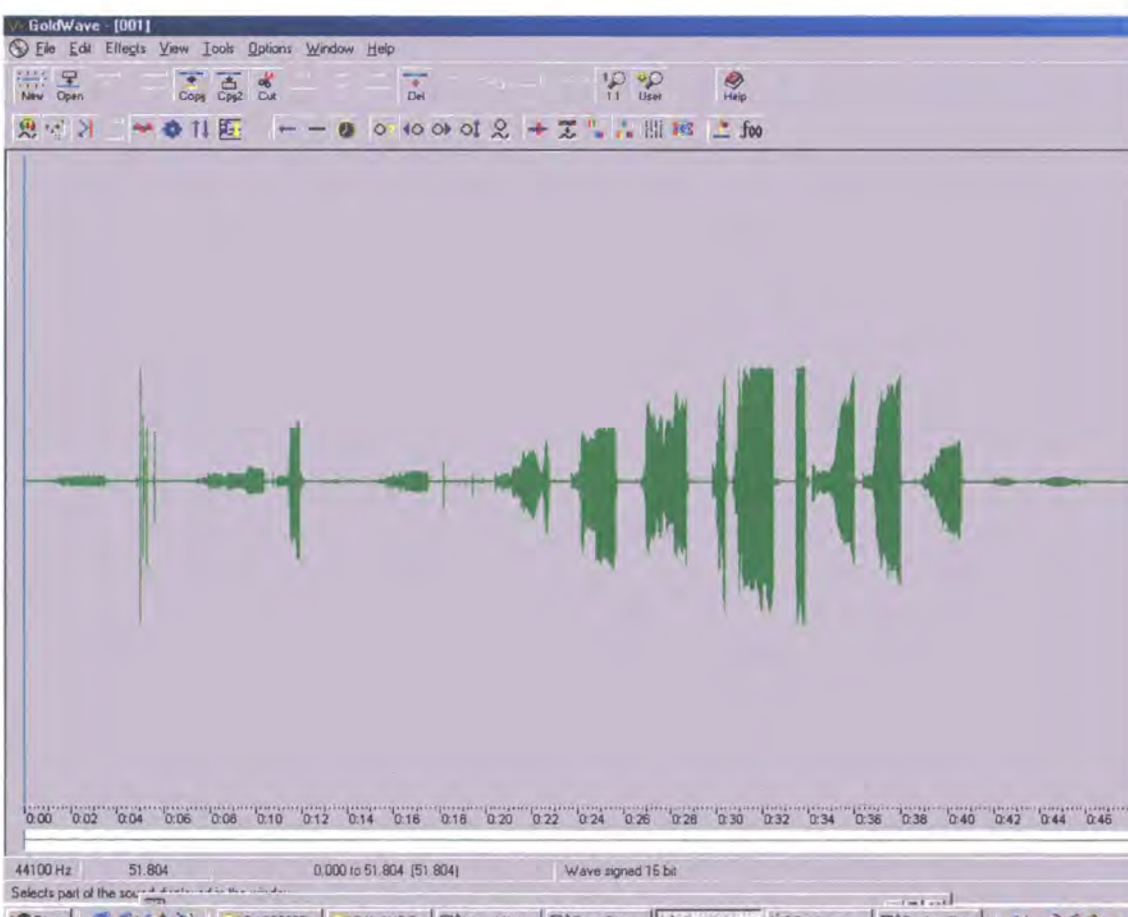

Figure 5-3 Screenshot of a waveform in Goldwave

Any waveforms can be saved as one of a number of different file types, including Wave files, MP3 files, text files and others. Opening pre-recorded sounds can be done with any one of the files types that Goldwave can save to as well as others such as avi files.

The spectrum of the wave can only be seen while recording in or when playing back the sound. It is possible to pause the playback of the sound so that the spectrum is still. However the image of the spectrum is small as can be seen in Figure 5-4.

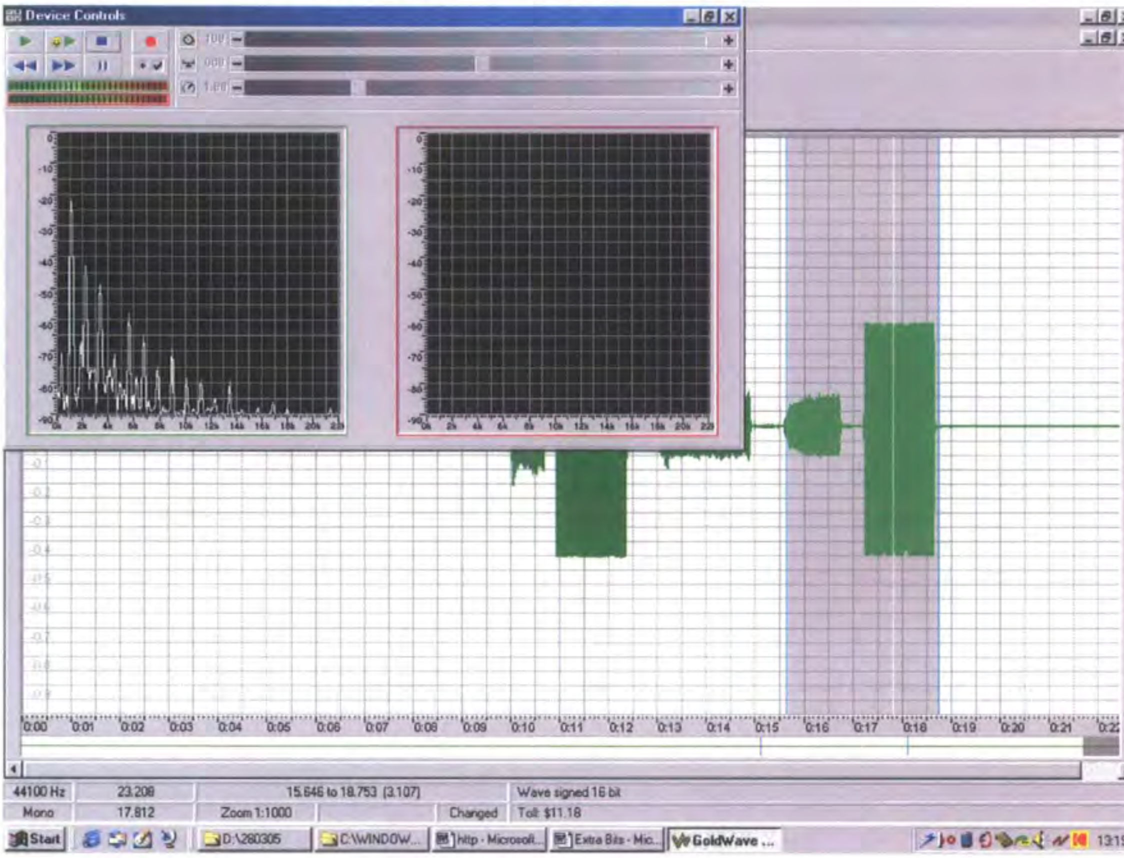

Figure 5-4 Screenshot of the frequency spectrum in Goldwave

The spectrum would have to be exported as a screenshot if it was required. As the size of the image is limited and the axis fixed then the actual frequencies of the various peaks cannot be found. There are a number of different ways that Goldwave will display the spectrum either as blocks of colours, different lines or as a spectrogram. None of the different displays have a more accurate axis and so they do not show any more information than the original spectrum.

The application has the ability to create waveforms from equations. So if the formula of a wave had been calculated and so needs to be checked, it could with Goldwave. However to analyse the spectrum it would have to be imported into another program.

As Goldwave did not produce a suitable frequency spectrum the program does not provide the functions required.

5.1.3 Audacity

The overall look of the application before starting to use it is that it is clearly set out and has many functions.

Recording into the software is simple as the buttons in the menu bar appear as the same as on any music player. Once the record button has been pressed the software will continue recording until either the stop button is pressed or the computer runs out of space of its hard disc. Once the sound has been recorded the waveform will appear, as is shown in the screenshot in Figure 5-5.

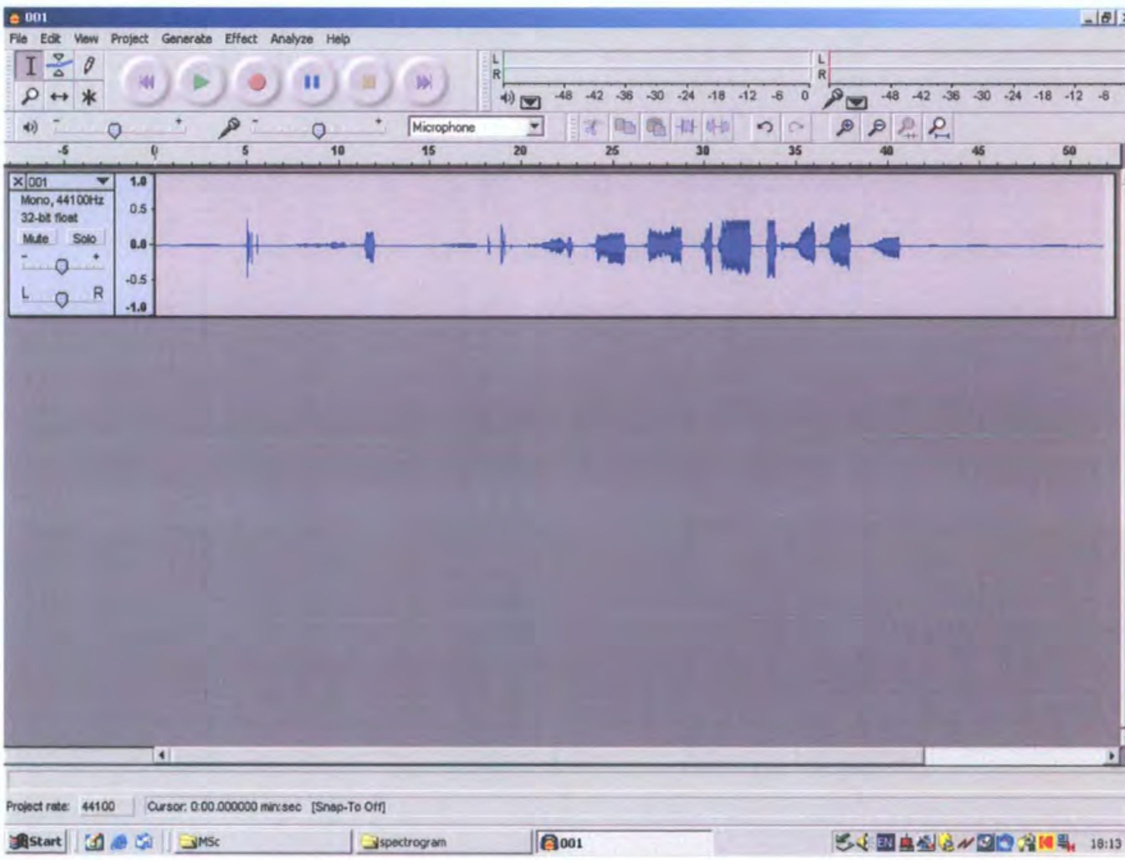

Figure 5-5 Screenshot of a waveform in Audacity

When the cursor is moved over the boxes at the bottom of the window the box shows how much time is left for recording. This relates to the amount of hard disc space left. The sound recorded can then be saved in one of four ways.

The first is to save it as an Audacity Project File, this format means that when opened again in Audacity it will appear exactly the same as it did before saving including any labels that have been added. This type of file is limited, it can only be opened in Audacity and the size of the saved file is large. For example for a 30 second recording of a pure tone at 440Hz the project file produced is 90Mb where as the other three methods produce files of 2Mb and smaller.

The sound can also be exported as a wave file, MP3 file or Ogg Vorbis file. For these three methods it is also possible only to export a specified selection of the waveform if required. To export as an MP3 a separate LAME MP3 encoder is required. Audacity allows for multiple tracks to be opened at any one time. This allows for comparison of the waveform. However, if saving the wave file the tracks will be merged into one.

Importing previously saved sounds can be done quite easily and the file type is not just limited to wave files. MP3 files and Ogg Vorbis files can also be imported along with raw data in a text file.

The zoom function within Audacity allows for any waveform to be zoomed in on so as to actually see the wave rather than a block of colour, this can be seen in Figure 5-6. At all times the point of time in the complete waveform can be seen at the top of the wave and the amplitude is shown at the side.

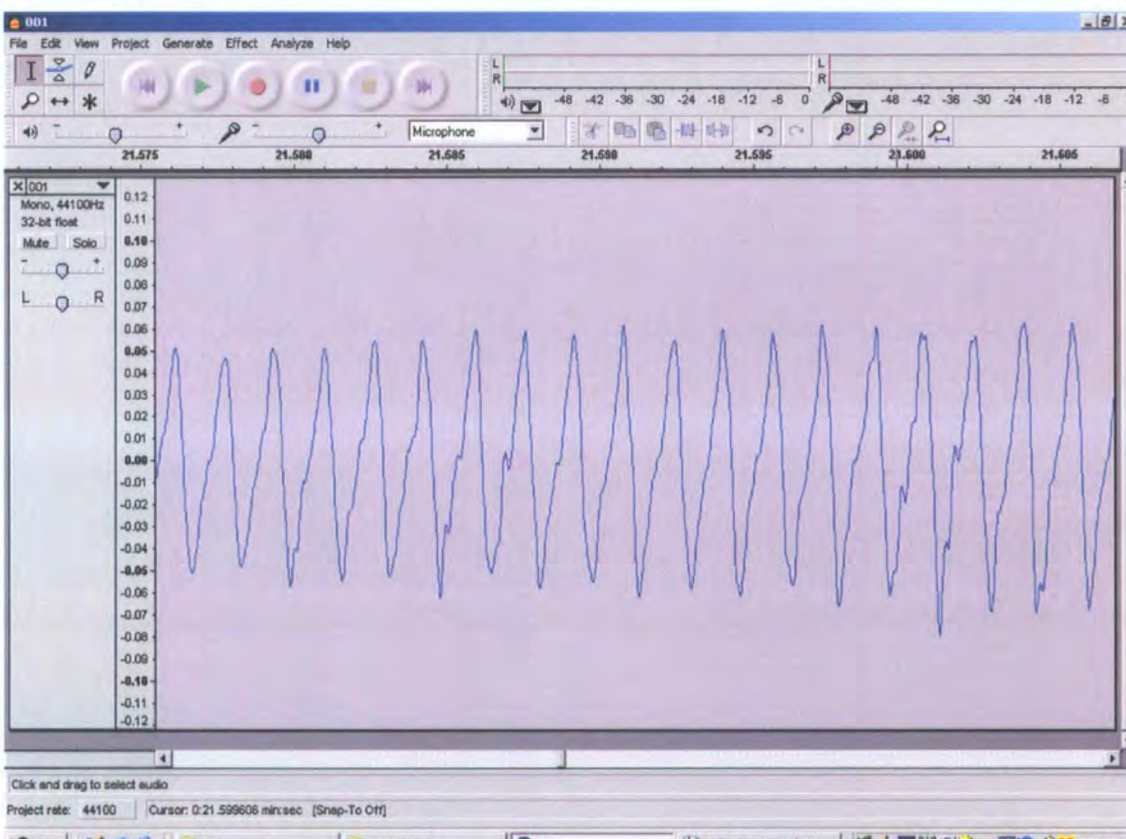

Figure 5-6 Screenshot of zoomed waveform in Audacity

Any waveform that has either been recorded directly into Audacity or that has been imported can be edited by selecting and removing sections, or by copying sections. There are also many other effects that can be used on the waveforms to alter the sound. These include Low and High pass filters, FFT filter, noise removal, delay and many others. [52]

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[52] [WAL04]

Analysing the data with a frequency spectrum can be done by highlighting the required portion of the wave and then using the edit menu to select the spectrum. The minimun size of the selection is directly proportional to the number of FFT points that are required. For 513 points the minimum selection is 0.0117seconds where as with 1024 points the minimum selection is 0.0233 seconds. The more FFT points that are chosen then the smaller peaks in the spectrum can be seen. This is useful when seeing which harmonics are evident within a wave however small. A screenshot of a frequency spectrum can be seen in Figure 5-7.

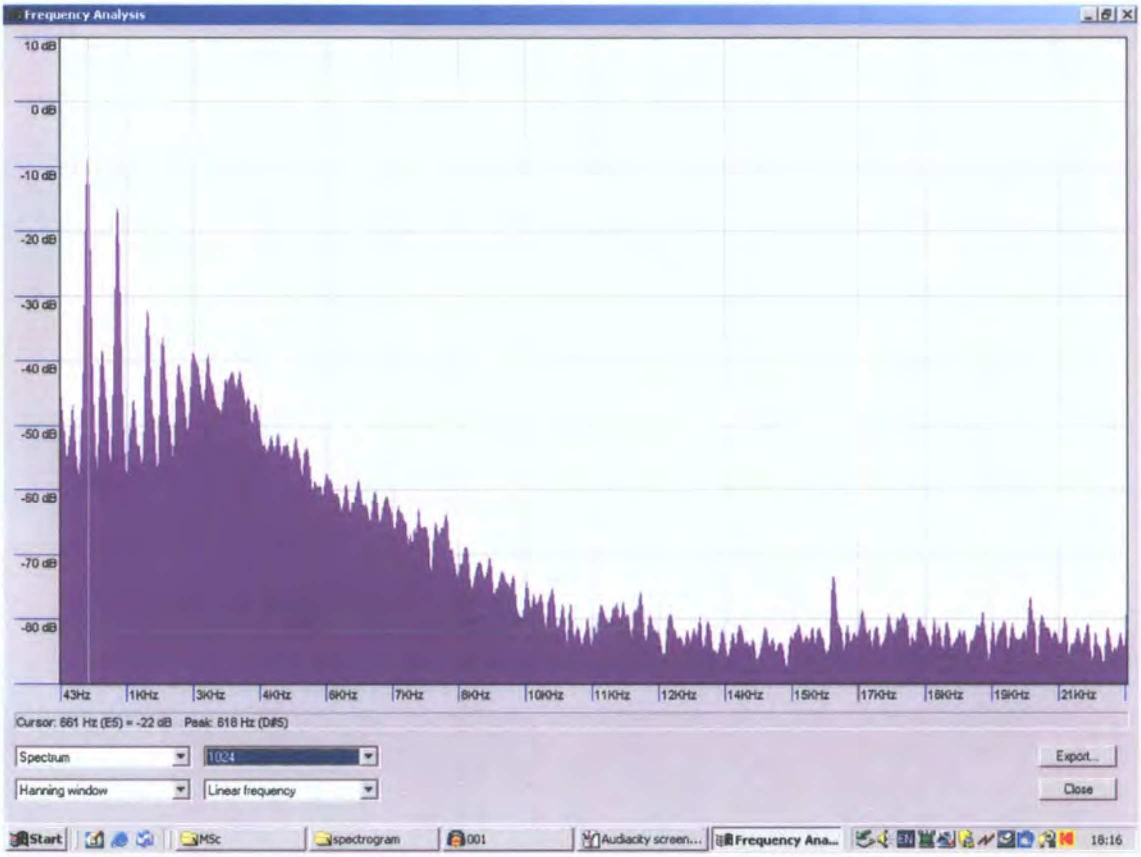


Figure 5-7 Screenshot of the frequency spectrum in Audacity

As the cursor is moved over the spectrum the nearest peak is highlighted and its frequency and note name is shown in a box at the bottom as well as the frequency and note name of where the cursor is. Also shown in the box is the decibel level for the waveform at the frequency where the cursor is. Showing the frequency of the peaks is very useful as it does not require the cursor to be in exactly the correct position when calculating the major frequencies included in a wave. The spectrum also has the option of having either linear frequency or log frequency. Viewing the spectrum with the log frequency helps with the identification of the low frequencies in the wave, with the linear scale they would be very close together and with the log scale they are spread further apart.

The data from the spectrum can be exported as a text file, which can then be imported into a spreadsheet for the creation of a chart. This enables clear spectrums to be included where the spectrum is a line rather than a block of colour. Importing the text files into a spreadsheet also enables more than one spectrum to be included on a chart for comparisons to be made of the frequencies.

Audacity is a complete audio editor and so includes many functions that would not be required when analysing the actual sound recorded. There are a number of extra functions on how the waveform can be viewed, these can be seen in the screenshot in Figure 5-8.

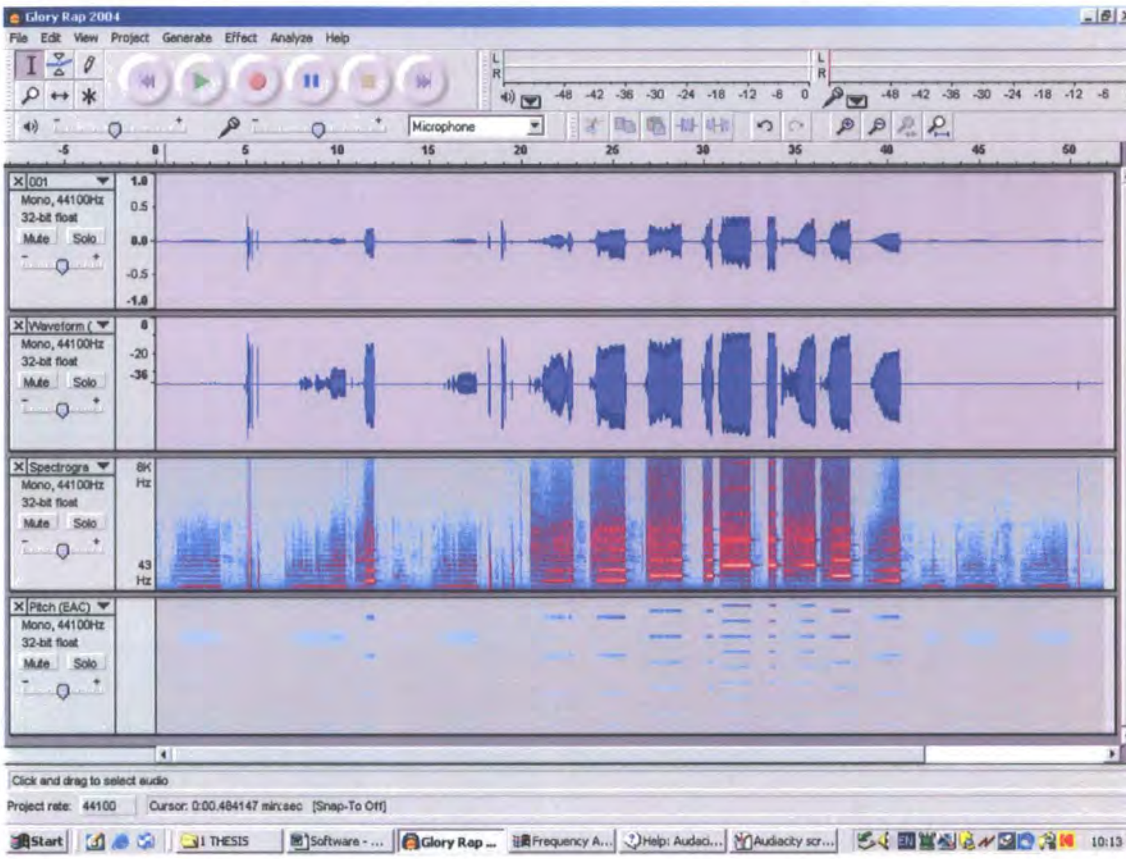


Figure 5-8 Screenshot of the alternative ways to present the waveform

- The first waveform is the standard view with the amplitude versus the time.
- The second waveform shows the waveform with the amplitude measured in decibels.
- The third waveform shows the spectrogram, which can be useful for the overall look of approximately which area of frequencies are strongest, however the information shown is not very accurate until further analysis is completed.
- The fourth waveform shows the pitch of the waveform versus the time. This does not show much information as there is no scale included on the pitch axis.

Overall Audacity performs the operations required to record and analyse the data for this thesis and so this application is the one that has been used throughout.

5.2 An Artificial Blowing system.

To compare the spectrum of different instruments and alterations to each instrument, the number of variables that might affect the spectrum needs to be reduced. These variables include; the embouchure shape, the angle at which the air jet hits the knife-edge, the pressure of the air-jet and the flow rate of the air jet.

The flautist's embouchure needs to be made unchanging, as the flautist would normally alter their embouchure for most notes they play to obtain the best sound. Even if the flautist tries not to move their embouchure they would move as some of the movement made would be made subconsciously. Along with the subconscious movement there would be movement when the flautist would remove the flute from by their mouth to change another variable and then play it again. In this case their embouchure is almost certainly to have changed from what it was before.

The angle at which the air jet hits the knife edge is important and small variations in the angle will vary the frequency as can be seen in Figure 5-9 with the fingering for A_4 this note can vary from 398Hz to 452Hz just by the angle changing.

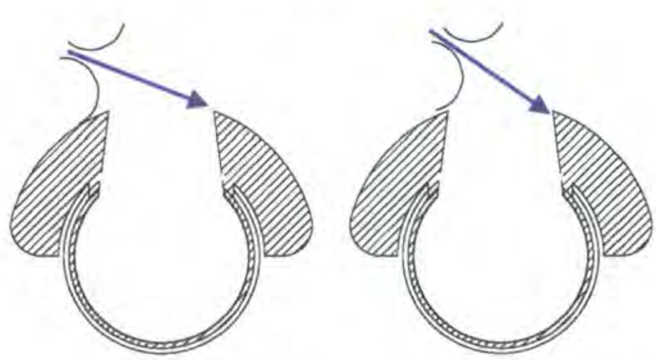


Figure 5-9 Angle of air jet hitting the knife edge

As the flautist starts to play a note and throughout the note there will be variations that are not caused by the embouchure of the flautist but by the flautist's lung capacity and muscles. Those variations occur because it is highly difficult to fully control the air coming out of the lungs to be of a constant pressure and velocity. Figure 5-10 shows how when playing the flute the flautist varies the flow and so the volume of the note varies.

Figure 5-10 Waveform of playing one note using a lung full of air

When breathing in and out it can be observed that the pressure of the air changes, as someone breathes out after taken in a complete lung full of air the air pressure starts relatively constant.

As the flautist uses up the air in their lungs it becomes increasingly difficult to maintain the pressure and velocity as they rely more and more on the muscles providing the pressure rather than the lungs, as they will have deflated and the muscles will be trying to 'squeeze' the air out. A highly skilled flautist may be able to 'circular breathe' where they breathe in without stopping breathing out, but not many flautists would be able to achieve this.

An artificial blowing system that controls the pressure, velocity and direction of the airflow would reduce the number of variables acting on the flute.

5.2.1 The Design

Before coming up with the design, preliminary experiments were conducted into whether or not the idea of a pipe directing the air-jet would be feasible. A straw was blown into, which was directed onto the knife-edge of the embouchure hole to see if the flute still produced a standing wave and therefore a note. A pipe directing an air jet onto the knife-edge is a practical method for the artificial blowing system.

The artificial blowing system design includes a compressed air supply and a regulator; the air needs to be of a pressure and velocity similar to the air from a flautist's mouth. The tubing attached to the regulator was chosen as the closest bore to the gap in the flautist's lips while playing the flute, and this was then used as the artificial lips along with some modelling clay to make the shape of the lips that cover a small area of the embouchure hole. Also this modelling clay allowed the tubing to be held in the same position throughout the experiment. A diagram of the artificial blowing device can be seen in Figure 5-11.

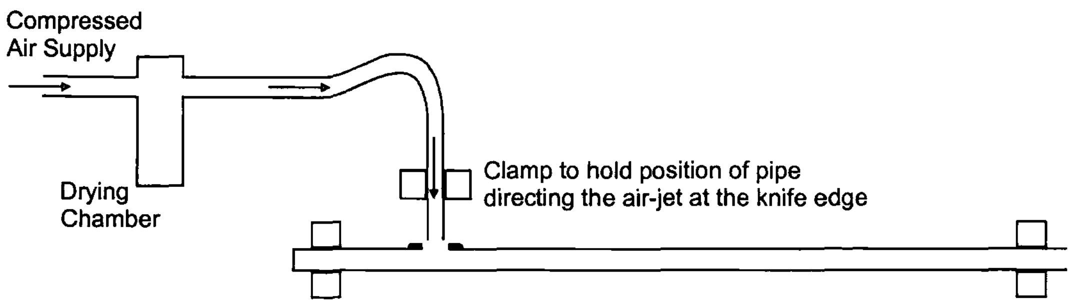


Figure 5-11 The artificial blowing device

The pressure needed to play the flute had to be found and so when thinking about the pressure needed to produce a sound on a flute a comparison with a recorder can be used. The recorder family uses the same principle to produce the sound with an air-jet hitting a knife-edge; the difference being that by blowing into the recorder's mouthpiece the angle of the air hitting the knife-edge is controlled. Figure 5-12 and Figure 5-13 show how the air jets hit the knife-edge in each instrument.

Figure 5-12 The air hitting the knife edge in the flute

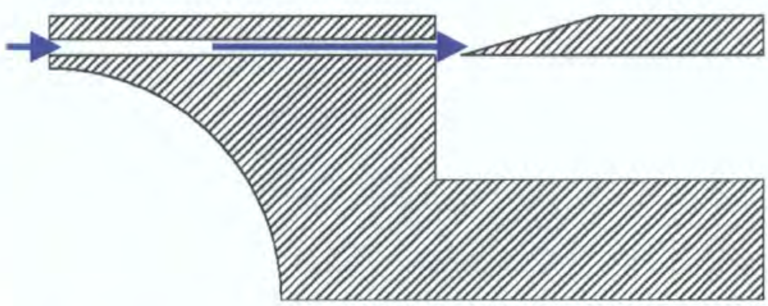


Figure 5-13 The air hitting the knife edge in a recorder

With the recorder, to play the higher register, the pressure of the air is increased as well as the half opening of the thumb tone hole, which creates a register hole, such as is found with the clarinet, to get the higher registers. Because of the fixed mouthpiece, the angle of the air hitting the knife-edge will not change. The larger the recorder, the more pressure and the larger airflow is required to make the instrument sound. There are more air molecules within the instrument to be excited therefore needing more pressure. The flute does need a higher pressure of air-jet but only so much as to cause the air inside the bore to oscillate the same as the larger members of the recorder family do. A flautist will change the angle at which the air-jet hits the knife-edge and the shape of their embouchure to play the higher registers.

5.2.2 The Problems

Using the artificial blowing system caused many problems such as the pressure, the angle and the noise within the compressed air.

- As a flautist plays the flute, they make very small changes to their embouchure as they play up a scale to ensure that each note is in tune.

- As the higher registers of the flute are played, the flautist changes their embouchure position to 'over-blow', which would have to be continued with the artificial blowing device to enable the notes to be played. However, to keep the variable fixed, so that the length of the bore was the only variable, at all times the tubing would have to remain in the same position throughout the experiment. But to play the different registers the position would have to alter so that the airflow was directed to hit the knife-edge at the correct angle.

- The pressure of the air coming out of a flautist's mouth would not be very high. This is due to the pressure being governed by their lungs and muscles. The pressure of the compressed air also needs to be low. As well as being at a low pressure the pressure needs to be variable so as to play the higher registers, because, just as the flautist changes their embouchure to play the higher registers, they also change the pressure of the air, therefore creating the same problem as with the fixed position. The compressed air source being used was very difficult to control at low pressures so as to have a constant pressure. The lowest pressure that could be kept constant was about 3Kpa and this would only overblow the flute. This meant that using this artificial blowing system the lowest register was not playable. Not being able to play the lowest register would mean that none of the fundamental frequencies of the flute would be playable and so reducing the range data from the experiments, which would not be acceptable.

- As the compressed air was used, the system created a lot of 'noise' as it came out of the end of the tubing: this causes problems when looking at the spectrum of the flute, as there are many frequencies that appear that should not be evident at that strength. The spectrum of the noise can be seen in Figure 5-14.

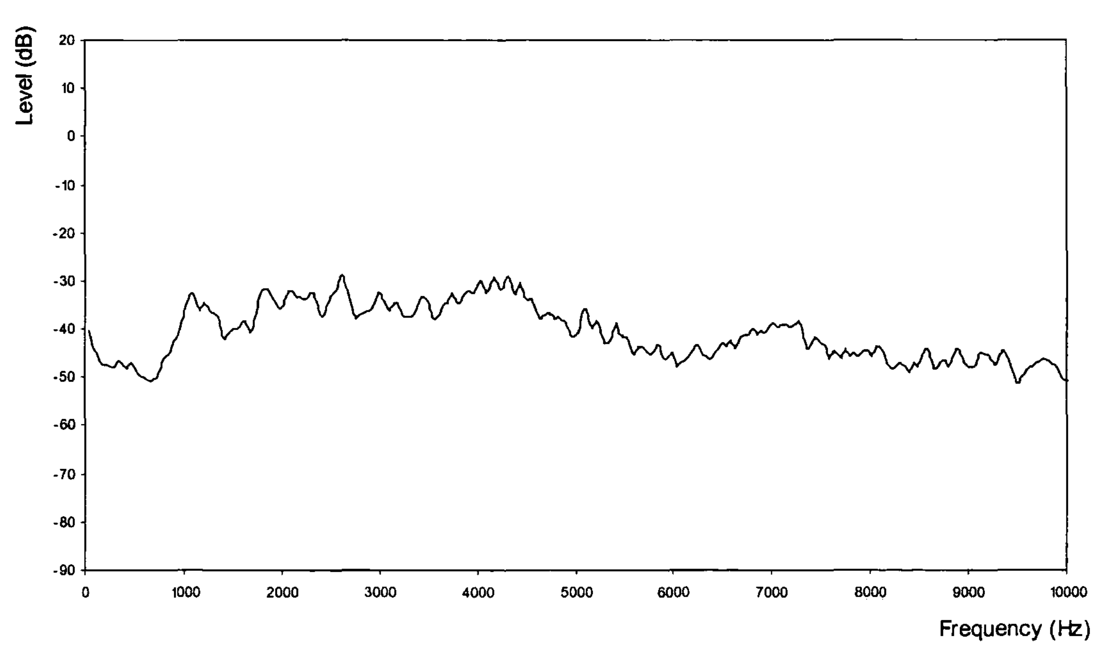


Figure 5-14 Spectrum of Noise produced by the Artificial Blowing Device

The spectrum of the 'plunger flute' being player by the artificial blowing system can be seen in Figure 5-15 compared to the same instrument being played by a human in Figure 5-16 and

Figure 5-17. With all the noise associated with the compressed air supply it may mean that some of the harmonics with less strength will not be noticeable in the spectrum of the instrument.

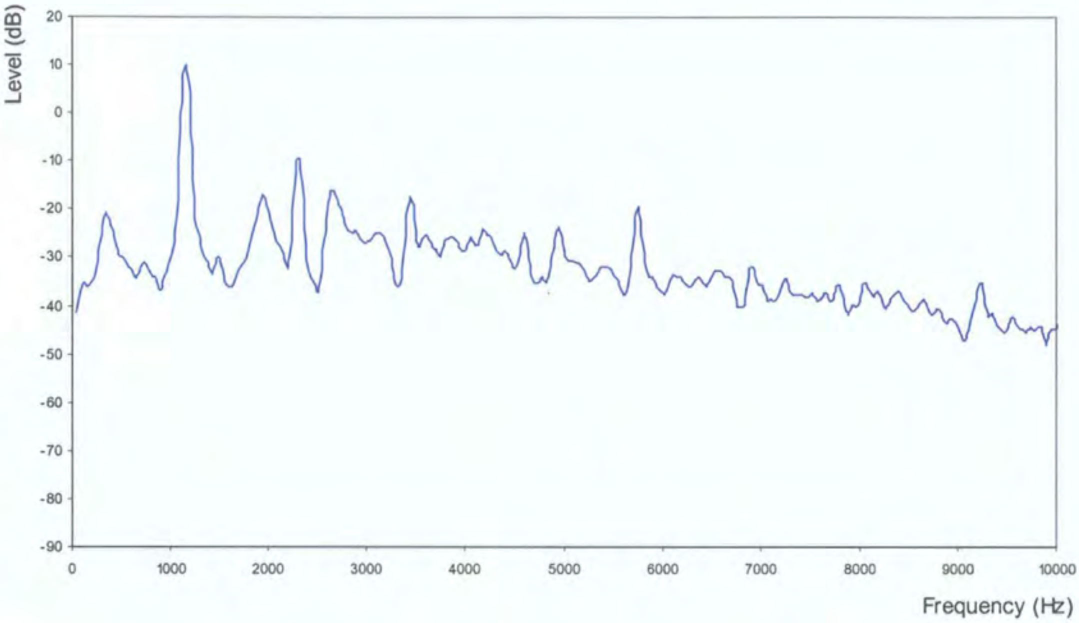


Figure 5-15 Spectrum of Plunger played by the artificial blowing device

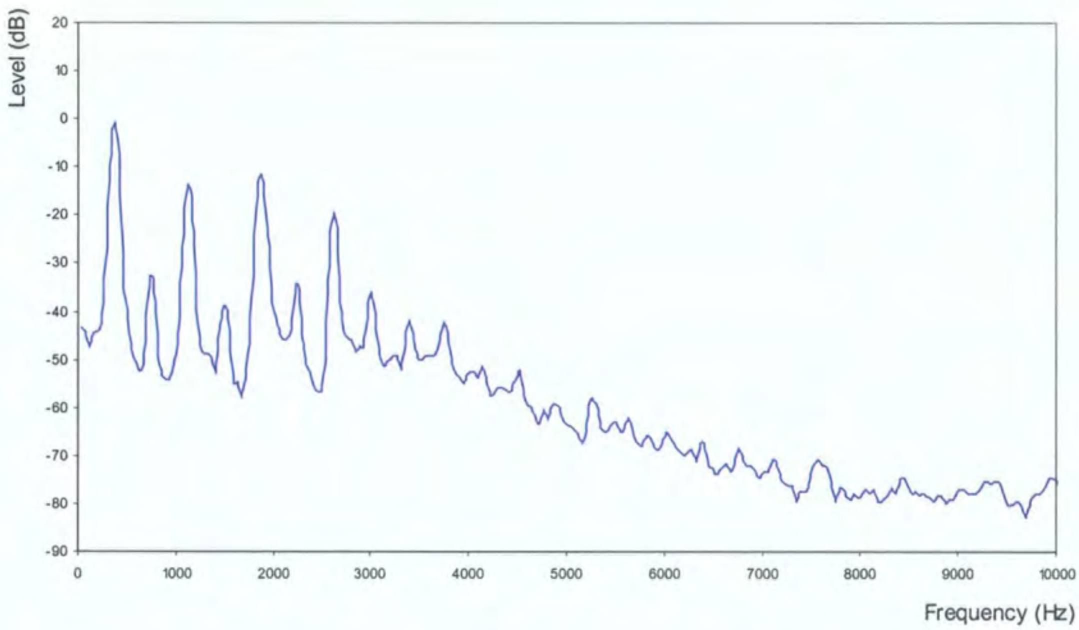


Figure 5-16 Spectrum of a human playing the plunger flute at 3Kpa

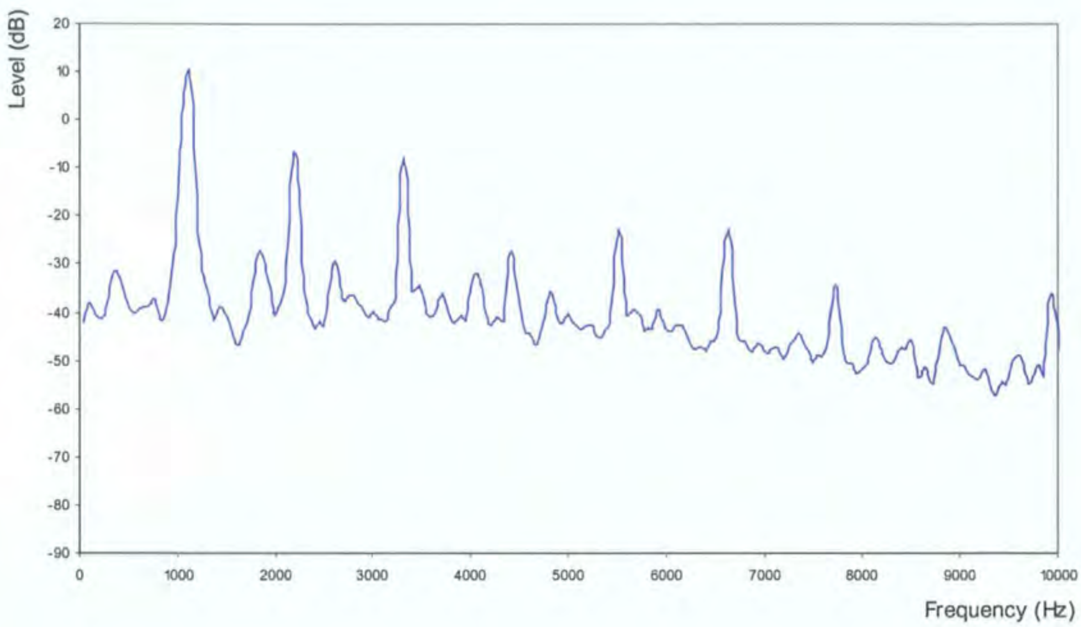


Figure 5-17 Spectrum of human over blowing the plunger flute

5.2.3 The Solution

After attempting to get results using the artificial blowing system, the system was abandoned and the flute was then played by a human. The artificial blowing device failed to be able to play the lower frequencies. Therefore, each note played would have the angle of the air jet correct for that note and the pressure would be correct. Using a human does mean that some human error will be included in the results as it is natural to try to tune the instrument slightly with changing the angle of the air-jet hitting the knife edge of the instrument how ever much the flautist tries not to.

With further research a suitable artificial blowing system may be found but it would have to comply with the following points.

- The system would have to have a much lower pressure and flow rate so as to allow the lower registers of the flute to be played and along with this there would need to be the flexibility of changing the blowing pressure and the angle of the air-jet to allow for all registers to be playable.

- The system would have to be able to repeat any of the settings exactly as it was set before to be able to do fair repeats.

- A much quieter source of the compressed air would be needed so as to not make an obvious change in the spectrum compared to when a flautist plays it.

- Most importantly the artificial blowing device needs to imitate how a flautist plays the instrument.

5.3 Conclusion

This chapter has shown that the most suitable software for the applications required is Audacity, which will also perform a number of other operations that would not be required.

An artificial blowing device is investigated and considerations given to how it would need further development to work. Reliance on human blowing introduces human error into the data for analysis of the flute. However, this would have a smaller effect on the result that the errors and noise associated with the artificial blowing device.

Having discussed how the data can be analysed the Boehm flute can now be investigated.

6 The Boehm Flute

The Boehm Flute, as previously stated, plays frequencies associated with 12-ET. Therefore, before any possible microtonal flutes are investigated the Boehm flute needs to be analysed. This needs to be done so as to have suitable data to compare with the data from new instruments. This chapter details the investigations into the Boehm flute, both with the key system and after the removal of the key system. Removing the key system allows for non-conventional tone hole closure patterns to be investigated to see whether the Boehm flute has any microtonal capabilities.

6.1 Boehm's Key System

The Boehm key-system contains sixteen holes, on a flute with a C foot, of which they vary in size from 7mm diameter to 16mm diameter. To be able to cover all the holes the key system has a mixture of levers and keys. The levers allow for holes away from the fingers to be operated. Figure 6-1 and Figure 6-2 show the positioning of these sixteen holes and Figure 6-3 shows the basic keys structure with which keys and levers are operated by which hand. Figure 6-4 shows the complete Boehm flute.

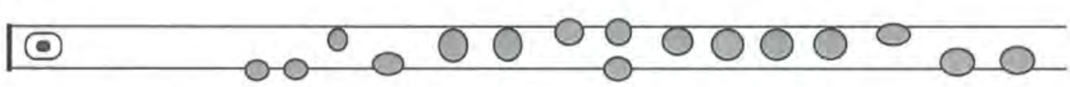


Figure 6-1 Tone Hole positions on the Boehm Flute

Figure 6-2 The Boehm flute with its keys removed

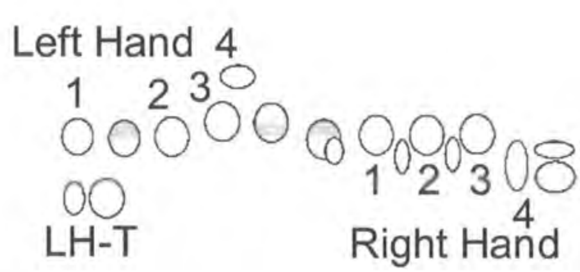


Figure 6-3 Key structure of the Boehm flute

Figure 6-4 The Boehm Flute

The Boehm key-system has reduced the number of forked fingerings that are required to play all the notes contained in 12-ET. A forked fingering is one where the tone holes are closed below that of the first open one. Previous flutes to the Boehm flute had less keywork and as more holes had to be directly covered by the flautist's fingerings, consequently many forked fingerings were needed. With the Boehm flute, the key work means for the notes that previously needed forked fingerings can just be obtained by opening or closing an extra tone hole. This is visible when comparing the Boehm flute to a recorder (which can be looked at as a duct flute where as the Boehm flute is a transverse flute) when playing B♭$_4$. For the recorder a forked fingering is required as shown in Figure 6-5.

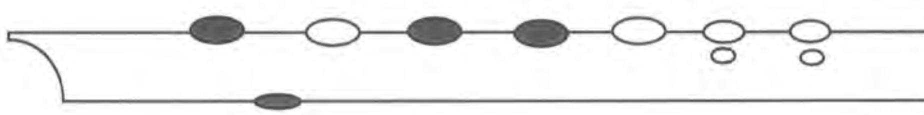


Figure 6-5 Recorder Fingering for B♭4

Whereas for the flute it may appear that it would be a forked fingering as there are tone holes that are closed below that of the first open hole as can be seen in Figure 6-6, which shows the sixteen tone holes of the flute without any of the key work.

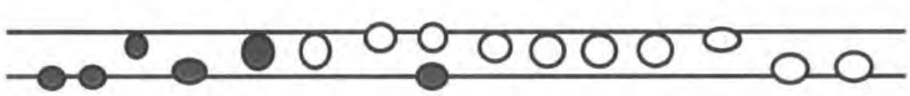


Figure 6-6 Tone hole pattern for B♭4

Where as the fingering is much simpler, as can be seen in Figure 6-7, only the left hand thumb and first finger as used and the right hand first finger, (the E♭ key, right hand 4th finger, is pressed to open the tone hole and is used in nearly every fingering). [53]

[53] The complete fingering chart for a modern Flute as well as which particular holes are closed by which keys can be found in Appendix A

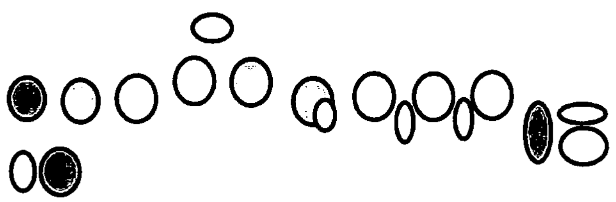


Figure 6-7 Flute fingering for B♭4

The Boehm key-system allows any one of the 24 major or minor keys to be played due to the extensive work that Boehm put into the development of the key-system. Boehm found the optimum placing and sizes of the tone holes and then had to produce a suitable key-system to work with them. The majority of the keys in the Boehm key-system are 'open keys' which means that in their unused position they produce an open tonehole, whereas a 'closed key' which closes a tone hole in its unused position are less common. There are only four closed keys in the whole of the Boehm key-system. Closed keys require much stronger springs than open keys, as they have to hold the key shut and air tight, so consequently open keys are easier to produce.

During Boehm's time the standard tunings were based on A_4 being 435Hz, at the time called 'normal pitch' but now called 'International pitch' or 'low pitch'. The standard tuning for A4 now is 440Hz, so although modern flutes are Boehm flutes they are very slightly sharper.

Boehm not only conducted experiments into key-systems and the materials to produce the best design, he also found the optimum size of the bore. In 1867 when Boehm was experimenting with the various sized bores, he found that when using a bore of 20mm diameter the higher notes did not sound as easily and that they were impossible to play *piano* but lower notes sounded better than with a smaller bore. Although the lower notes were better with a bore of 20mm diameter he decided on the optimum diameter to be 19mm, for a standard flute based on the range of notes that the flute was most often required to play, those being in the higher registers. Boehm also found that for bass flutes 26mm was best and 20.5mm for Alto flutes.

Boehm's key-system allowed many keys to close the same tone hole without the flautist touching the particular key over the tone hole. This was enabled by a series of linked rods that Boehm designed for example hole 9, see Figure 6-8, which itself is not closed by the key being pressed directed, can be closed by three different keys. Figure 6-9, Figure 6-10 and Figure 6-11 show the three keys of the right hand that can close hole 9.

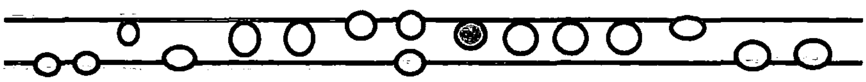


Figure 6-8 Tone hole '9'

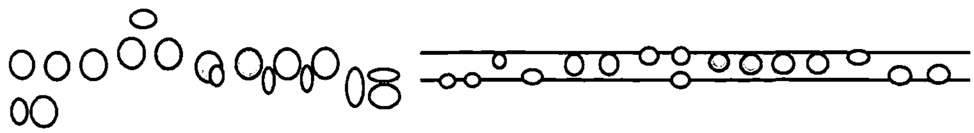


Figure 6-9 Right Hand first finger will close hole '9'

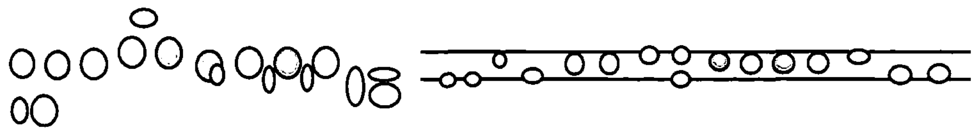


Figure 6-10 Right hand second finger will close hole '9'

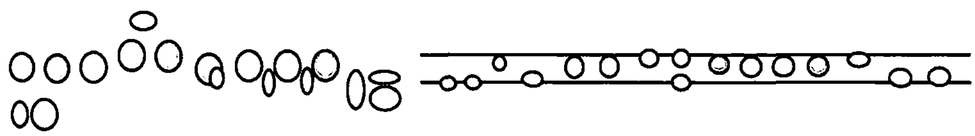


Figure 6-11 Right hand third finger will close hole '9'

Within the Boehm key-system there are a number of alternative fingerings, which can be used. These fingering do not necessary produce the best in-tune sound but are there to be used in cases where the primary fingerings would not be suitable, such as with some trills. Figure 6-12 shows the fingering for C_5 and the two fingerings for D_5 can be seen in Figure 6-13 and Figure 6-14.

C5

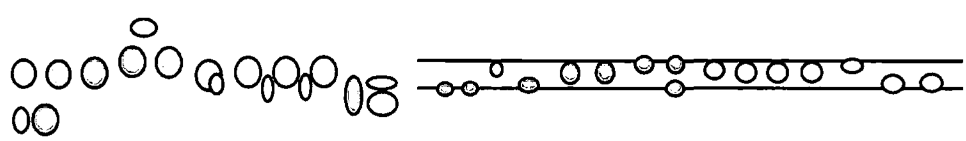


Figure 6-12 Fingering and Hole pattern for C_5

D5

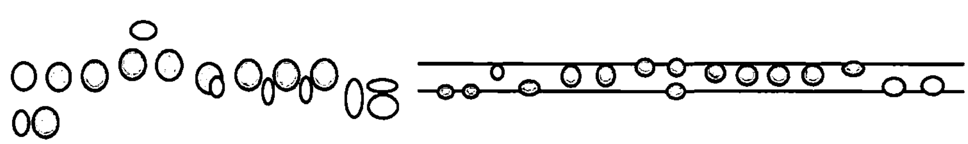


Figure 6-13 Fingering and hole pattern for D_5

D5
Trill

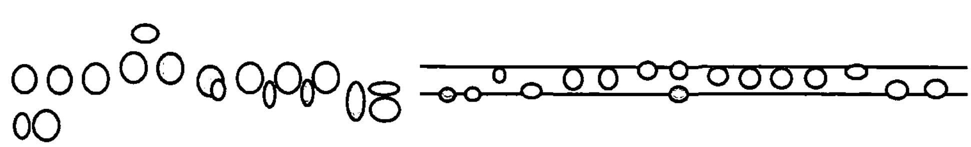


Figure 6-14 Alternative fingering and hole pattern for D_5

When trilling between C_5 and D_5 it is not practical to use the conventional fingering of D_5 as in Figure 6-13 due to the speed at which the notes need to change from one to the other throughout the course of the trill, instead the alternative fingering (Figure 6-14) is used. With the alternative fingering only one finger has to move rather than six.

6.2 The spectrum of a modern high quality flute

Before any changes are made to the flute and tested, the modern Boehm flute needs to be analysed. Every note that can be played on the instrument using the primary fingerings needs to be looked at. The primary fingerings can be seen in Figure 6-15, and more detail into which holes are opened and closed can be found in Appendix A along with the alternative fingerings. The range of notes that can be played on a modern Boehm flute is from C_4 up to $A\#_6$ although flautists with a higher skill can reach up as high as $F\#_7$.

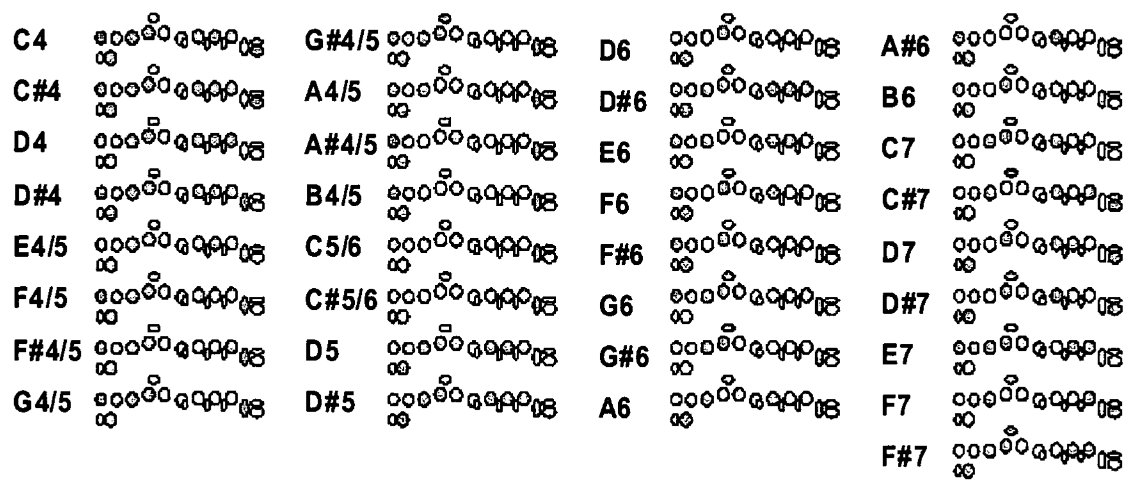


Figure 6-15 Primary Fingerings for the Boehm Flute

For each note played, the frequency of the first peak on the spectrum is found, which is the fundamental frequency for the note. This frequency is then compared to the expected frequency which has been found using A_4 as 440Hz. These can be seen in Table 6-1.

Note Name	Expected Frequency (Hz)	Actual Frequency (Hz)
C4	262	265
C#4	277	278
D4	294	290
D#4	311	314
E4	330	328
F4	349	355
F#4	370	368
G4	392	399
G#4	415	416
A4	440	444
A#4	466	473
B4	494	497
C5	523	530
C#5	554	570
D5	587	597
D#5	622	624
E5	659	662
F5	698	703
F#5	380	746
G5	784	793
G#5	831	839
A5	880	882
A#5	932	946
B5	988	1003
C6	1047	1056
C#6	1109	1129
D6	1175	1187
D#6	1245	1261
E6	1319	1348
F6	1397	1435
F#6	1480	1518
G6	1568	1608
G#6	1661	1666
A6	1760	1792
A#6	1865	1855

Table 6-1 Frequencies played compared to the expected frequencies

As nearly every frequency is sharp compared to the expected frequency it can be deduced that the instrument being analysed was slightly sharp. The fact that it was sharp does not change how the spectrums it produced are used. As the instrument was not tuned to a tuning fork or other tuning device prior to the recording it is not actually surprising that it is not in-tune.

The spectrums of the various notes can be used to compare with the spectrums of any other instrument that is analysed. The spectrum of E_4, E_5 and E_6 can be seen in Figure 6-16, Figure 6-17 and Figure 6-18 showing how the higher registers have harmonics in the spectrum that continue to much higher frequencies. With E_4 the harmonics have decreased in strength by 6kHz and it starts to get more difficult to distinguish the harmonics. With E_5 and E_6 the harmonics are strong up until 10kHz and beyond. The higher the fundamental frequency of the note the stronger the harmonics are. Also the higher notes require a higher pressure being blown onto the knife-edge and so consequently the volume of the note is louder and the levels of the harmonics will be louder.[54]

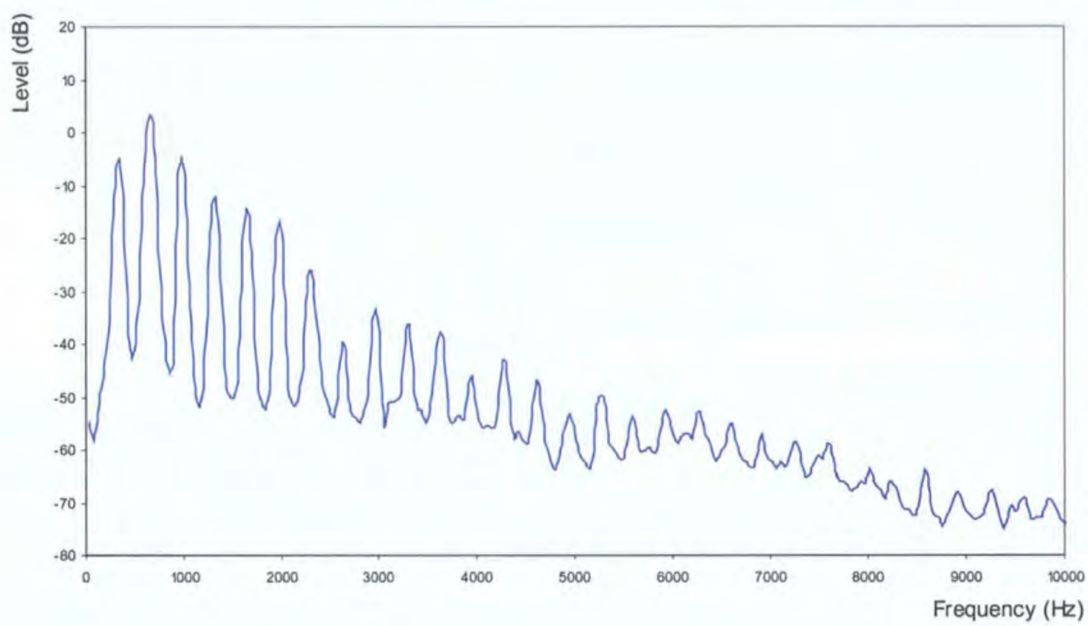


Figure 6-16 Spectrum of E_4 on the Boehm Flute

[54] The Frequency Spectra for the complete frequency range of the Boehm flute can be found in Appendix B

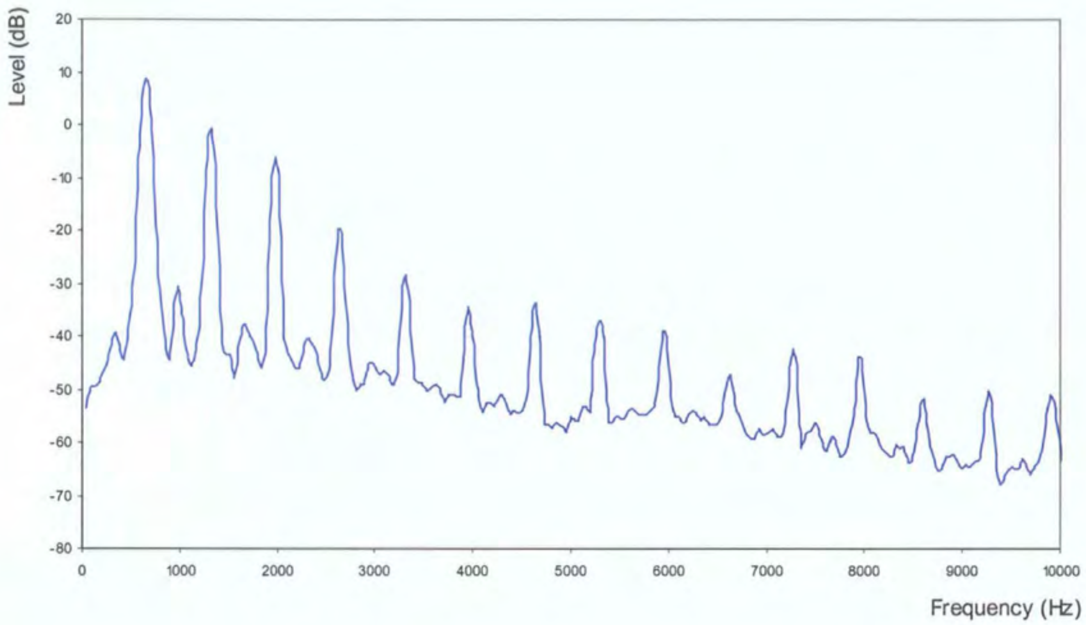


Figure 6-17 Spectrum of E_5 on the Boehm Flute

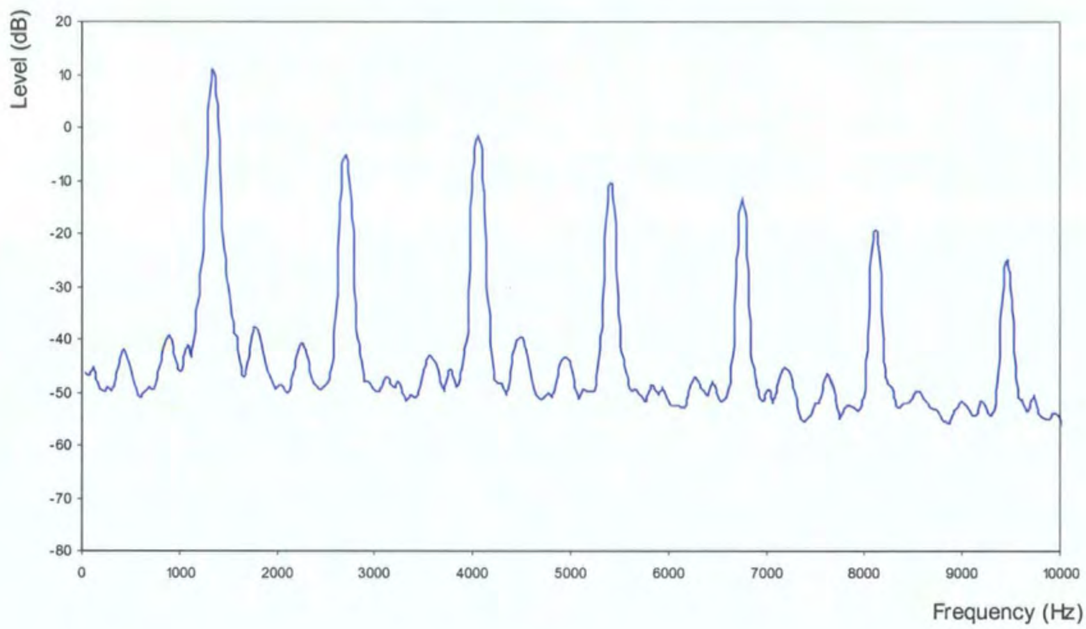


Figure 6-18 Spectrum of E_6 on the Boehm Flute

6.3 The Spectrum of a Boehm flute with the keys removed

All the key work was removed from the flute so that experiments could be carried out where individual tone holes could be covered without being linked to any other. This would enable any hole combination to be used. As the keys and springs had been removed and the holes were too large and there were too many to be covered by just fingers, another method needed to be found. The method needed to produce an airtight seal over the hole, which could also be removed and replaced easily. A material that seemed to fit the criteria was Blue-Tac as it would be airtight if pushed on well enough and would not encroach on the bore shape, as it could be moulded to the desired shape. For these experiments a different flute was used to the flute that was used when investigating the spectrum of the Boehm Flute with its keys. This was due to not wanting to damage the first flute. All the keys would have to have been removed and to replace them once finished; this would have required a large amount of training to calibrate the springs and keys. The flute used for the spectrum with the keys removed also would not have been suitable to investigate the spectrum with the keys as some of the springs were worn and to get the keys into perfect working order would have been hard work as some were miss aligned and did not cover the tone holes fully anymore.

Having chosen to cover the holes with Blue-Tac the effect of this different material covering the holes would need to be found. Figure 6-19 shows the spectrum for when the same holes were covered as are when playing E_4 on the Boehm flute.

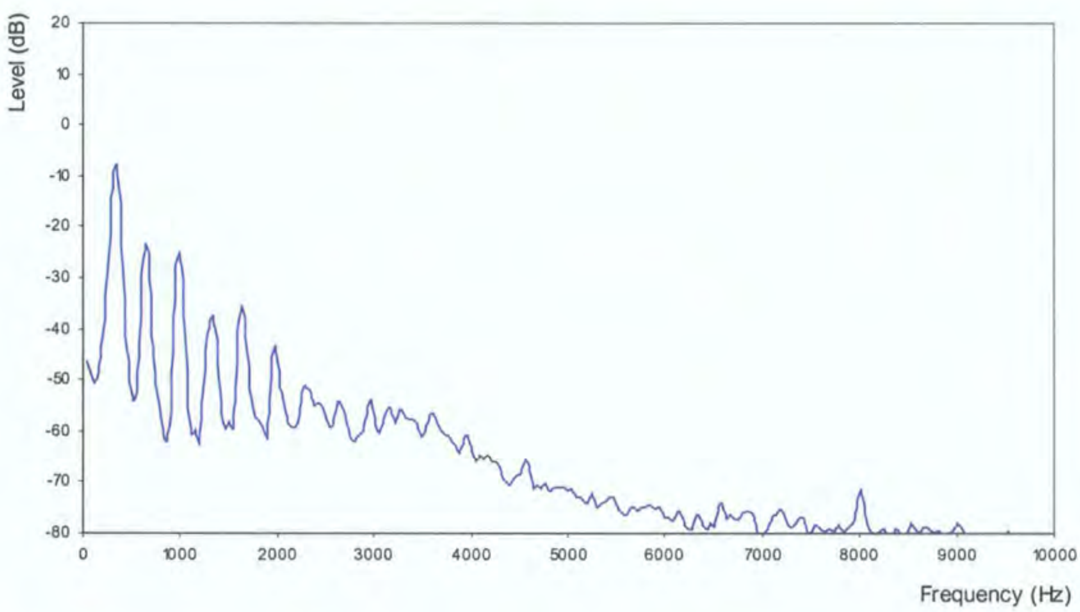


Figure 6-19 Spectrum of E_4 on the Boehm Flute with the keys removed

As can be seen when comparing the spectrum to that of E_4 on the Boehm flute (Figure 6-16) the two main differences are the levels are lower without the key-system and that the harmonics that can be detected only go up to 2kHz as opposed to 6kHz for the Boehm flute. This could be due to the difference in the instrument, the flute used for the original Boehm experiments was a high quality flute so that the best results possible were achieved whereas the one used to be taken apart was a much older and less expensive one as there was a question on how suitable it would be to play after having had all the keys removed and then put back. The fundamental frequency found for the note was 326 Hz, which is slightly flatter than was expected. This is not a result that should alarm as the notes were rarely completely in tune. $D\#_4$ was very slightly sharp, but D_4 was much nearer in tune, in fact it was only 0.66Hz out from what was expected from the calculations. [55]

6.4 The Flexibility of the Boehm flute in relation to Microtonal music

To see if microtones can be played on the Boehm flute without the key-system many different hole combinations were used. As there are sixteen tone holes on the flute the total number of possible open and closed hole configurations are

$$2^{16} = 65536$$

65536 combinations is too many to deal with sensibly, and so the number of combinations was limited to only the ones where the open tone holes were together, this mean that there were 137 combinations to be tested.

When looking at G_4 whose expected frequency is 392Hz which played on the Boehm flute was 399Hz (all the results appeared to be sharp). Therefore when played on the flute with the keys removed a frequency between the two would be expected. The results for the same holes covered (with blue-tac) gave 401Hz (see Figure 6-20:A for the hole configuration).

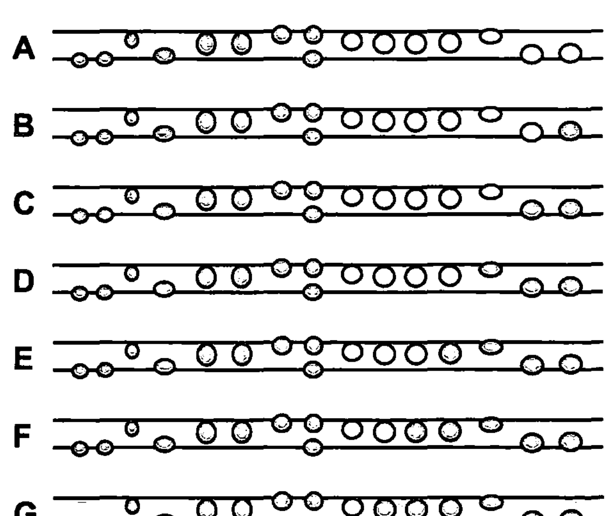


Figure 6-20 Hole configurations for G_4

[55] This calculations can be found in Appendix C

It would be expected that as tone holes are covered from the lower end of the flute then the frequency would decrease. There would be less opportunity for the air to escape and end the standing wave. With the holes down from the first hole closed the end effect would be greater. The smaller the tone hole the greater the end effect and so reducing the number of tone holes open would have the same effect. If any of the combinations with these holes covered was going to have an effect on the tuning then it would be the one where only one tone hole is open. In this case where there is only the one tone hole open, see Figure 6-20:G the frequency was 398Hz. Compared to the frequency when many of the holes were open there is hardly a difference and, as the frequencies for the configurations in between gave similar results, see Table 6-2[56], it can be concluded that the Boehm flute will not play microtonal music by changing the open hole pattern. There may be suitable hole combinations amongst the other 65399 untested combinations but the combinations would become very complicated and identification would be very time consuming.

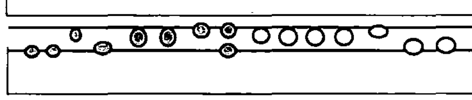
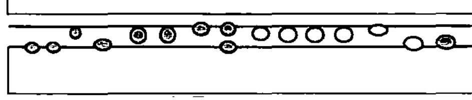
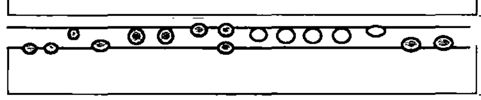
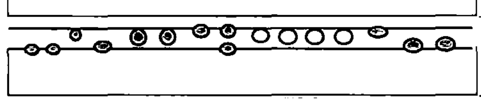
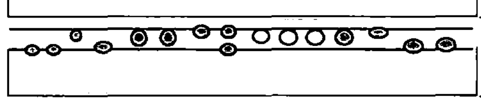
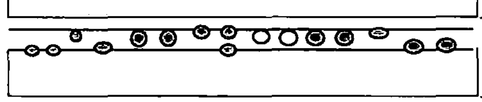
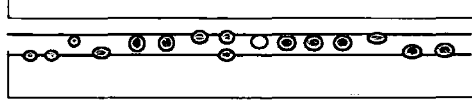
Hole Configurations	Frequency (Hz)
	401
	401
	402
	400
	399
	400
	399

Table 6-2 Frequencies obtained from hole configurations for G_4

Although it appears from the experiments conducted that the flute will not play microtonal music, previous investigations have shown that it is possible. Robert Dick in his book 'The Other Flute' details fingerings for quarter-tones on a flute with a B foot[57]. It also indicates the dynamic range of each note as well as the intonation. Although the fingerings are for a B foot flute Dick says how they can be translated to the C foot by lipping down. Within the book Robert Dick does not talk about the frequencies of each of the notes produced from the various fingerings, this makes it very difficult to compare with the results of the experiments. Many of these fingerings involved complicated forked fingerings where the open tone holes are not together and due to the large number of possible combinations these were not investigated, as it would be very time

[56] See Appendix C for full results.

[57] Pages 56-71 in [DIC89]

consuming. As the intonation of each of these fingerings is not perfect, Robert Dick indicates whether the note will be slightly sharp or flat, and that the flutist's embouchure would be important so as to improve this. The investigations tried to reduce the amount of change in the embouchure so as to reduce the variables affecting the frequency produced.

From this it can be seen that the Boehm flute would not be suitable for playing microtonal music based on just opening and closing the tone holes. The effect of the angle of the air jet has much more of an effect in small frequency changes.

6.5 Conclusion

This chapter has shown how the Boehm flute behaves to provide a reference basis for comparison of future flute designs. The complete range of the flute could be seen and the changes in the spectrum between the registers.

The effect that removing the key system from the Boehm flute had on the frequencies obtainable could be seen, and consequently it was shown that the Boehm flute could not play microtones with the keys removed. The effect of closing the tone holes at the lower end of the instrument, while the higher tone holes were open, was found to be negligible, reaffirming that the Boehm flute is designed for the one tuning system only.

7 Plunger Flute.

Having investigated the Boehm flute and the methods for analysing the data, the possible designs for microtonal flutes can be investigated. The first of these, the plunger flute is looked at in this chapter.

Firstly the reasons for the design and how it would be expected to behave is discussed. Once the design has been discussed, the data from the design can be analysed. Finally having analysed the data, the design can be reassessed and possible improvements are suggested along with factors that would appear to be unavoidable.

7.1 Principles for the Plunger Flute.

One way a microtonal instrument can be produced is to have an instrument with a continuous frequency range. This does not mean that without a continuous frequency range it is not microtonal. However, a continuous frequency range produces the only way that a true microtonal instrument can exist. This allows any chosen frequency to be played whether or not it is in a specific tuning system based on A being 440Hz.

In an orchestra there is only one non-stringed instrument that is a true microtonal instrument, that is the trombone. The trombone, like the strings, does not use its microtonal abilities in the music it plays. Within the flute family there is the 'Swanee Whistle'[58], a recorder like instrument that is part of the percussion family, which has a plunger that moves up and down to change the length of the bore. Both these instruments have a sliding method to change the bore length.

7.1.1 Acoustics

The acoustics of the plunger flute will be quite different from that of the Boehm flute. As the plunger flute has the plunger blocking the open end, the bore becomes a closed cylinder. This means that the wavelengths and the interval between the fundamental and the first overblown harmonic are similar to the clarinet. The fundamental wavelength produced will be four times the length of the bore making the plunger flute sound an octave lower than the Boehm flute of the same length.

[58][MVT05]

The first overblown register will be a twelfth above the fundamental, the same as for the clarinet, as closed cylindrical bores cannot play the even harmonics.[59] The spectrum of the various notes played on the instrument will have greater similarity to the clarinet than the Boehm flute, as the even harmonics will be missing.

7.2 Design for Plunger Flute

The design of the plunger flute consists of a cylindrical bore, which is fitted on to a flute head joint. Within the cylindrical bore there is a moveable plunger. This plunger should be as air tight as possible so that the air resonating in the bore cannot escape past the plunger.

Due to available cylindrical piping the bore has to be 20mm in diameter, which is 1mm larger than the diameter of the Boehm flute. As a standard head joint is attached to the bore the plunger will only be able to slide up as far as the start of the head joint if its going to be as airtight as is possible. Ideally the cylindrical bore should be the same diameter as the head joint to achieve the highest notes possible in each register. Following Boehm's discoveries the bore should be 19mm to produce the best sound.[60]

The plunger flute can be seen in Figure 7-1. It was designed to be slightly longer than the Boehm flute to allow for the plunger to have some room at the end so as not to get stuck at the longest length. The plunger flute produced had a minimum bore length of 189mm and a plunger that could change the bore length to 579mm, all measured from the centre of the embouchure hole. This can be seen in Figure 7-2.[61]

Figure 7-1 The Plunger Flute

Figure 7-2 Cut through section of the plunger flute bore

As the plunger can move smoothly up and down the instrument, theoretically any frequency within its range can be played, but what is the realistic accuracy of the instrument? As the wavelength is four times the length of the bore, any change in the length is going to have twice the effect compared with the same change in the length would have on an open cylindrical bore.

[59] As can be seen in section 2.3.2

[60] Page 20 in [BOE64]

[61] A fully dimensioned drawing can be found in Appendix F.

7.3 Results

The spectrum of the fundamental frequencies compared to that of the Boehm Flute can be seen in Figure 7-3 and Figure 7-4. It would be expected that there would be no even harmonics however as Figure 7-4 shows, they are there just far weaker than the odd harmonics.

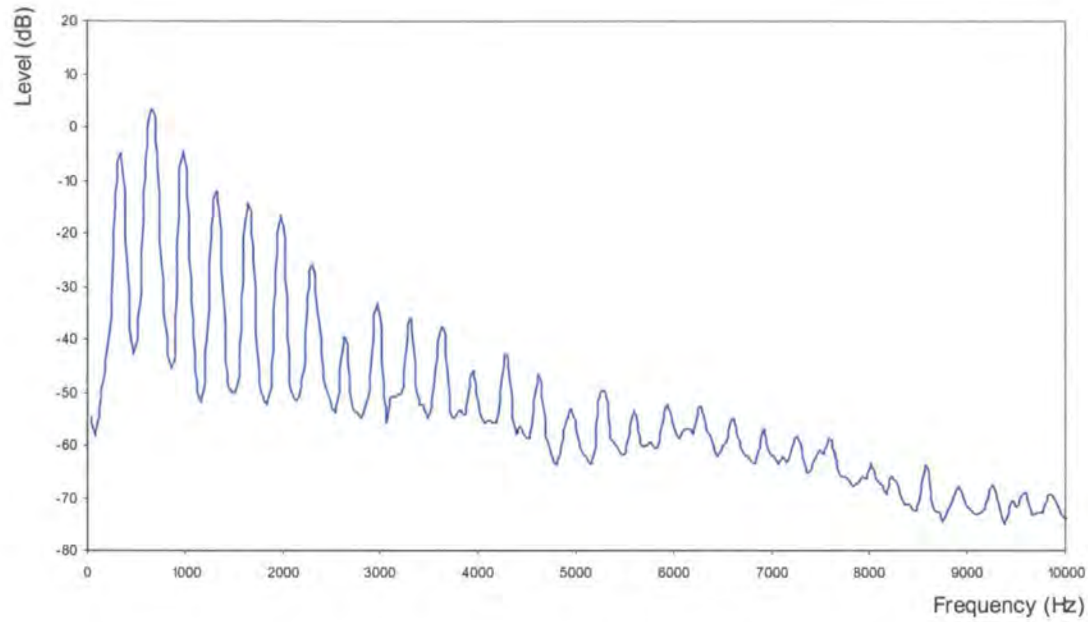


Figure 7-3 Spectrum of E_4 on the Boehm Flute

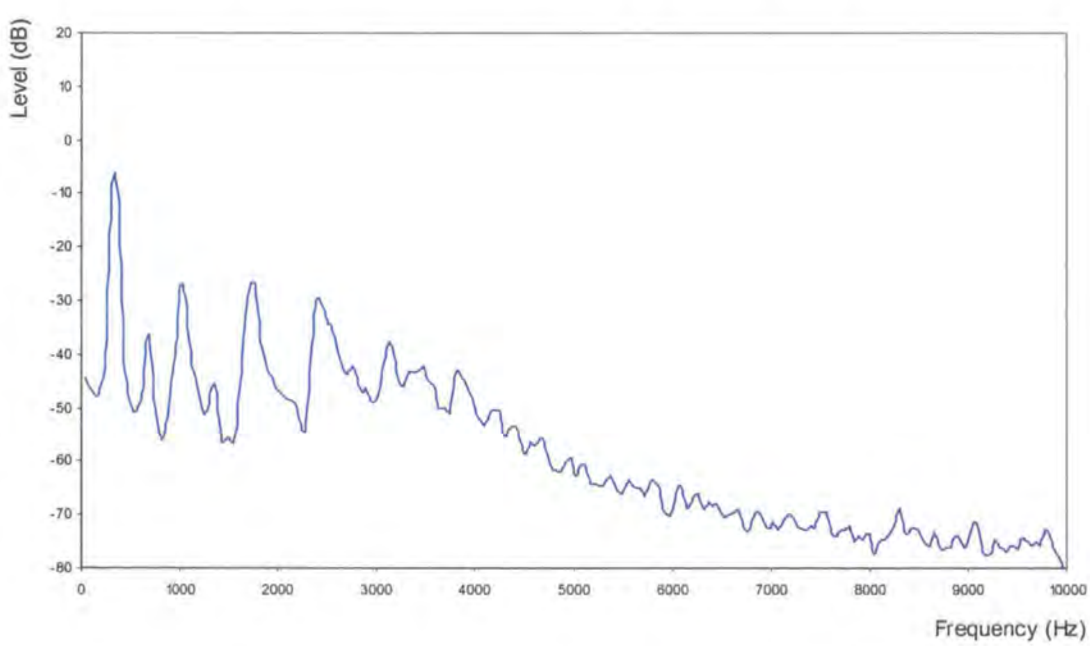


Figure 7-4 Spectrum of E_4 on the plunger flute

When playing the plunger flute the fundamental frequencies can be achieved until the plunger has been pulled out 236mm, making the bore length 425mm. At this point the flute produces the spectrum that can be seen in Figure 7-5. When compared with the spectrum in Figure 7-6 when the plunger has not been pulled out (bore length being 189mm) it can be seen how much weaker the fundamental is, at the longer bore lengths.

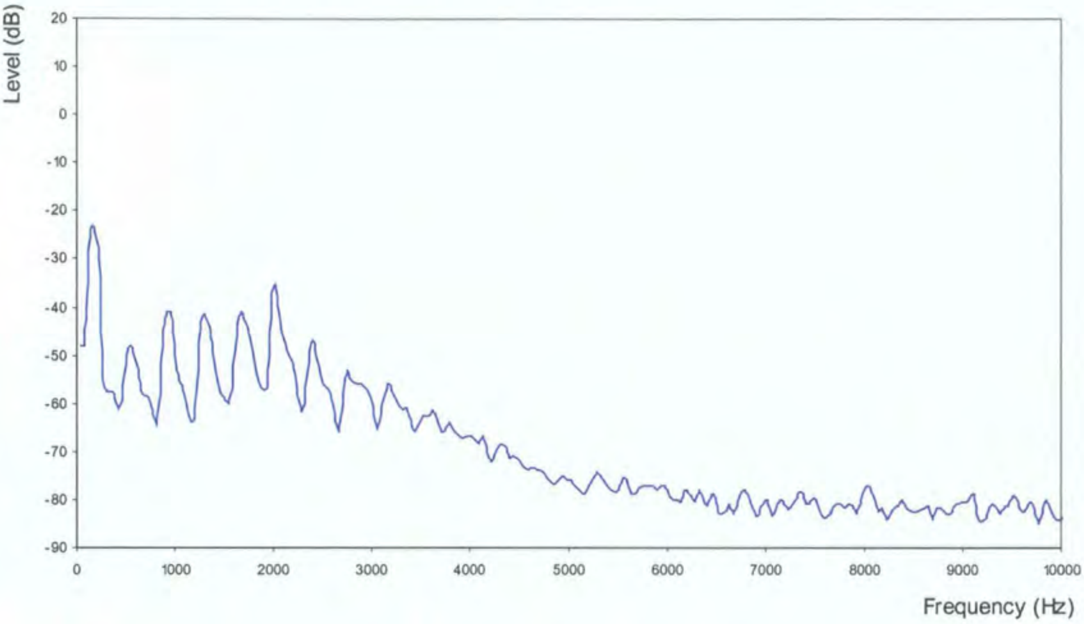


Figure 7-5 Spectrum of plunger flute with a bore length of 425mm

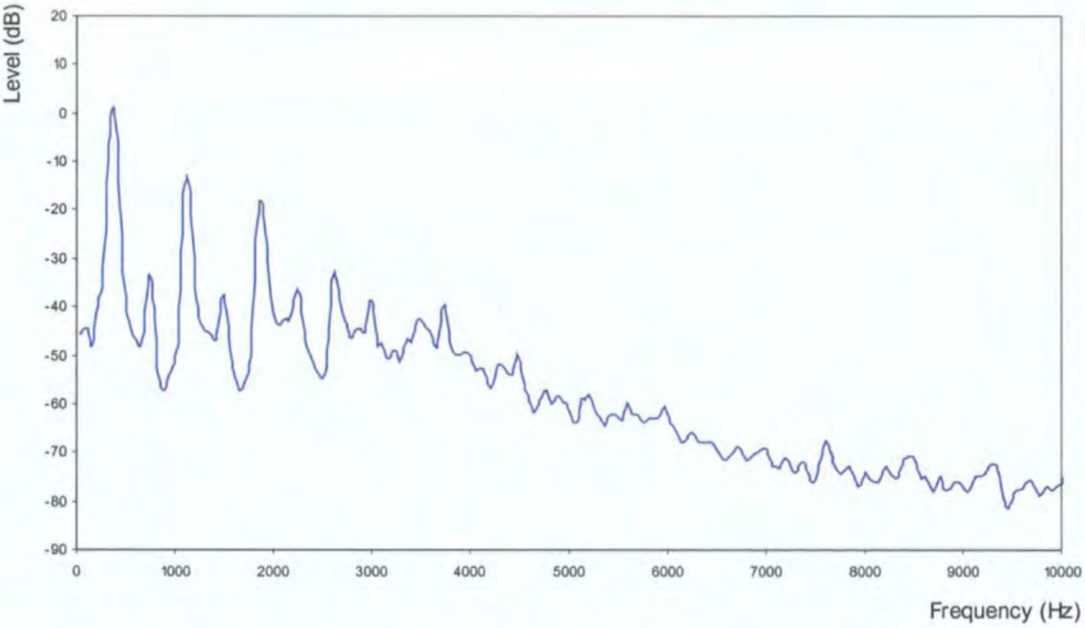


Figure 7-6 Spectrum of plunger flute with a bore length of 189mm

The plunger flute allows the plunger to move out 390mm at its maximum and the total bore length at this point is 579mm. At this length the frequency of the overblown note produced was 415Hz ($G\#_4$): this would therefore be the lowest note in the first overblown register. As the highest note in the fundamental register is 372Hz ($F\#_4$) then the current plunger flute does not play the full range of notes even from the standard 12-ET tuning system.

The length of the instrument at its lowest note needs to be at least three times the length of the instrument at its shortest length. This is to allow all the frequencies within the range to be played. As the lowest note when overblown will produce a note a twelfth above its fundamental the frequency of the highest fundamental must be at least a twelfth above, so that the range is continuous.

The length of the bore when fully out (579mm) is more that three times the length of the bore when the plunger is fully in (189mm) which is when it would be expected that the notes would start to overlap. The only way to combat this problem would be to increase the maximum length. When looking at the results produced by the plunger flute it can be seen that when calculating the predicted frequency, no end effects have been taken into account.[62] By comparing when the predicted frequency approximately matches the actual frequency for the plunger pushed in the approximate end effect can be seen. For the plunger flute this appears to be about 42mm. This does not mean that this is the correct end effect: further calculations and investigations would have to be undertaken to determine the end effect for the plunger flute. As the end effect at the embouchure hole for the Boehm flute is approximately 33mm, depending on the size of the embouchure hole, it would be assumed that the plunger flute's end effects will be similar because only the embouchure hole is there to produce them. Taking the end effect to be 42mm then the length the bore would have to be to play the same note in the overblown register would be 693mm.

7.4 Problems and Solutions

There are various problems associated with the plunger flute's design. They fall into these main areas

- Spectrum and timbre
- Movement of plunger
- Register breaks
- Production of sound

Some problems can be solved by modification of the design but others are inherent in the design such as the spectrum and timbre and where the register breaks fall. A closed cylindrical bored instrument is always going to have the even harmonics missing and going to overblow at the twelfth due to the need for there to be a non atmospheric air pressure at the closed end of the bore for the air to resonate.

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[62] The table of results can be found in Appendix D

7.4.1 Spectrum and Timbre

As the plunger flute's spectrum does not include the even harmonics, the timbre will be different to that of the Boehm flute. This means that the plunger flute could not be used instead of the Boehm flute, when playing a piece if it was required to sound the same. The plunger flute therefore is an instrument in is own right not just a slightly modified flute.

The spectra produced with the Plunger flute can not be classified as either loud or soft as it was attempted to get a strong sound out of the instrument that was relatively loud, however, limitations found with the design, eg the bore diameter did not allow for this and so many frequencies only just sounded. These were not possible to play any louder without overblowing to the next harmonic. Ideally the instruments would be analysed playing at all different volumes for each note so that the full characteristics of the instrument can be understood.

As stated when discussing the acoustics of the plunger flute, the timbre is different to that of the Boehm flute. To produce a true microtonal flute the timbre of the instrument should be as close to that of the Boehm flute as possible. This would allow the instrument to blend into the music as a flute sound when playing microtonal music that cannot be played on the Boehm flute.

7.4.2 Movement of Plunger

As the plunger slides up and down the bore it is not possible to jump between two notes instantaneously. If the music was meant to be played legato there would be a problem, as changing from one note to the next would create a glissando effect. The time it takes to change from one of the higher notes to one of the lower notes could cause a problem, as it would restrict how fast the music could be played.

As the plunger is nearly air tight within the bore there is some friction as the plunger moves. This friction means that it takes time to move the plunger. On the trombone the sliding mechanism lengthens and shortens the bore but as there is one bore inside the other at the sliding point there is not as much friction, allowing easier movement.

The plunger flute in its current state does not allow the flautist to glissando from the bottom note to the top note of the register without stopping. This is due to the length of the plunger when playing the lowest note it is impossible to reach the end of the plunger. An explanation for this is that half way though the glissando there has to be a pause to readjust where the plunger is being held so that it can be pushed all the way in to the bore. Modifying the design so that the end of the plunger can be reached at all lengths would solve this problem, as can be seen in Figure 7-7. The plunger would be lengthened and then fold back on its self.

Figure 7-7 Modified design of plunger flute

7.4.3 Register Breaks

As shown with the acoustics of the plunger flute, it overblows at a twelfth, the same as the clarinet. To play the music as seen in Figure 7-8 would be easy on the Boehm flute as it just requires overblowing to reach the higher note.

Figure 7-8 Music that would require over blowing on the Boehm flute

However, on the plunger flute it could not be changed by over blowing, it would have to be changed by altering the length of the bore to a third of length of the lower note. This would not be so much of a problem if an almost instantaneous change could happen between the two lengths of bore, as with the clarinet, but this is not possible. So, when coupled with the problems found with the movement of the plunger, this creates a more noticeable and unavoidable problem.

7.4.4 Production of Sound

The fundamental frequencies get harder to play as the bore length increases. Once the bore is 241mm or longer it is impossible to play the fundamental to any reasonable volume. One reason for this is that the plunger flute as seen in Figure 7-9 plays fundamental frequencies an octave lower than that of the Boehm flute. Therefore the plunger flute is more like a bass microtonal flute. Boehm found that the optimum diameter bore for the bass flute should be 26mm,[63] therefore it would follow that the plunger flute should have a similar diameter.

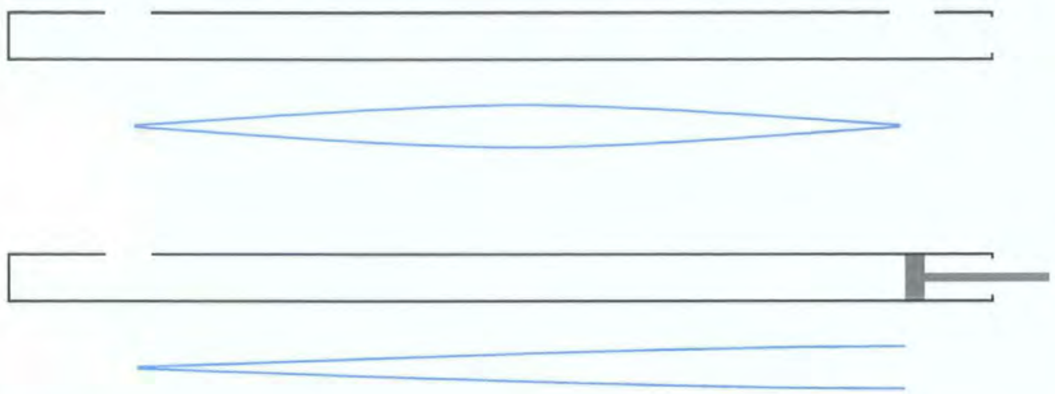

Figure 7-9 The wavelengths produced by the plunger flute in comparison to that produced by the Boehm flute

For the plunger flute to play the same bottom note as the Boehm flute does, the length of the instrument needs to be halved. This would make it the same length as a piccolo, however, the bore diameter would not have to be altered. This can be seen with the fundamental frequencies for when the bore length is 241mm and shorter.

7.5 Conclusion

The plunger flute has been seen to have a continuous frequency range within each octave; however, it has some major faults when it compared to the Boehm Flute. As the spectrums of the various registers are so different to the Boehm flute's and therefore the timbre is different, the instrument cannot really be called a flute.

[63] Page 20 in [BOE64]

8 Sieve Flute.

This chapter investigates two designs for the sieve flute which, unlike the plunger flute, will behave like a flute. The sieve flute's capabilities are discussed and the sieve flute compared to the Boehm flute and its suitability to various tuning systems. Throughout the chapter only quartertones are investigated. However, the option of whether other tunings systems would be suited is mentioned for further investigation.

8.1 The principles of a sieve flute.

The sieve flute would create an instrument that was microtonal but with some restrictions. The instrument would allow a number of different tuning systems to be implemented, so as to give some choice but would not be exhaustive as to the frequencies it will play. The number of frequencies played by the instrument would be determined by the number of tone holes that were in the instrument. The sieve flute would need as many holes as possible to allow a near continuous range of frequencies to be obtained.

8.1.1 The design

The sieve flute design has a number of different factors that would have to be included into the design, to see what effect they have. These are the size of the tone holes, the placing of the tone holes and the number of tone holes. Also, the diameter of the bore will affect the frequency. Ideally this would be the same as for the Boehm flute, however, due to the availability of materials the original design used a bore of 20mm diameter. From having the larger bore diameter, and from Boehm's discoveries during selecting the optimum bore diameter, it can be deduced that the sieve flute will be harder to play than the Boehm flute. Also the lower register would sound much better, and the higher registers would be harder to sound and especially to try to play *piano*.

The sieve flute is designed to have a cylindrical bore with tone holes of equal size placed every 20mm opposite to each other. Two different sieve flutes, see Figure 8-1 and Figure 8-2, were produced, one with tone holes of 14mm diameter and the other with tone holes of 10mm diameter. For this sieve flute the tone holes were placed at perpendicular points on the bore, (see Figure 8-3 and Figure 8-4 for the exact positions of the holes on each instrument).[64] With the tone holes of 14mm diameter displaced by 10mm from the next hole on the opposite side and with the 10mm diameter holes displaced by 5mm from the next set of holes thus creating a type of spiral effect.

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[64] Fully dimenisioned drawings can be found in Appendix F

Figure 8-1 14mm sieve flute

Figure 8-2 10mm sieve flute

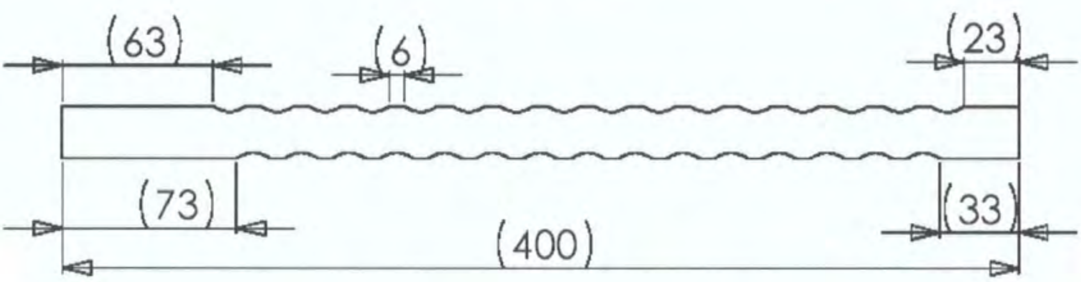

Figure 8-3 Dimensions of 14mm sieve flute

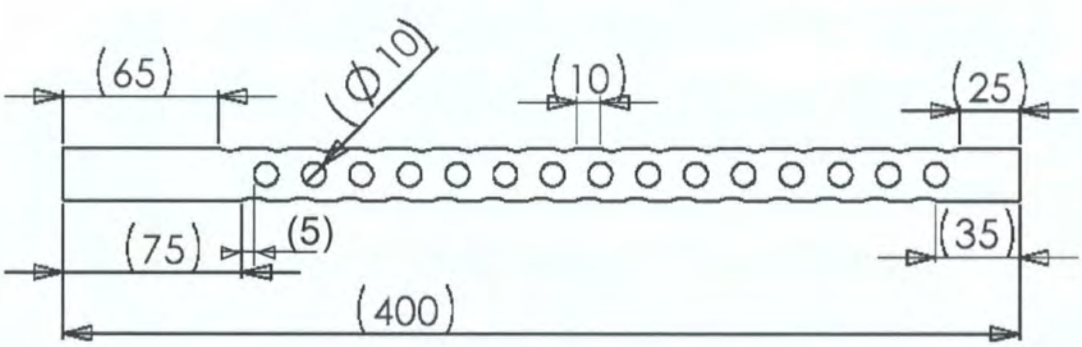

Figure 8-4 Dimensions of 10mm sieve flute

One question that needs to be answered is the effect the size of the tone holes has on the frequency produced. From looking at the Boehm flute it can be seen that the tone holes are much larger at the foot joint than they are at the other end of the instrument. By using the two different flutes the effect of the hole size can be identified, however, it will not identify whether or not the size of the holes needs change throughout the length of the bore. Only the difference between the two extremes of hole size will be seen. When calculating the location of tone holes in simple flutes Mark Shepard stated the larger the hole, the higher the frequency of the note will be.[65] Therefore, it would be expected that for a hole on the sieve flute with the 20mm diameter tone holes, the frequency would be higher than with the sieve flute with 10mm diameter tone holes in exactly the same positions on the bore.

In theory the more tone holes that there are in a flute bore then the greater number of frequencies that can be played. Whether or not the holes can be equally spaced for the instrument to play the various notes in tune is a different matter. As seen with the Boehm flute, the tone-holes are not equally spaced, so it would follow that with any instrument they would not be equally spaced. However, with a sieve flute, the greater the number of holes and the smaller they are, then the more equally spaced they can be, and still have as many frequencies in-tune. The Boehm flute has 16 tone holes and register holes, which in various combinations allow all notes in the 12-ET scale to be played. Therefore, in theory this would suggest that, the larger the number of holes in a given length, then the greater the number of pitches that can be played.

The first step in deciding whether an instrument design could be expanded to allow any microtone to be played is to see whether the notes of the 12-ET tuning system can be played. As quartertones are half way between semitones it seemed the logical next step, as all the semitone frequencies would be included. If an instrument cannot play quartertones accurately then it would not be able to play microtones, that are smaller than a quartertone or ones that are between quartertones and semitones, as they would require different placing of the tone holes. The number of cents between the different notes of the tuning system would vary greatly between the different systems.

The following Table 8-1 compares three tuning systems 12-ET, 19-ET and 24-ET, and shows how the frequencies of 19-ET do not match those of 24-ET at any point in the scale, except the octave, when using A_4 as 440Hz.

[65] [SHE02]

12	19	24
220	220	220
		226
	228	
233		233
	237	
		240
	245	
247		247
		254
	255	
262		262
	264	
		269
	274	

12	19	24
277		277
	284	
		285
294		294
	295	
		302
	306	
311		311
	317	
		320
	329	
330		330
		339
	341	

12	19	24
349		349
	354	
		359
	367	
370		370
	380	
		381
392		392
	394	
		403
	409	
415		415
	424	
		427
440	440	440

Table 8-1 Comparisons of 12-ET, 19-ET and 24-ET

In Table 8-2 these same tuning systems are shown in cents, this enables any octave to be calculated independent of what frequency note it is starting on.

12	19	24
0	0	0
		50
	63.16	
100		100
	126.32	
		150
	189.47	
200		200
		250
	252.63	
300		300
	315.79	
		350
	378.95	

12	19	24
400		400
	442.11	
		450
500		500
	505.26	
		550
	568.42	
600		600
	631.58	
		650
	694.74	
700		700
		750
	757.89	

12	19	24
800		800
	821.05	
		850
	884.21	
900		900
	947.37	
		950
1000		1000
	1010.53	
		1050
	1073.68	
1100		1100
	1136.84	
		1150
1200	1200	1200

Table 8-2 Comparison of the tunings systems using cents

This shows that an instrument designed to play in any one specific tuning system is not easily able to play another tuning system, there are exceptions such as an instrument designed to play in 24-ET (quarter-tones) can also play in 12-ET. If many of the intervals measured in the number of cents away from the first note of the octave are the same as in other tuning systems, then the instrument would be able to play in another tuning system. To calculate whether there are any repeats of the frequencies in the other tuning systems required, the number needs to be divisible by the same integer. If the tuning system's number is a prime number then the only time there will be repeats of the frequency are when the other tuning system's numbers required are multiples of the prime number. 19-ET is an example of this case and so the next time that there will be frequencies the same in another tuning system will be 38-ET.

To be able to cover the holes, some other method needs to be found, as there are too many holes to be covered with eight fingers and two thumbs. For the means of experimentation the holes can be covered with tape to seal them. The tape ensures that there is an airtight covering and that the covering is not encroaching on the bore size in any way. The instrument does not have chimneys at each tone hole like the Boehm flute does, and so a flat covering over a tone hole would make the bore non-cylindrical, see Figure 8-5. The tape stays in position and if therefore accidentally knocked does not change shape. It stayed where it was put until a concerted effort was made to remove it.

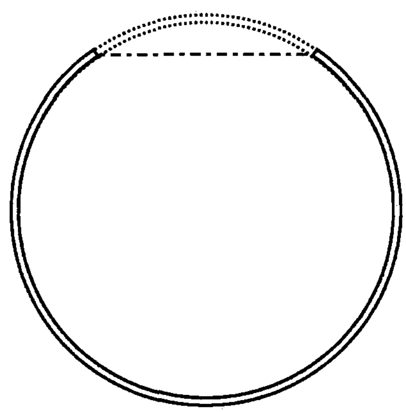

Figure 8-5 cylindrical bore without chimneys becoming non-cylindrical

8.1.1.1 14mm Diameter Holed Sieve Flute

As the sieve flute with 14mm diameter holes has a total of 31 holes along its length, by just opening the holes from the lower end up towards the head joint there should be 32 different frequencies. Theories would suggest that if sixteen of the tone holes were in the same positions as the tone holes on the Boehm flute, then the frequencies should be the same. If the other fifteen tone holes were in between the sixteen tone holes, then it would suggest that the number of possible pitches obtainable would increase. It would be hoped that if the extra fifteen tone holes were in the correct placing on the bore then quartertones would be achievable. The tone holes on the 14mm diameter holed sieve flute are equally spaced along the length, so it would be surprising if it was able to play quartertones in tune. However, it should still be possible to see the effect of the extra 15 tone holes.

Limiting the number of hole combinations to where there are no holes closed below any of the open tone holes means that there are a total of 32 different combinations. If all hole combinations were to be used there would be a total of 2^{31} combinations (2,147,483,648 combinations).

8.1.1.2 10mm Diameter Holed Sieve Flute

The sieve flute with 10mm diameter tone holes has a total of 62 holes, and following the same method as with the 14mm diameter holed sieve flute, there should be 63 different obtainable frequencies. The 10mm holed sieve flute should be able to play eighth tones if the holes were positioned correctly. With the 62 holes equally spaced there is more chance that the quartertones will be in tune than with the 14mm diameter holed sieve flute. The flute may be playing frequencies that can be associated with another tuning system. Just because the instrument may not play quartertones from 12-ET it does not exclude it from playing notes in other tuning systems.

As with the 14mm diameter holed sieve flute, only the hole combinations where there are no holes closed below an open ones were used. This limits the number of combinations to 63 rather than the total possible to 2^{62} (4,611,686,018,427,387,904 combinations).

8.1.2 Physically playing the instrument

As the sieve flute has many tone holes it is not possible to cover the holes with the number of fingers available. Therefore, some other method of opening and closing the tone holes needs to be found. Using some sort of logic where the eight fingers can be in any combination of open or closed then there are 256 possible combinations, if one of the thumbs is included this increases to 512. Whether the thumb is needed or not depends on the total number of holes required by the spacing to achieve the full range of notes wanted.

As the tone holes are only opened from the one end of the instrument then it would be possible to have some sort of sleeve that slid up and down the instrument but as with the plunger flute this would create problems when wanting to jump from a low note to a high note without tonguing in between.

The other option would be to have many little devices over the tone holes to open and close them when necessary: this would allow large numbers of holes to open at the same time making the transition between notes flawless. To allow this to happen there would have to be some control software with the suitable logic, which at the same time would be suitable to play. As it would mean the musician learning a whole new set of fingering patterns then the fingering system would have to be relatively logical for the musician to play.

8.2 The results in depth from the Sieve Flute

As with the Plunger flute due to the limitations with the design such as the bore diameter the notes played on the sieve flute did not necessarily have the flexibility to be played at different volumes. This problem is something that could be reduced by changing the bore diameter to the same as a Boehm Flute. Both the sieve flutes would overblow many times until highest overblown note reached approx 1850Hz when that harmonic would then no longer sound. This means that the shorter the bore the fewer overblown notes are achieved. Although the instrument can be overblown many times, it only needs to be overblown once, to increase the range by an octave and then a second time to increase the range by another two tones. Figure

8-6 and Figure 8-7 show the frequencies obtained for the sieve flutes and how the higher frequencies are repeated.

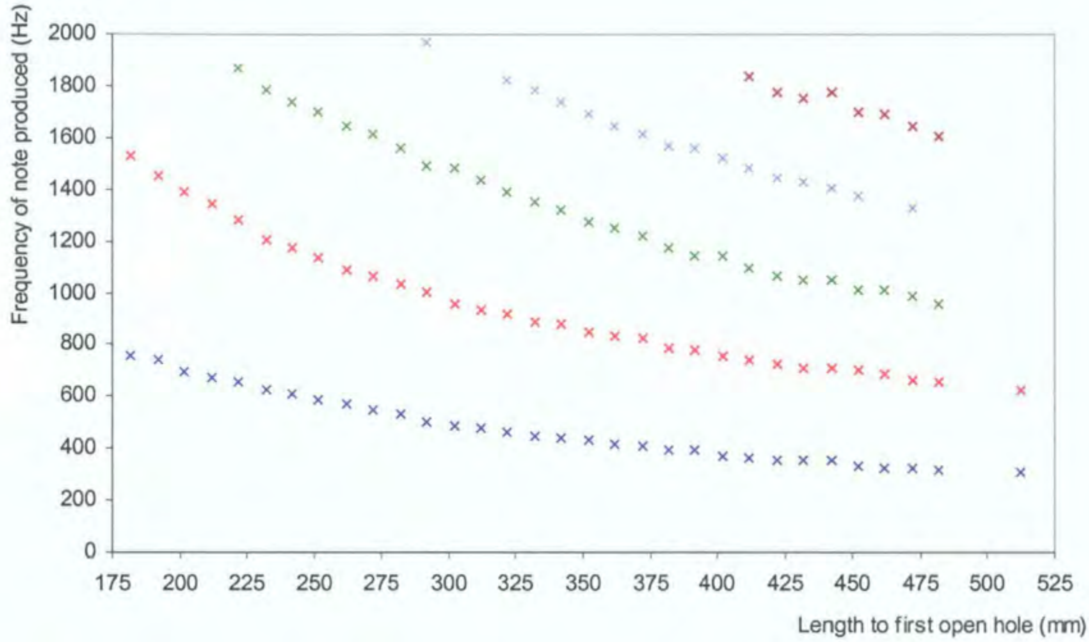

Figure 8-6 Frequencies produced at different lengths on the 14mm sieve flute

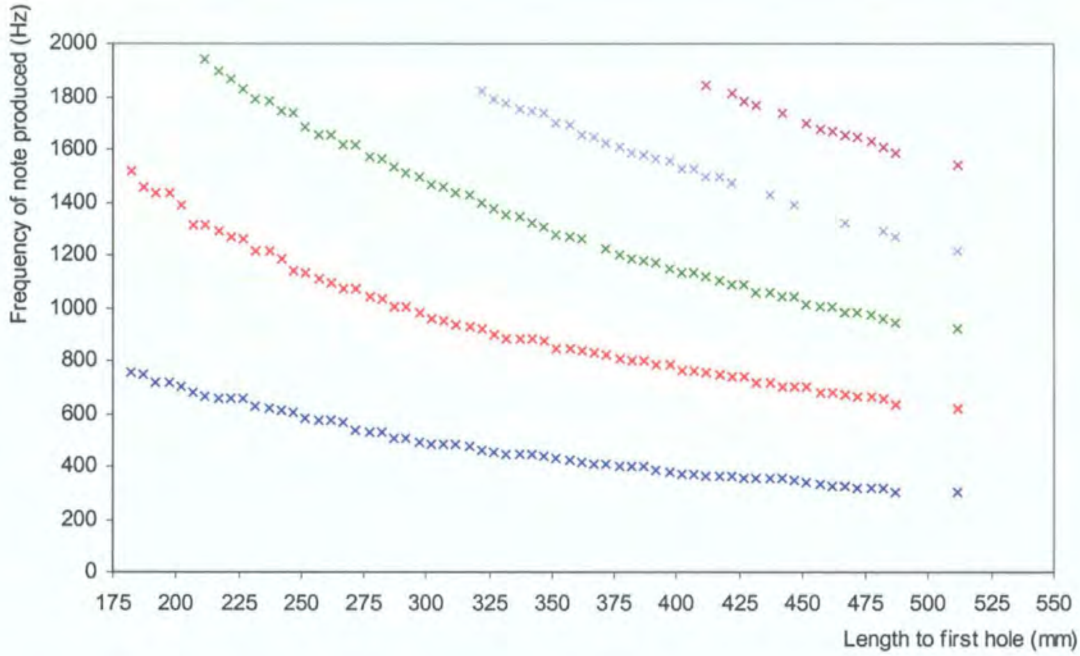

Figure 8-7 Frequencies produced at different lengths on the 10mm sieve flute

The fundamental frequencies produced by both the 14mm sieve flute and the 10mm sieve flute when the tone-holes on it were opened in turn can be seen in Table 8-3[66].

[66] The complete set of data can be found in Appendix E

Length of Bore in millimetres	Fundamental Frequencies 10mm Sieve Flute	14mm Sieve Flute
512	299	310
487	305	
482	317	314
477	320	
472	320	323
467	323	
462	326	328
457	331	
452	339	334
447	345	
442	353	353
437	355	
432	355	355
427	357	
422	360	356
417	365	
412	366	366
407	370	
402	371	374
397	379	
392	383	392
387	398	
382	398	396
377	402	
372	406	409
367	405	
362	413	415
357	421	
352	433	435
347	441	
342	444	444
337	447	
332	446	450
327	452	
322	460	460
317	477	
312	484	478
307	484	
302	486	486
297	489	
292	502	499
287	505	
282	528	535
277	532	
272	539	549
267	565	
262	570	572
257	573	
252	581	586
247	604	
242	615	613
237	618	
232	627	622
227	654	
222	656	657
217	659	
212	661	671
207	677	
202	700	698
197	714	
192	715	743
187	744	
182	753	575

Table 8-3 The Fundamental Frequencies of the two sieve flutes

As the sieve flute is the same basic structure as the Boehm flute, i.e. open ended cylindrical bore of a similar diameter then the spectrum of the notes should be the same, as the aim was to keep the timbre of the flute. If the timbre of the instrument was different to the timbre of the flute then it would stop sounding like a flute and consequently no comparisons between the instrument and a flute would be reasonable. Figure 8-8, Figure 8-9 and Figure 8-10 show the spectrum of the fundamental frequency on the Boehm flute and the two sieve flutes. The fundamental peak is as strong on the sieve flute as the Boehm flute but the harmonics are far weaker. One of the reasons for this may be the larger diameter bore, however, this could only be confirmed with a sieve flute made with a 19mm diameter bore.

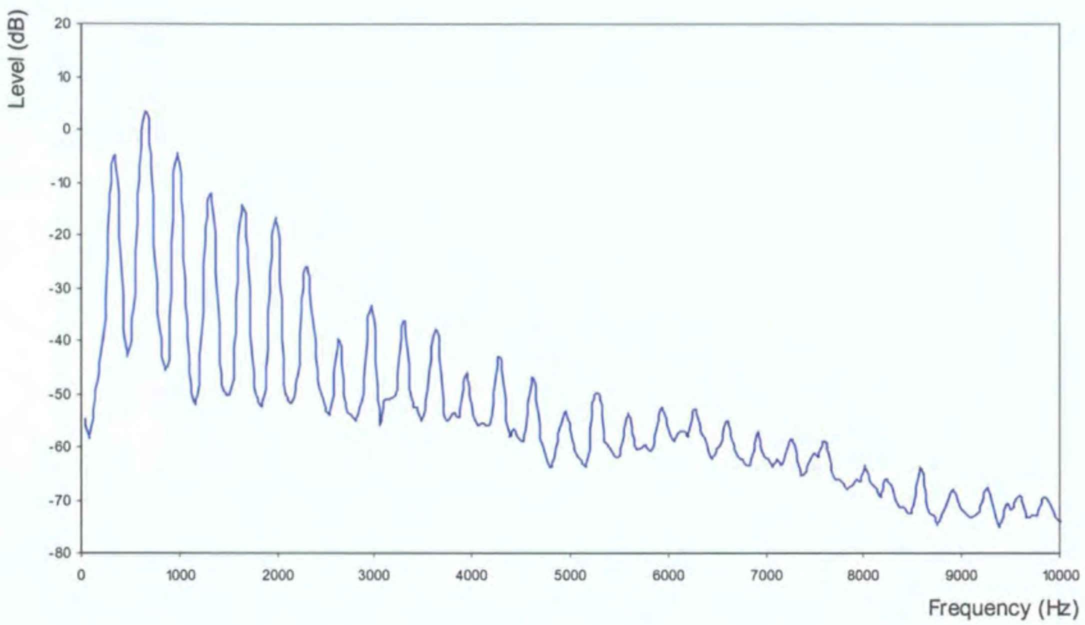

Figure 8-8 Spectrum of E_4 on the Boehm flute

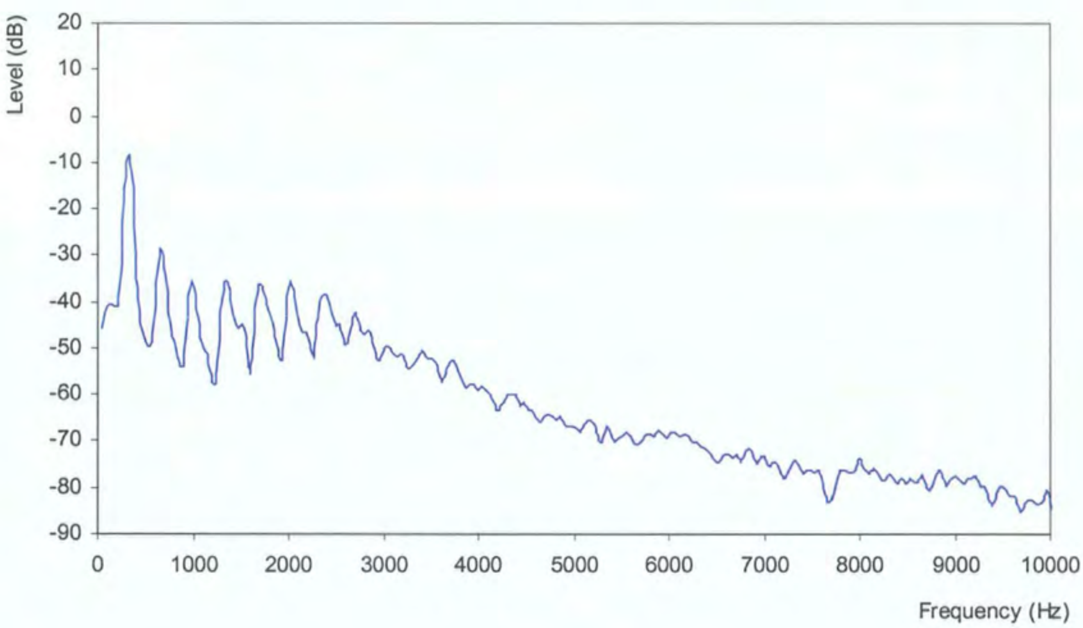

Figure 8-9 Spectrum of E_4 on the 14mm sieve flute

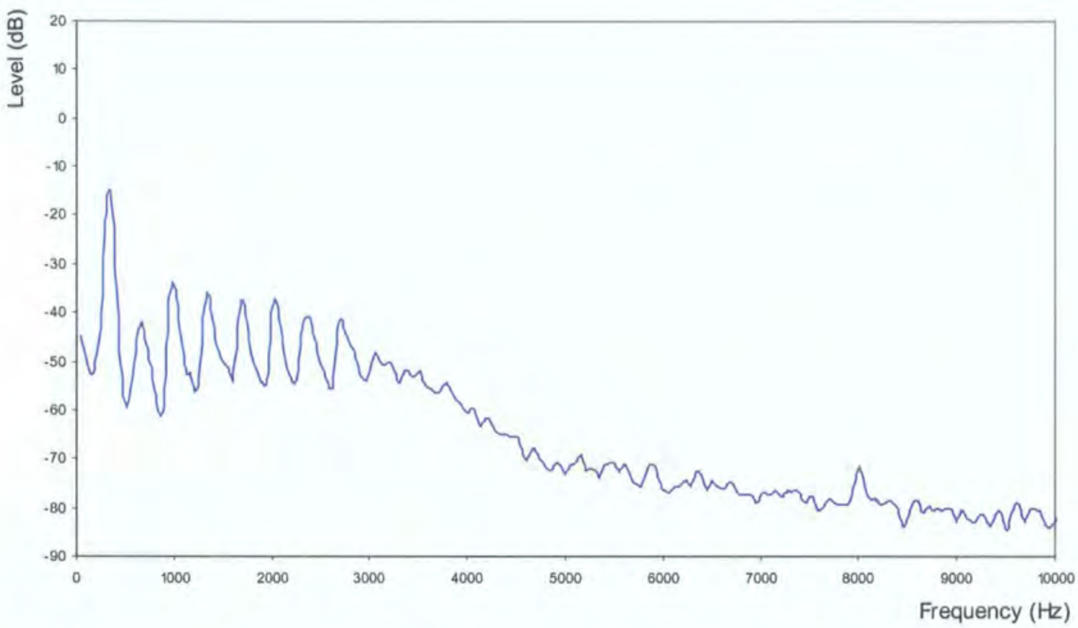

Figure 8-10 Spectrum of E_4 on the 10mm sieve flute

8.2.1 14mm Sieve Flute

With 32 different combinations for the holes to be open, it would be anticipated that there would be 32 different pitches, and so to check whether this is the case, frequencies obtained were compared to the actual frequencies in the western 12-ET scale and with the 24-ET scale where A_4 is 440Hz. It would be anticipated that as there are 24 different frequencies in the 24-ET scale and 31 holes throughout the length of the instrument then all the quartertones would be able to be played.

It was found that although there were more tone holes than the Boehm flute, the 14mm sieve flute's frequencies did not match up to the frequencies from the 12-ET. The tone holes were the same size as the largest tone holes on the Boehm flute and so a smaller tone hole size may be more suited throughout the length of the bore.

8.2.2 10mm Sieve Flute

When analysing the frequencies produced by the 10mm sieve flute, firstly the frequencies produced were categorized into which quartertone band they would be in for when A_4 is 440Hz. This means that every frequency was in one band or another as it was not looking at how in-tune with the quartertone it was, rather whether there where enough different frequencies to play approximately the nearer quartertone. This produced results where there where only three 'missing' quartertones in the whole of the 2 ½ octaves range.

However, once this had been completed then the frequencies had to be analysed into how in-tune they were, this was checked in a number of different ways. When seeing how in-tune an instrument is, the value is measured in cents so the tolerance value needs to be set for testing how in-tune the sieve flute is. The amount of cents that the sieve flute is out of tune by is 21.6 cents for F½#$_4$. This is a considerable amount and therefore a reasonable tolerance value needs to be decided upon. When playing any traditional wind instrument with other instruments the musician will try to get their instrument in-tune by one or two cents.

8.2.2.1 2-cent Tolerance

Only the first register was looked at, this is because if it is not in-tune then the overblown registers will not be in-tune either. When using A_4 as 440Hz only eight different quartertones were actually in the tolerance range and if it was changed to using A_4 as 444Hz only six were in the tolerance range. Standard western tuning uses A_4 as 440Hz today, but other areas of the world use different tunings for A and in the past different frequencies have been used for A, such as in the time of Boehm when A_4 was 435Hz[67]. So by seeing if there was a greater accuracy with A_4 as 444Hz demonstrates whether the instrument is actually just playing in a different tuning or not. In the case of this sieve flute the accuracy of the instrument has not improved with a different A, in fact it has decreased.[68]

8.2.2.2 Higher Tolerances

If the tolerance is increased to three cents then with A_4 as 440Hz the number of quartertones within the tolerances becomes 9 and with four cents becomes 13 quartertones. Figure 8-11 shows how many cents out of tune the frequencies are from the quartertone of the band that they are in.

[67] Page 40 in [BOE64]

[68] The tables of data for these can be found in Appendix E

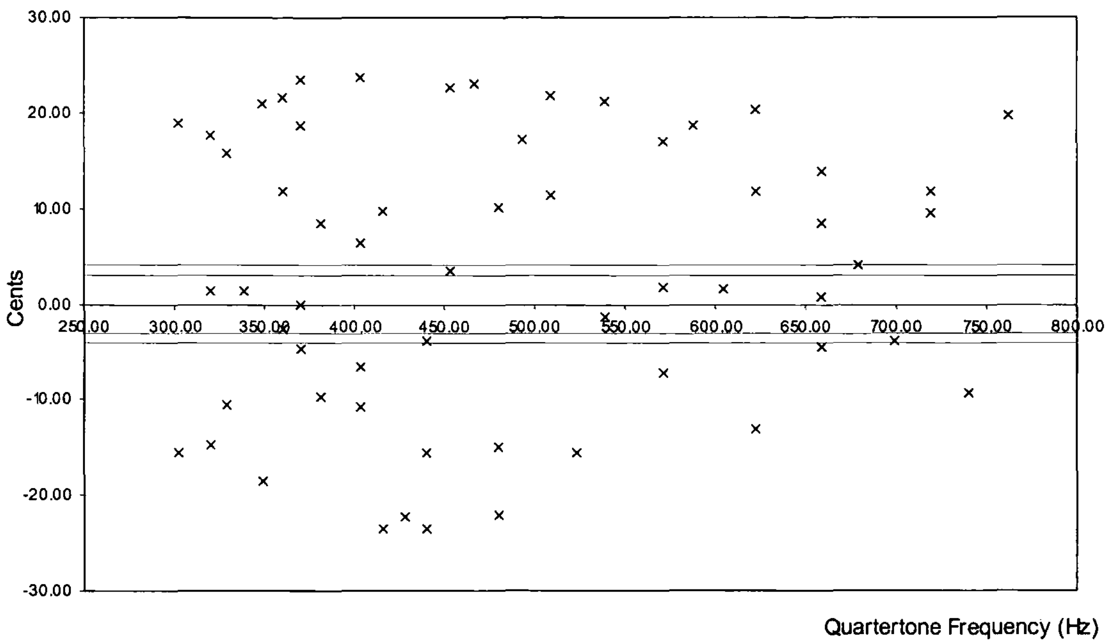

Figure 8-11 Difference in Cents between the actual frequencies and the quartertones with 3-cent and 4-cents bands

From this it can be said that the instrument with the 62 holes at a diameter of 10mm, would be able to play in tune if more experimentation was carried out into the placing of the holes. As the variation of cents from the required frequency is high, the positioning of the holes is incorrect.

Comparing the results with the frequencies of the quartertones only shows how much they are out of tune. There is no allowance for if the tuning system does not include the frequency 440Hz as a pitch. It does not show whether the instrument itself behaves as it is expected. To do this the frequencies produced need to be compared to the theoretical frequencies for the desired length. From the results in Figure 8-12 it can be seen that the experimental frequencies appear to be very close to the theoretical values, but how accurate are the experimental frequencies?

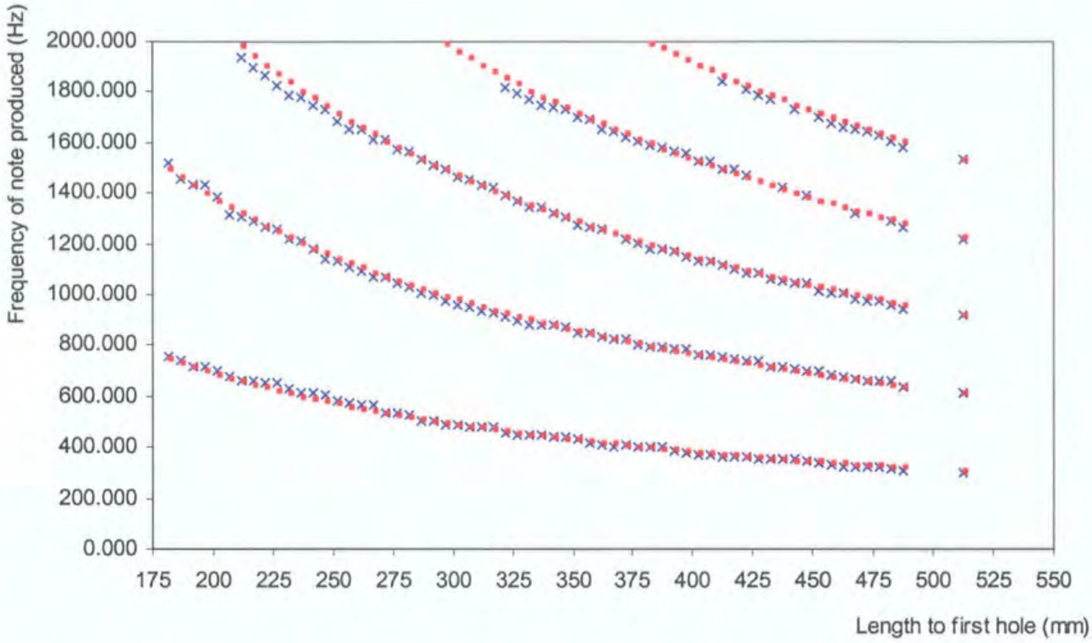

Figure 8-12 Comparison of the theoretical frequencies and the actual frequencies obtained with the 10mm sieve flute

Figure 8-13 shows the same results, however, with added 2% error bars. The error bars show that the frequencies are not as close to the theoretical values as would be presumed from Figure 8-12. The higher frequencies produced all appear within the 2% error, however, the lower frequencies have a large proportion out of the range. The error bars appear to show that the higher frequencies are always in tune. This can only be confirmed by looking at the difference in cents between the experimental frequencies and the theoretical frequencies.

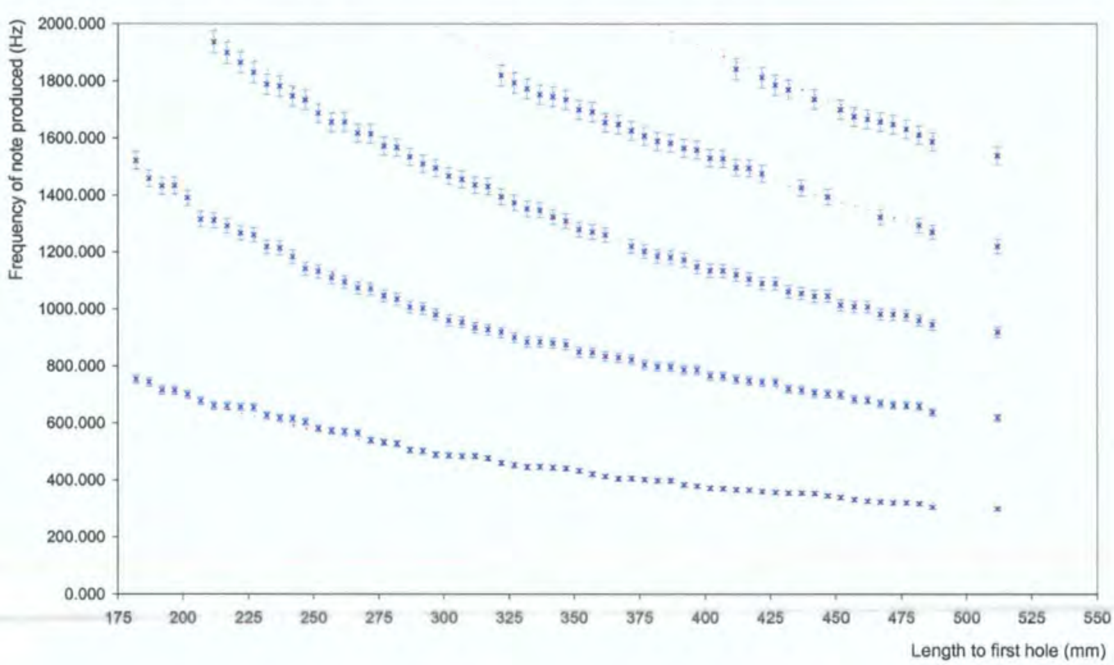

Figure 8-13 Comparison between the theoretical and actual frequencies including 2% error bars for the 10mm sieve flute

Figure 8-14, Figure 8-15, Figure 8-16, Figure 8-17 and Figure 8-18 are graphs of the number of cents versus the length of the bore for the fundamental and each of the overblown registers. As can been seen by the band of 5 cents either side of the theoretical frequency there are only a few of the frequencies that fall within the band. When the average of the number of cents in each register is calculated it can be seen that for the fundamental register and the first overblown register then they both have an average of –15 cents.

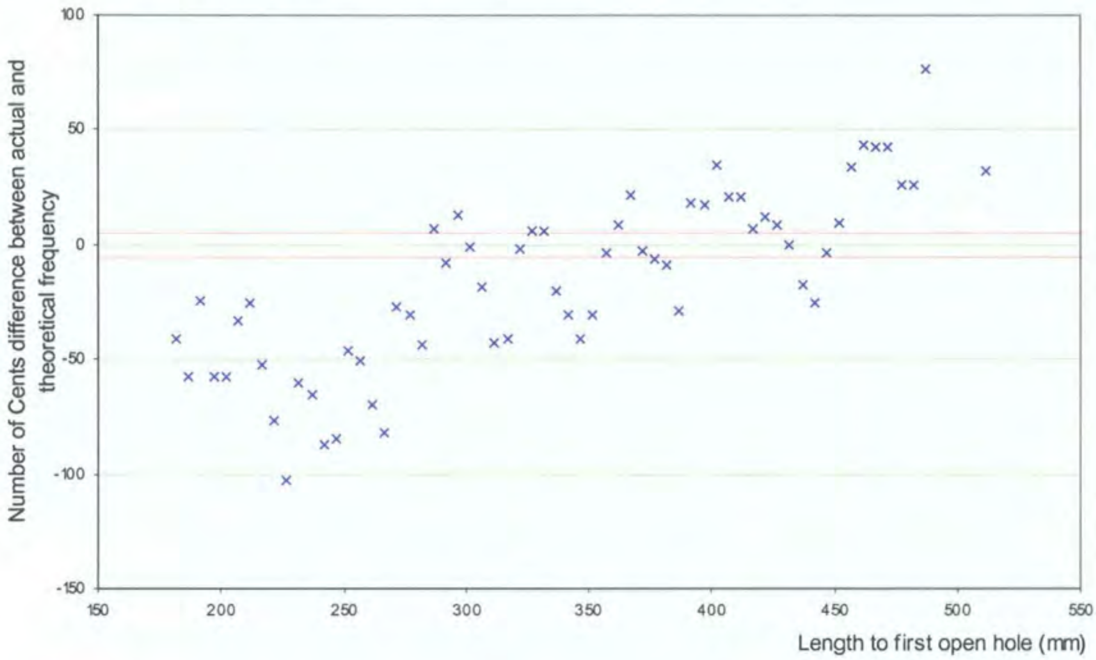

Figure 8-14 Comparison of the number of cents away from the theoretical frequencies for the fundamental frequencies

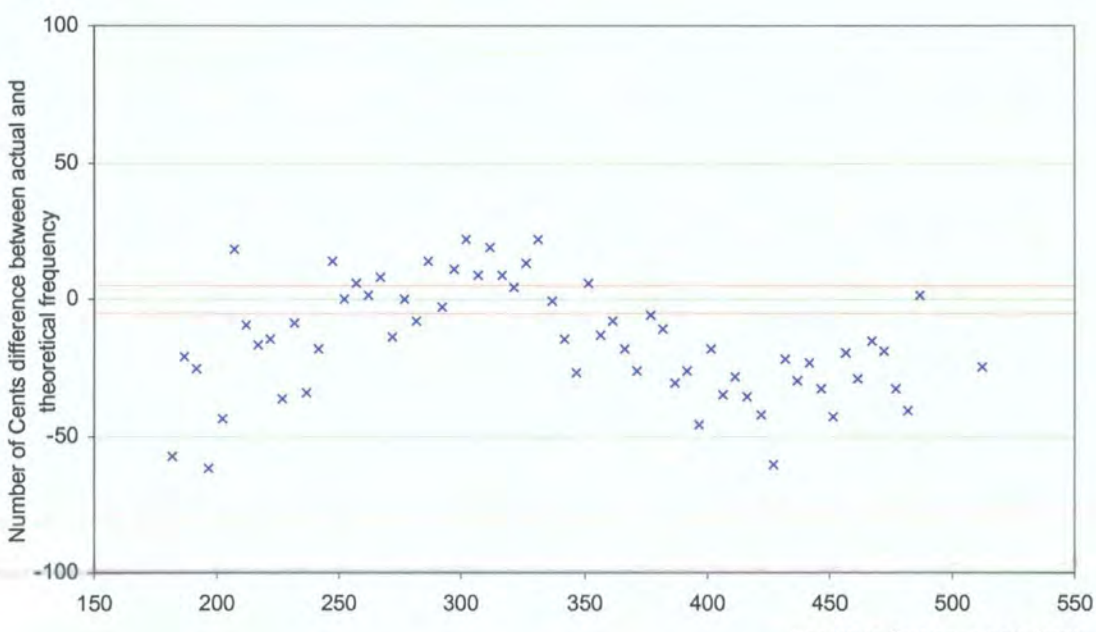

Figure 8-15 Comparison of the number of cents away from the theoretical frequencies for the 1st overblown frequencies

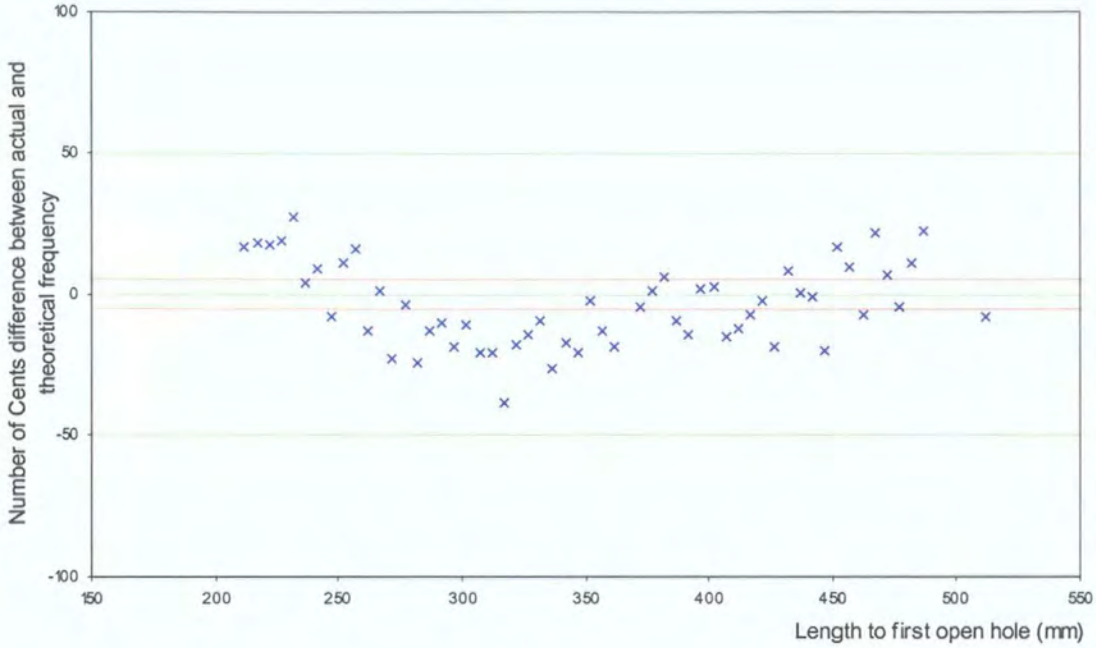

Figure 8-16 Comparison of the number of cents away from the theoretical frequencies for the 2nd Overblown frequencies

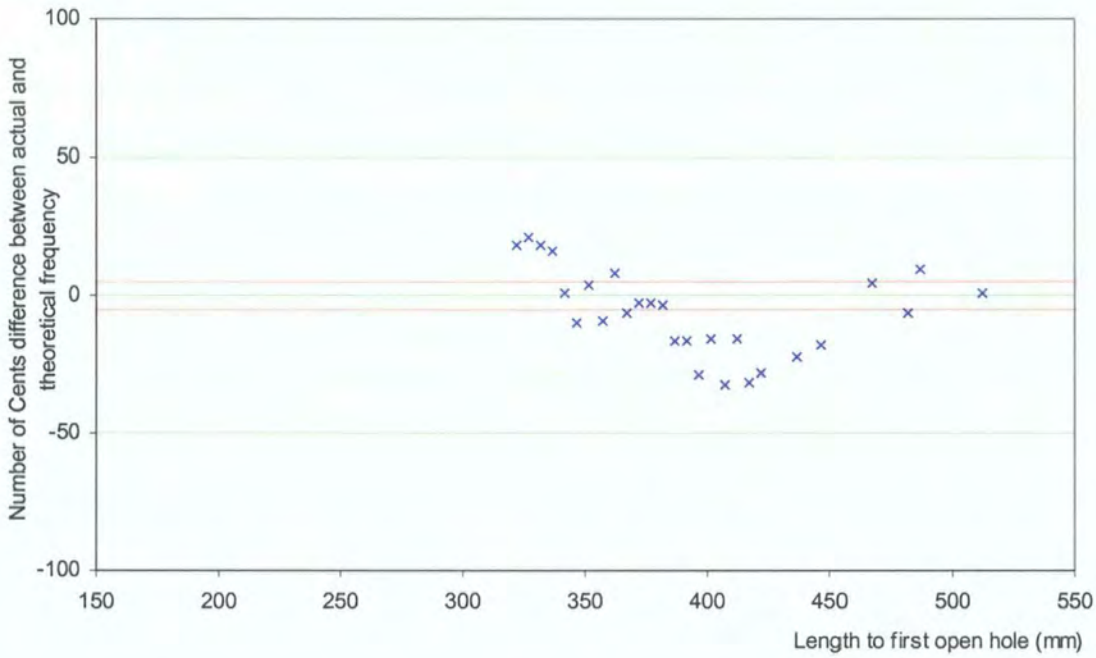

Figure 8-17 Comparison of the number of cents away from the theoretical frequencies for the 3rd Overblown frequencies

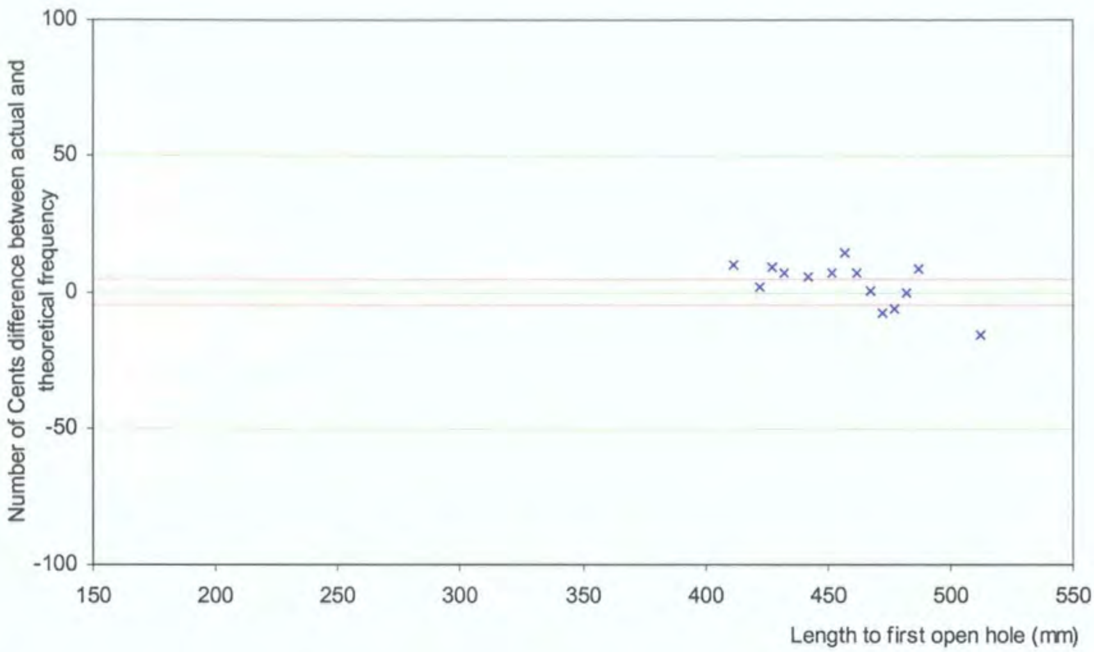

Figure 8-18 Comparison of the number of cents away from the theoretical frequencies for the 4th Overblown frequencies

Having an average of –15 cents would suggest that the end effect used in the theoretical formula is incorrect and should be less. If the end effect is reduced to 48mm then the average of the number of cents is +1.38 cents therefore, suggesting that the formula may be more accurate.[69]

However, the graphs show a different pattern where there are fewer frequencies that fall within the 5-cent band, these can be seen in Figure 8-19, Figure 8-20, Figure 8-21, Figure 8-22 and Figure 8-23. The general trend in the graph showing the values from the fundamental frequencies is that there is a lower experimental frequency than the theoretical frequency when the instrument's bore is shorter and a higher experimental frequency than the theoretical frequency at longer bore lengths.

[69] The data can be found in Appendix E

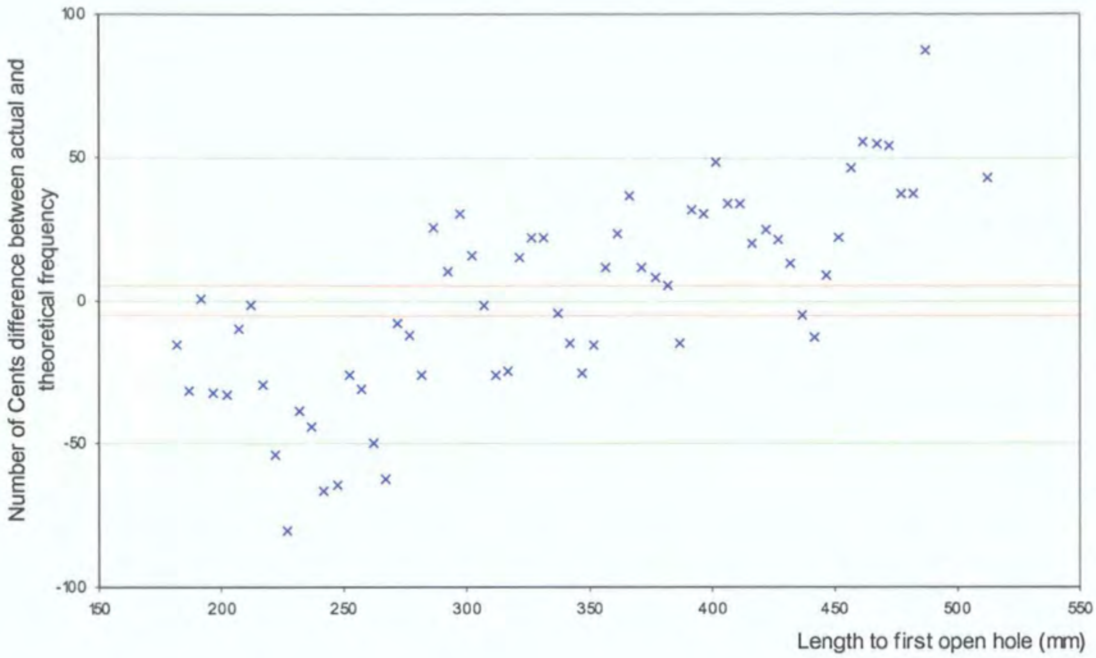

Figure 8-19 Comparison of the number of cents away from the theoretical frequencies for the fundamental frequencies with modified end effect

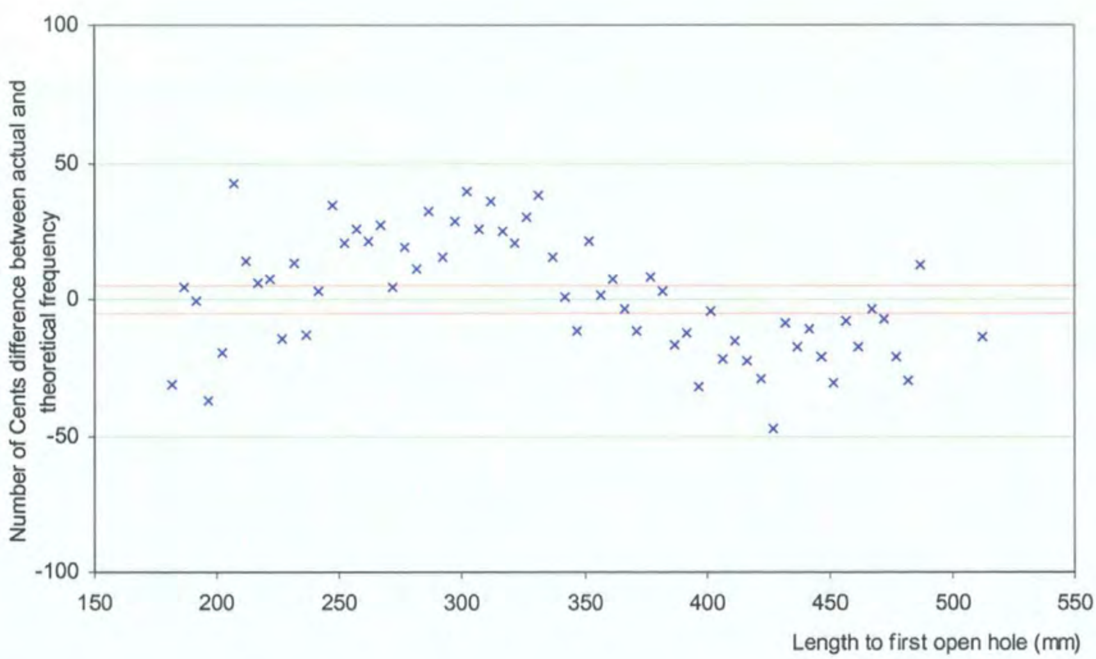

Figure 8-20 Comparison of the number of cents away from the theoretical frequencies for the 1st Overblown frequencies with modified end effect

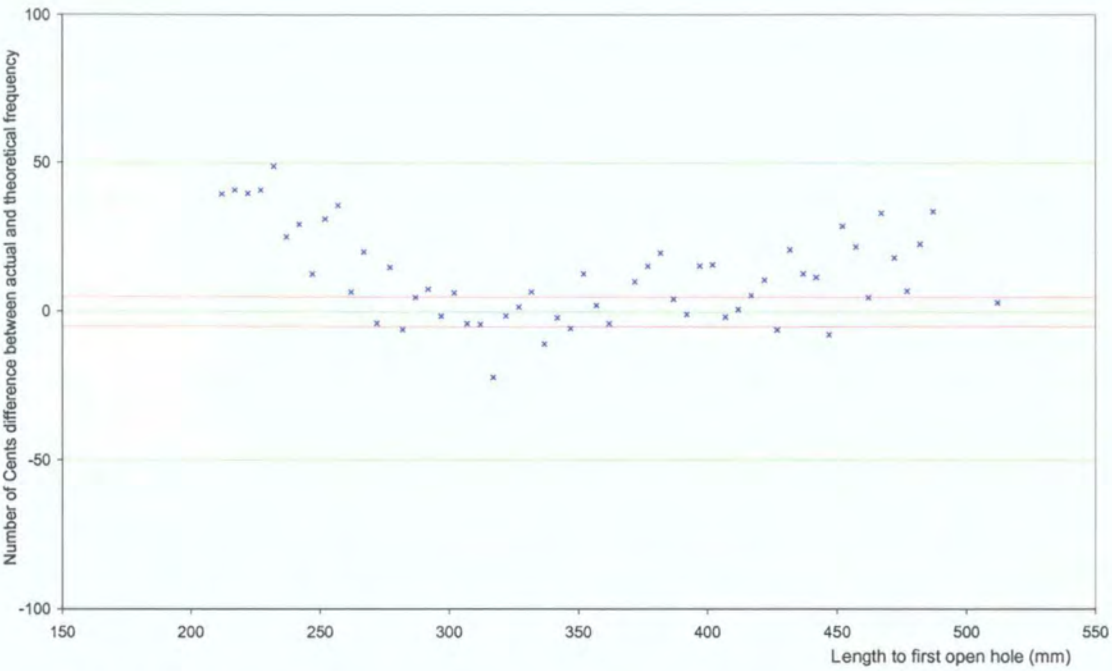

Figure 8-21 Comparison of the number of cents away from the theoretical frequencies for the 2nd Overblown frequencies with modified end effect

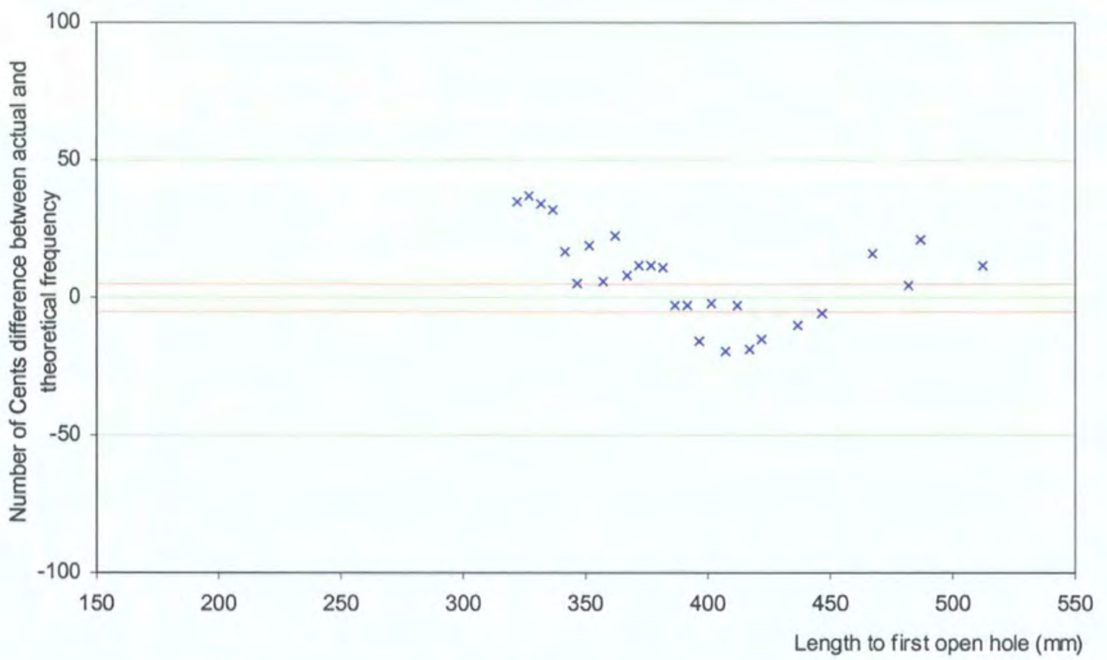

Figure 8-22 Comparison of the number of cents away from the theoretical frequencies for the 3rd Overblown frequencies with modified end effect

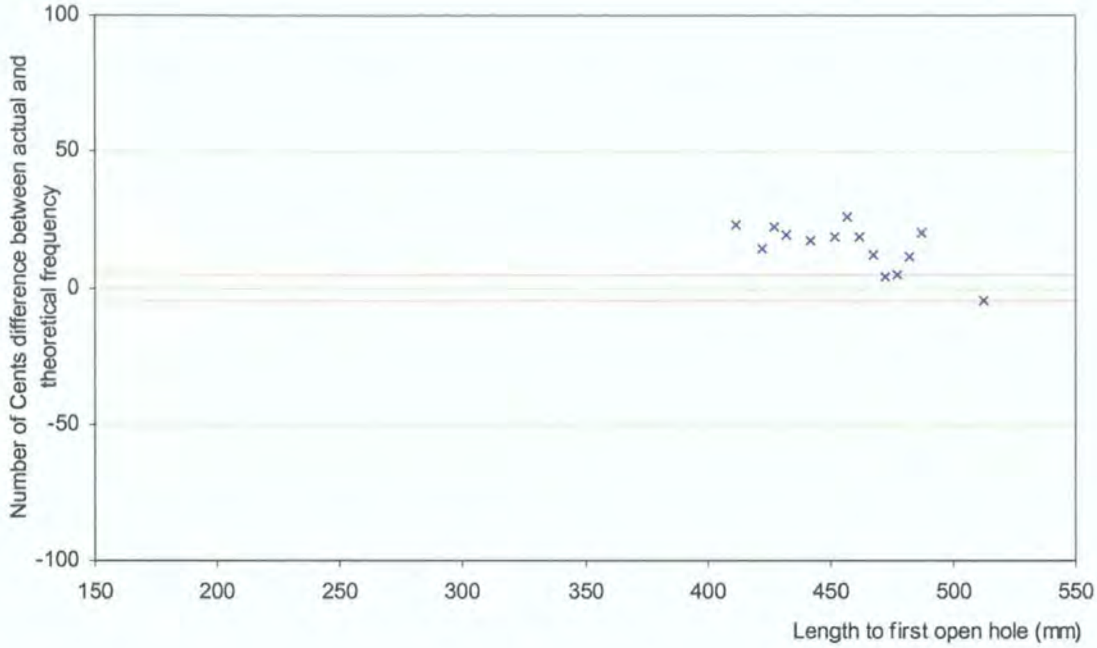

Figure 8-23 Comparison of the number of cents away from the theoretical frequencies for the 4th Overblown frequencies with modified end effect

This suggests that the end effect for the instrument needs to take into account the number of tone holes that are open. So far the end effect used in calculating the theoretical value has been constant throughout but the results show that this is not the case. The results show how even though the results look as if they are very similar to the theoretical values, as seen in Figure 8-13, and most of the time within the 2% errors when they are analysed more closely they are actually not very accurate at all.

Some of the tuning problems encountered with the sieve flute could be due to flautist's error. A very skilled flautist would alter how they were playing the instrument to ensure that it was in tune. However, when designing a flute it needs to be designed so that the minimum amount of human correction is needed to get each note in tune. The instrument should be designed with both the most skilled player and the lesser skilled player in mind. A flautist would be unlikely to encourage others to play the instrument if they themselves had to make large compensations with their embouchure to play the notes in tune.

8.3 Possibilities for Further Development

Although the sieve flutes have been shown to not be able to play 24-ET or even 12-ET (as a Boehm flute can) there is still the question of whether it can play notes from another tuning system. To calculate whether the sieve flute is able to, first the frequencies of a number of Equal Tempering tuning systems based on having the lowest note as 305 Hz (the frequency obtained when one hole is open on the 10mm sieve flute) it does not matter that the frequency 440Hz does not appear as an instrument is still microtonal no matter whether it has a fixed common frequency with all other tuning systems. Western Music uses A_4 as 440Hz but as shown before, the standard has changed over time and in different countries. To alter the standard frequency with so many holes covered can be achieved by altering the length of the instrument.

Once the frequencies for the various tuning systems have been obtained then they can be compared to the frequencies produced when playing the two sieve flutes. It can then be seen if there are any tuning systems ranging from 12-ET to 48-ET that either of the instruments can play.[70]

The frequencies were compared to the nearest hertz so as to ensure that if any were nearly in-tune then the best result possible would be produced. Although if an instrument is 0.5 Hz out of tune from the desired frequency it would sound out of tune, it is normally near enough to the desired frequency that the musician can alter their embouchure to compensate. Ideally an instrument should not have any leeway into the frequency band. If comparisons had been conducted comparing the frequencies to within cent tolerances, more notes would have appeared possible. However, the notes would be more out of tune and therefore a false result would have been obtained.

Investigations found that to play a microtonal scale the design of the sieve flute needs to be revised. To obtain frequencies in-between the ones already achieved in the 10mm sieve flute the number of holes would need increasing. To increase the number of holes, the size of the holes would need to be decreased to retain the rigidity in the bore.

Reducing the tone hole size to 5mm and the spacing of the holes so each one was 2mm offset from the previous hole, would mean that the number of holes in one circumference would have to be increased from four to six. This would allow a reasonable space between the holes ensuring rigidity in all the directions from a hole. By decreasing the offset of each hole from the previous hole would mean that at any one point the length of the instrument could only be a maximum of 1mm out from the required length. This 1mm would be approximately 8.5 cents for the shorter bore lengths and 2.8 cents at the longer bore lengths. The 8.5 cents would be a noticeable tuning difference but if the holes were only displaced by 1mm then the holes would have to be smaller to retain the rigidity of the bore. 5mm diameter holes displaced by 1mm with six holes in one circumference would mean there was only 1mm between one hole and the next in that particular direction along the bore. With having one hole every 2mm along the length of the instrument the total number of holes along a bore, the same length as the 10mm sieve flute would be 155. This would mean that if closing the holes in any pattern would give the total possible combinations as:

$$2^{155} = 4.567 \times 10^{46}$$

With the amount of holes and the spread of the holes they could be closed from the top down to give the frequencies required rather than having numerous combinations of open and closed holes, which it would not be possible to achieve with only eight fingers to control them.

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70 Tables containing the data can be found in Appendix E

In the Boehm flute the tone holes decrease in size and the frequency increases. The smallest hole that Boehm included in his flute is 7mm diameter. How would holes smaller than this effect the predicted frequency?

8.4 Conclusion

The sieve flutes were unable to play a complete scale in any of the tuning systems investigated. However, with careful redesigning of the instrument, either by repositioning the tone holes so they are equally spaced, or by increasing the number of tone holes the instrument could be improved. Both these cases would have to be investigated in the further work. The sieve flute was found to be a suitable design to be investigated further in the search for a microtonal flute.

9 Further Work.

Throughout this thesis, possible designs for microtonal flutes have been investigated as well as methods for reducing the effect of the numerous variables. From these there are a number of areas that could be taken forward as they would justify further work.

This chapter looks at the various areas that could be expanded and what could be investigated next in the search for a microtonal flute. Other areas that do not necessarily help towards finding microtonal flutes are also discussed, as the information gathered may be useful in analysing future designs.

9.1 Plunger Flute

The plunger flute, as has been shown, does not have the same timbre as a transverse flute would have and so cannot be really called a flute. However, even though the investigation shows that it can't be a microtonal flute, there is no reason why it could not be investigated further as a microtonal instrument in its own right. To be come a suitable instrument in its own right a number of factors would have to be improved.

The time that it takes to change from one note to another where the plunger has got to move any distance will cause a problem, which would need to be investigated further. Possible methods might include a control and propulsion system where the musician uses a series of sensor pads to indicate which note was desired by their fingering. The instrument would have to be connected to a computer, which would control the propulsion system to move the plunger the desired distance. This would also alleviate the problem of the musician not being able to reach the plunger when pulled out to its full length as with the original design.

A suitable propulsion system would therefore need investigating and ideally would control the plunger so that the instrument was the same length, no matter where the plunger was in the bore. An instrument requiring a large amount of space for the musician playing it would not be desirable, as it would take up useable space.

9.2 Sieve Flute

From the investigations into the two sieve flutes it can be seen how the number of possible frequencies increased when the number of tone holes are increased. However, there are many aspects of the sieve flute that require further investigation, such as into the tuning of the instrument, hole placement and closure methods of tone holes. With further investigations into these aspects it should be possible to produce a more suitable sieve flute that could be called a True Microtonal Flute.

The two sieve flutes investigated both had a larger bore for the main part of the instrument than there was for the head joint. Investigating a sieve flute with a constant bore size would eliminate the problems associated with the larger bore and the sudden change in bore size between the head joint and the rest of the instrument. Through this it would be hoped that the problems relating the difficulty of producing note of different volumes would be over come.

If the number of tone holes was increased further and each tone hole was closer to the next, then the number of possible frequencies would be increased further. With more possible frequencies produced by the instrument there would be more opportunity for the instrument to be able to play in a different tuning system.

As can be seen on either of the sieve flutes it is physically impossible to cover the holes with eight fingers and two thumbs. This means that a suitable key system would be needed. As the number of combinations of the holes is very large they would need to be reduced so that they could be played with the available fingers.

Having lots of holes allows for a greater number of pitches to be played and to get the best quality of the notes. Investigating the best possible tone hole combinations for the various notes would improve the sound. With the 5mm sieve flute and its 155 holes there would be a possible 4.567×10^{46} combinations[71] however the instrument would not produce that many separate notes. With the fundamental register on a Boehm flute there are very few tone holes that are closed below the open tone holes so when comparing this to the sieve flutes the same principle could be applied.[72] Taking this into account the main hole combinations for the 5mm sieve flute would have the upper holes closed and the lower ones open, however there will be some of these hole combinations that do not produce the best sound. To investigate a higher quality sound the tone hole combination for this note would have to be investigated further and in this case tone holes below the first open one may have to be closed.

Closing holes below the open ones would only be necessary to improve the sound of a specific pitch. Only investigating other tone hole combinations away from the stand higher end closed and lower end open would drastically reduce the number of combinations that need to be analysed.

Investigating a 5mm sieve flute would also give more of an idea into the effect that the tone hole size has on the frequency of the note produced. Also the difference in the effect depending on

[71] See section 8.3

[72] Appendix A shows the Boehm flute fingering chart

where the tone hole is on the bore i.e. what effect do the tone hole's size have on the frequency at each end of the bore.

Only once the tone hole combinations that provide the best quality notes have been found can the logic for key system be investigated. The number of notes that need to be playable would be dependant on how in tune the instrument could be and the quality of the notes in the various tuning systems. Although the instrument may play many frequencies associated with different tuning systems they may not all be of a suitable quality.

The keys that the musician presses to play the notes and the hole closures would need be controlled by a programmable logic circuit or linked up to a computer and so the combinations of which holes close for which finger combination could be changed without making a mark on the instrument. This would allow a transposing instrument to be played using music for a C instrument, where the musician would play the same fingering as they would normally for the notes they see on the page, however, the instrument would sound different as the hole combinations would have been changed.

Suitable tone hole closures would need to be investigated. As was seen with the logical woodwind, solenoids would be unsuitable.[73] A solenoid is relatively heavy and for the number required, especially for the 5mm sieve flute, it would make the instrument too heavy. Further investigation into the tone hole closure methods would have to be undertaken. The method would have to satisfy the following criteria to be suitable.

- The tone hole closure would have to be lightweight enough so as to not make the instrument much heavier than the Boehm flute. The weight of the Boehm flute is what a flautist is used to and so anything significantly heavier would be awkward. This would be especially important with the 5mm sieve flute where there are 155 tone holes. The weight of each tone hole closure would have a far greater effect on the 5mm sieve flute than for the 10mm sieve flute or the 14mm sieve flute where there are 62 and 31 tone holes respectively to be covered.

- The tone hole closure would have to be as quiet as possible, so that when playing a piece of music, no noise would distract from the music. Once again this would be more important for the 5mm sieve flute than the others as the number of holes closing or opening at once would amplify the sound made by just one closing.

- The tone hole closure would have to be small enough so that it did not get in the way of any other tone hole. The tone holes would be quite close together with less that 10mm between the holes for any of the sieve flute.

[73] See section 4.2

- The hole closure would have to make sure that there was an airtight seal at the hole. If air escaped thought the hole closure the quality of the sound produced would deteriorate drastically.

Patrick Ozzard-Low talks about three possible methods of tone hole closures but rules two of them out.[74]

9.3 Acoustic Impedance

No investigations were carried out into the acoustic impedance of the instruments. However to compare the quality of the sound produced by the instrument the acoustic impedance would have to be investigated.

Before any investigations into the sieve flute and the plunger flute's acoustic impedance could be undertaken, the acoustic impedance of the Boehm flute would have to be investigated so as to understand the data obtained before the comparison with the two other flutes. Investigating the acoustic impedance of the Boehm flute would be a repeat of the work carried out by the Music Acoustics Department at the University of New South Wales, Australia[75]. This repeat of their work would need to be done so as to understand how the acoustic impedance was measured and analysed.

9.4 Other Microtonal Woodwind Instruments

Following on from the search for a microtonal flute the information gathered from the investigations could be used to draw up possible designs for other microtonal woodwind instruments. These designs would have to allow for how the different structures affect the acoustics of the instrument. As the clarinet is a closed cylindrical bored instrument, the design using the plunger flute would not work due to there being nowhere for the air to escape. Similarly for the Oboe and Saxophone, which have conical bores, the air would need somewhere to escape so as to project the sound.

Once again the fingering system designed for the flute could be transferred onto other microtonal woodwind instruments. This would be regardless of what the key system for the standard instrument would be. In the case of the clarinet where the instrument over blows at a twelfth, the same fingering could be implemented as with a microtonal flute just with a different programme closing the relevant tone holes, therefore allowing a universal fingering system for all woodwind instruments. This has already been investigated by Brindley, Norbeck and McGill each looking at a different instrument for the standard tuning. This has not be taken any further due to musicians being used to the fingering patterns on their relevant instruments when playing

[74] Page 72 in [OZZ98]

[75] [UNSW05]

any music in 12-ET. However, when looking at fingering patterns for microtonal instruments there are no standards, due to there note being any commercially available instruments, except the Osten-Brannen Kingma quartertone flute.[76] Therefore a universal fingering system would not be unsuitable.

9.5 Conclusion

This chapter has discussed how the plunger flute could be redesigned to improve the speed at which it could play, as well as ideas to improve the range of the instrument. The sieve flute has been discussed with regard to possible directions that could be developed. It can be seen that theory would suggest the sieve flute would be able to play many microtones if the holes were correctly positioned and there was enough of them. However, there are still many questions relating to the control system and the tone hole closures that need to be investigated.

Any microtonal instrument would have to have their acoustic impedance investigated so as to show the quality of the sound the instruments produce. This chapter also discusses how by investigating possible microtonal flutes, other microtonal instruments could possibly be investigated.

[76] [BRA05]

10 Conclusion.

This thesis has presented the background theory into tuning systems as well as the history of the development of the flute. It also illustrates the need for research into microtonal instruments.

It has shown how the flute and clarinet have developed over time. The acoustics for the two instruments have been detailed, including which harmonics are to be expected in the spectrum for the different registers of each instrument and the construction factors that affect the frequency detailed.

The various tuning systems and the methods used to calculate the frequencies have been detailed. It has been shown how some tuning systems when compared to Just Intonation have notes that correspond exactly, whereas other systems do not.

Previous attempts at microtonal woodwind instruments have been discussed and from these other possible designs have been investigated. Previous investigations and future directions for investigations into control systems for tone hole closures were discussed. It was shown how the keys which are pressed are connected to the pads over the tone holes by a circuit and not by a mechanism.

An artificial blowing device has been investigated and considerations given to how it would need further development to work.

The Boehm flute has been analysed to provide a reference basis for comparison of future flute designs. The effect that removing the key system from the Boehm flute had on the frequencies obtainable could be seen, and consequently it was shown that the Boehm flute could not play microtones with the keys removed. The effect of closing the tone holes at the lower end of the instrument, while the higher tone holes were open, was found to be negligible, reaffirming that the Boehm flute is designed for the one tuning system only.

It has been shown that even though complete microtonality is only reached through a continuous frequency range this is not always the most practical for playing music. Although the plunger flute in a modified form, with a longer bore and a more reachable plunger, may seem ideal it would cause problems when it came to playing fast music accurately. The flautist would have to learn the exact positions for the microtonal notes and as the microtonal pitches would not be as known to them as the pitches from 12-ET it would be easy for them to miss place them. As the spectrums of the various registers are so different to the Boehm flute's and therefore the timbre is different, the instrument cannot really be called a flute. This would be more evident in that the flute's tuning changes as the instrument changes temperature, and so if the instrument was not tuned properly, the positions for each note would change.

The sieve flutes showed how by even spacing of the tone holes, not many of the pitches expected even for 12-ET were obtained. However, with careful redesigning of the instrument, either by repositioning the tone holes so they are equally spaced, or by increasing the number of tone holes the instrument could be improved. The principle of having lots of tone holes not far away from each other seemed to work and so, with the further investigation as was discussed, the sieve flute could be a viable microtonal instrument. When conducting further investigation into the sieve flute, the mechanisms for the tone hole closures and the control system including the programming would be one of the most important aspects.

The discussion into the possibilities for further work included how the plunger flute could be redesigned to improve the speed at which it could play, as well as ideas to improve the range of the instrument. However, the acoustical differences between the plunger flute and the Boehm flute would not be able to be overcome. The sieve flute has been discussed and the possible directions that could be developed. It can be seen that theory would suggest the sieve flute would be able to play many microtones if the holes were correctly positioned and there were enough of them. However, there are still many questions relating to the control system and the tone hole closures that need to be investigated.

From what was found from previous research, it would seem that although it is a growing area musically with the increase of contemporary music, there is actually not much research being undertaken currently or recently into suitable instruments to play such music and their key structure. This is therefore an area that has large scope for further research.

This thesis has investigated the possible methods for a microtonal flute and has indicated directions that further work could be taken. The instruments investigated in this thesis although not microtonal have shown the ideas that would warrant being taken further.

References

[ADA*] Adams K., *The History of the Construction of the flute*, Retrieved February 2004, http://www.geocities.com/Vienna/Choir/6877/history.html, year unknown

[BAR99] Barrett G., *This History of the Clarinet's Development*, Retrieved February 2004, http://www3.niu.edu/music/barrett/Cl_history.htm, 1999

[BAT79] Bate P., *The Flute*, Ernest Benn Ltd, London, UK, 1979

[BEN90] Benade A. H., *Fundamentals of Musical Acoustics*, Dover Publications Inc., New York, USA, 1990

[BOE64] Boehm T., *The Flute and Flute Playing*, Translated Miller D. C., Dover Publications Inc., New York, USA, 1964

[BRA05] Kingma system flutes and Glissando head joints, Retrieved March 2005, http://www.brannenflutes.com/kingma.html

[CAU03] Causse R, Micro Interval Instruments, Retrieved October 2003, http://ww.ircam.fr/produits/technologies/systememicro-e.html

[COL71] Coltman J. W., "Effect of Material on Flute Tone Quality", *The Journal of the Acoustical Society of America*, vol. 49, no. 2, pp. 520-523,

[COL73] Coltman J. W., "Material used in Flue Construction", *Woodwind World*, vol. 12, no. 1, pp. 20-21, February 1973

[DIC89] Dick R., *The Other Flute*, Multiple Breath music Company, New York, USA, 1989

[DIC05] Dick R. Glissando Head joint for the Flute, Retrieved March 2005, http://www.robertdick.net

[DIMT05] Sound Spectrum, Retrieved March 2005, http://www.dmit.nl/soundtheorie.asp

[EBA05] Oehler System Clarinet Images, Retrieved January 2005, http://cgi.ebay.de/ws/eBayISAPI.dll?ViewItem&category=23296&item=3777231457&rd=1

[EBA05a] Albert System Clarinet Images, Retrieved January 2005, http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&category=10182&item=3777759575&rd=1

[FLE91] Fletcher N. H. and Rossing T. D., *The Physics of Musical Instruments*, Springer-Verlag, New York, USA, 1991

[GRO04] Timbre, Cent, Interval, Pentatonic, Microtonal Instruments, Well-tempered clavier, Microtone, Equal Temperament, Clarinet, Flute, Retrieved January 2004 http://www.grovemusic.com

[IRC03] Clarinet mouthpiece with variable tuning, Retrieved October 2003, http://www.ircam.fr/equipes/instruments/cs2000/becvar/accueil.htm

[LAS97] Lasocki D., When is a "flute" not a flute?, Retrieved November 2004 http://www.library.yale.edu/cataloging/music/flute.htm

[MVT05] Slide Whistle, Retrieved March 2005, http://www.music.vt.edu/musicdictionary/texts/Slidewhistle.html

[NED69] Nederveen C. J., *Acoutical Aspects of Woodwind Instruments*, Frits Knuf, Amsterdam, Netherlands, 1969

[NUS05] Chinese Pentatonic Scale, Retrieved January 2005, http://www.math.nus.edu.sg/aslaksen/gem-projects/maa/Early_Mathematics_in_Chinese_Musical_Scale/pentatonic.htm and http://www.math.nus.edu.sg/aslaksen/gem-projects/maa/Early_Mathematics_in_Chinese_Musical_Scale/lack2.htm

[OSB03] Osborne W., *German Orchestral Instruments*, Retrieved February 2004, http://www.osborne-conant.org/instruments.htm, 2003

[OZZ98] Ozzard-Low P., *21st Century Orchestral Instruments*, Retrieved October 2003, http://www.c21-orch-instrs.demon.co.uk, 1998

[SHE02] Simple flutes, Retrieved March 2005, http://www.markshep.com/flute/books/Simple.html

[UWM05] China and Japan, The Music of China and the Chinese pentatonic scale, Retrieved January 2005, http://www.uwm.edu/Course/660-310/04Chinajapanoutline

[UNSW05] Music Acoustics (1997-2005). Retrieved October 2003 – March 2005 from http://www.phys.unsw.edu.au/music/.

[WAL04] Walker M., "PC Music Freeware Roundup", *Sound on Sound*, vol. 19, no. 9, pp. 204-214, July 2004

[*02] Double Bored Clarinet, Retrieved March 2005, http://www.museum-markneukirchen.de/holz.htm translated using http://babelfish.altavista.com

Bibliography

[BEN85] Benade A. H. and Larson C. O., Requirements and techniques for measuring the musical spectrum of the Clarinet, *Journal of The Acoustical Society of America*, vol. 78, no. 5, pp. 1475-1498, November 1985

[BOW99] Bowles E. A., *The impact of technology on musical Instruments*, Retrieved December 2003, http://www.cosmos-club.org/journals/1999/bowles.html, 1999

[BRY76] Brymer J., *The Clarinet*, Macdonald and Jane's Publishers Ltd., London, UK, 1976

[CAM87] Campbell M. and Greated C., *The Musician's Guide to Acoustics*, J. M. Dent & Sons Ltd, London, UK, 1987

[CAM97] Campbell J. A., Precision Strobe Tuners, Retrieved January 2005, http://www.precisionstrobe.com/apps/pianotemp/temper.html

[DAL95] Dalmont J. P., Some aspects of tuning and clean intonation in reed instruments, *Applied Acoustics*, vol.46, pp. 19-60, 1995

[DUC03] Ducasse E., A physical model of a single-reed wind instrument, including actions of the player, *Computer Music Journal*, vol. 27, no. 1, pp. 59-70, 2003

[FOR00] Forster C. M. L., *Equations for the Placement of Tone Holes on Concert Flutes and Simple Flutes*, Retrieved February 2004, http://www.chrysalis-foundation.org/flute_tone_holes.htm, 2000

[FRI03] Fritz C. Wolfe J. Kergomard J. and Caussé R. Playing frequency shift due to the interaction between the vocal tract of the musician and the clarinet, *Proceedings of the Stockholm Music Acoustics Conference, (SMAC 03)* pp. 263-266, 2003

[HOW01] Howles V. E. and Trefethen L. N., Eigenvalues and musical instruments, *Journal of Computational and Applied Mathematics*, vol. 135, pp. 23-40, 2001

[JAK96] Jakeways R., "Hoots, Hertz and Harmonics - part 1", *Pan – The Journal of the British Flute Society*, vol. 14, no. 4, pp. 18-23, December 1996

[JAK97] Jakeways R., "Hoots, Hertz and Harmonics – part 2", *Pan – The Journal of the British Flute Society*, vol. 15, no. 2, pp. 20-24, June 1997

[JAK98] Jakeways R., "Hoots, Hertz and Harmonics – part 3", *Pan – The Journal of the British Flute Society*, vol. 16, no. 1, pp. 26-29, March 1998

[JAK99] Jakeways R., "Hoots, Hertz and Harmonics – part 4", *Pan – The Journal of the British Flute Society*, vol. 18, no. 1, pp. 20-27, March 1999

[JAK00] Jakeways R., "Hoots, Hertz and Harmonics – part 5", *Pan – The Journal of the British Flute Society*, vol. 19, no. 3, pp. 26-28, September 2000

[JAK04] Jakeways R., "Hoots, Hertz and Harmonics – part 6", *Pan – The Journal of the British Flute Society*, vol. 23, no. 3, pp. 17-21, September 2004

[KAN03] Kanno M., Thoughts on How to Play intune: Pitch and Intonation, *Conetmpory Music Review*, vol. 22, no. 1, pp. 35-52, 2003

[LOY99] Loy J., The Well-Tempered Scale, Retrieved January 2005, http://www.jimloy.com/physics/scale.htm

[MAC*] Machnik M. *The Evolution of the Clarinet*, Retrieved February 2004, http://www.arts.ufl.edu/music/clarinet/Evolution%20of%20the%20Clarinet.doc, year unknown

[PER98] Pergler M., *The Inhalation-Sharpening effect*, Retrieved February 2004, http://www.woodwind.org/clarinet/Misc/breatpit.pdf, 1998

[REI03] Reitman B., *Hisotry of Mathematic Approcaches to Western Music*, Retrieved February 2004, http://boris.reitman.name/math_music_hist.pdf, 2003

[SMI00] Smith J. Fritz C and Wolfe J., A new technique for the rapid measurement of acoustic impedance of wind instruments, *Proceedings of the Seventh International Congress on Sound and Vibration*, vol. 3 pp. 1833 – 1840, 2000

[WOL01] Wolfe J. Smith J. Tann J. and Fletcher N. H., Acoustic impedance of classical and modern flutes, *Journal of Sound and Vibration*, vol. 243, pp. 127-144, 2001

[WOL03] Wolfe J. Smith J. and Green M., The effects of placement of the head joint stopper on the impedance spectra of transverse flutes, *Proceedings of the Eighth Western Pacific Acoustics Conference*, Australian Acoustics Society, 2003

[*01] Musical Note Intervals, Retrieved January 2005, http://www.tunesmithy.connectfree.co.uk/musical_note_intervals.htm and http://www.tunesmithy.netfirms.com/fts_help/Scales_and_Fractal_Tunes.htm

Appendices

Appendix A

Fingering Chart for the Boehm Flute

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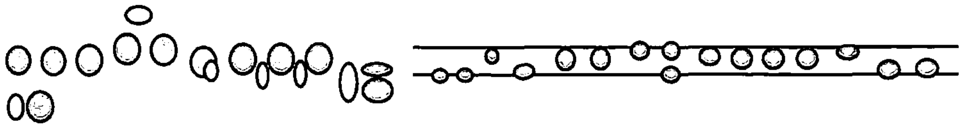

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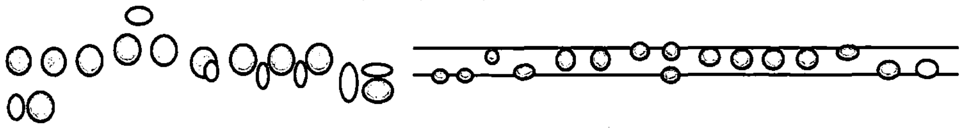

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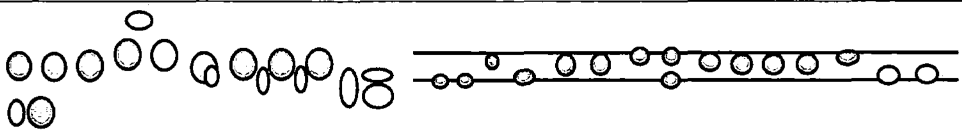

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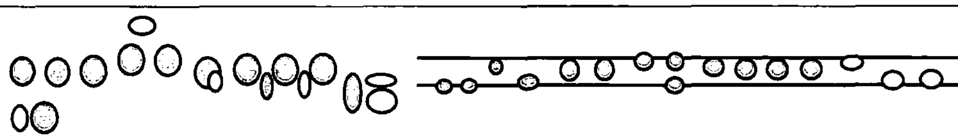

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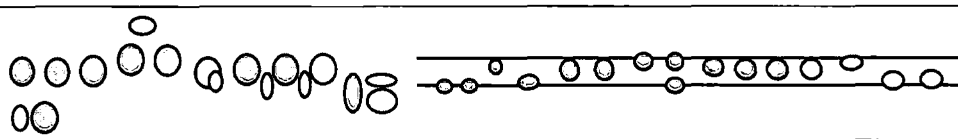

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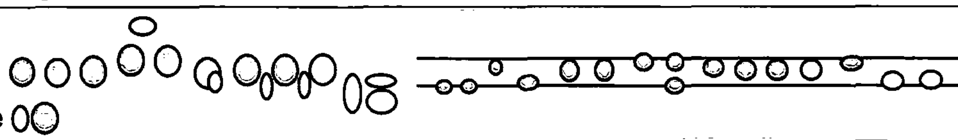

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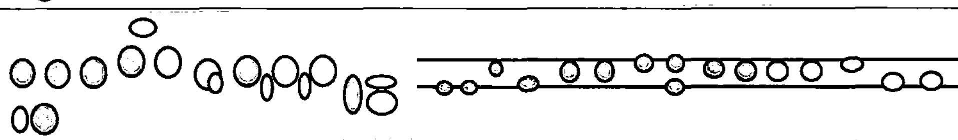

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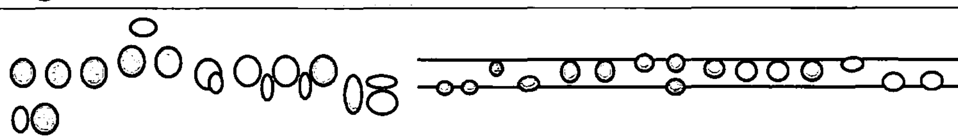

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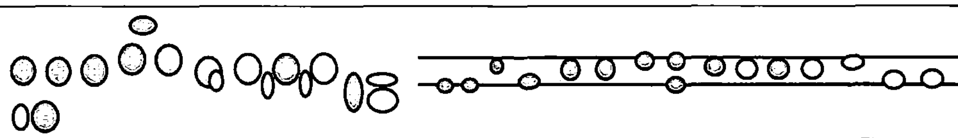

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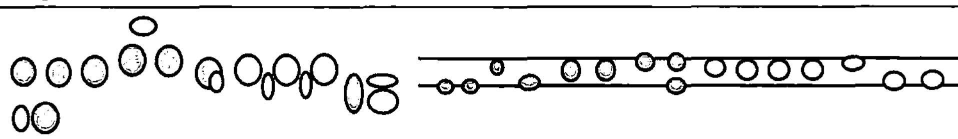

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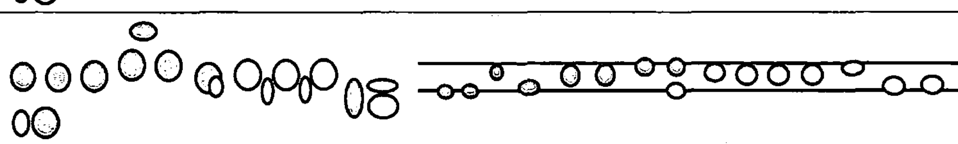

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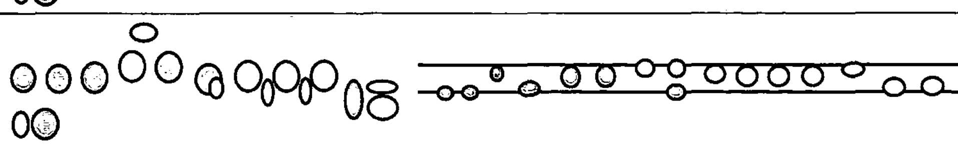

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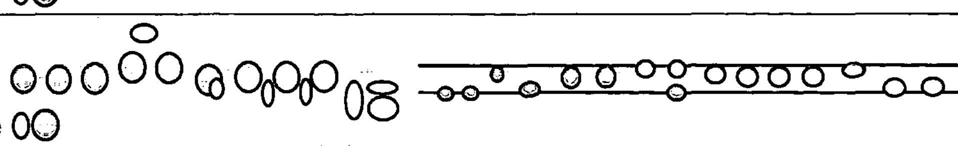

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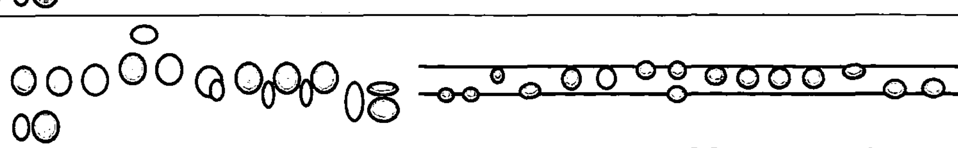

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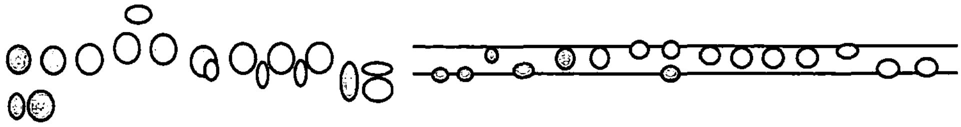

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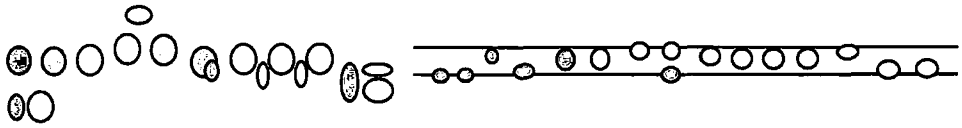

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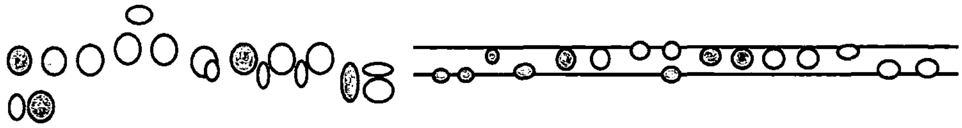

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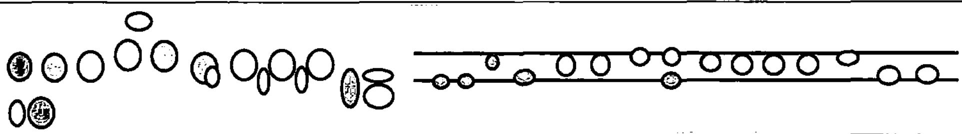

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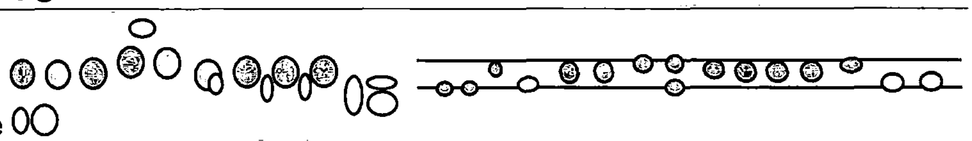

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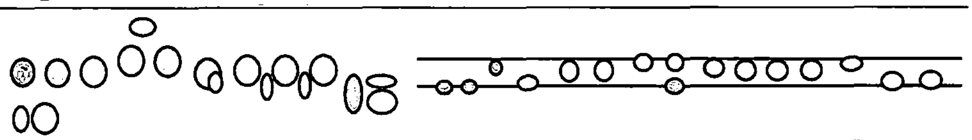

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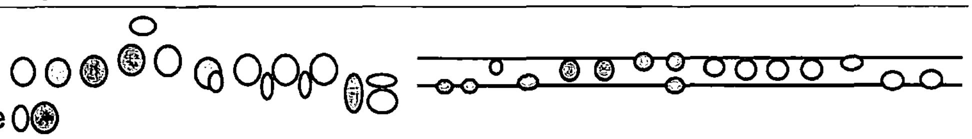

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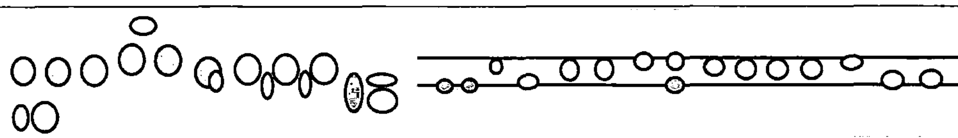

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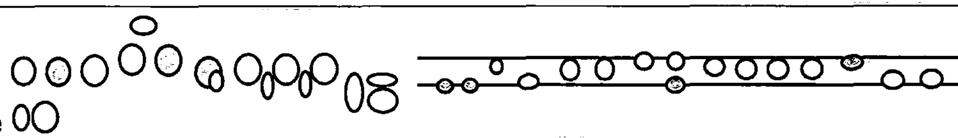

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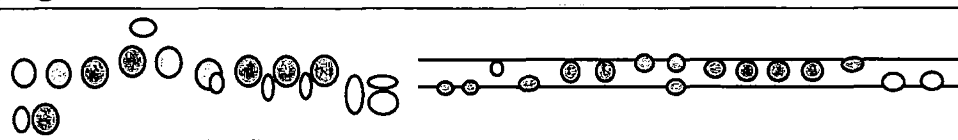

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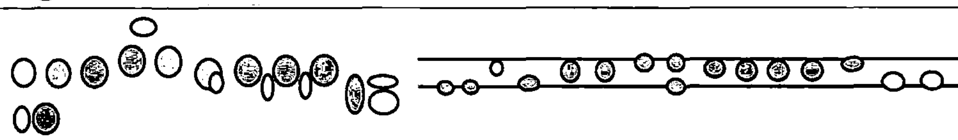

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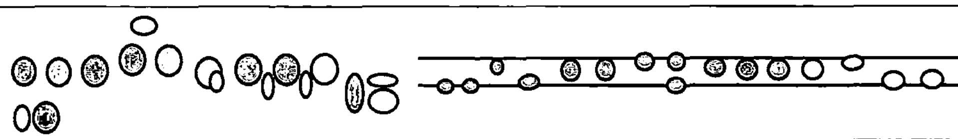

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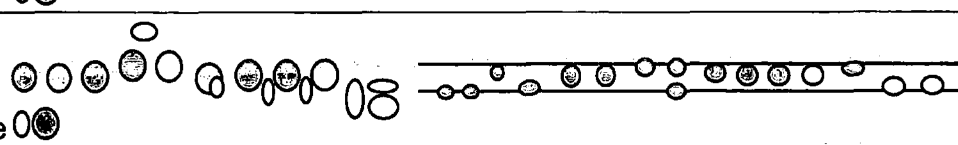

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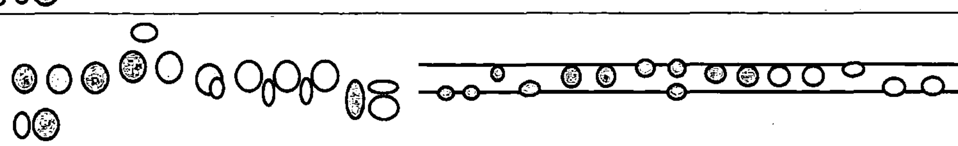

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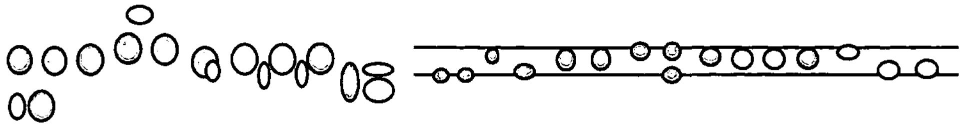

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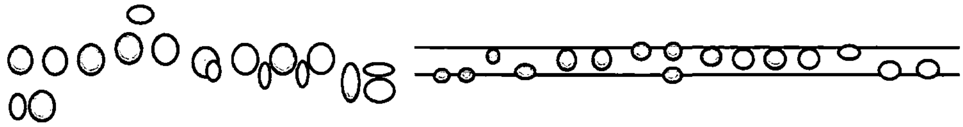

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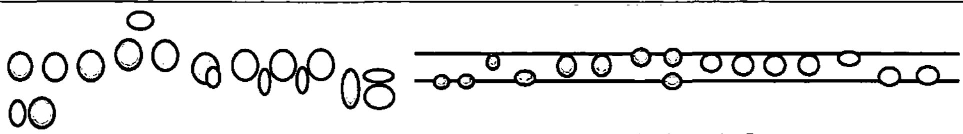

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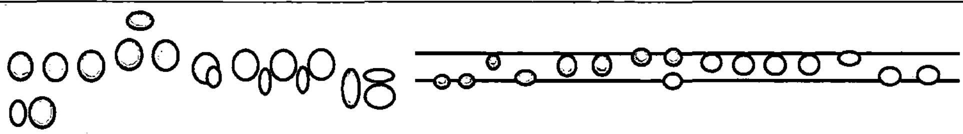

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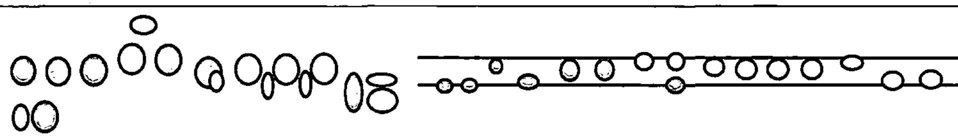

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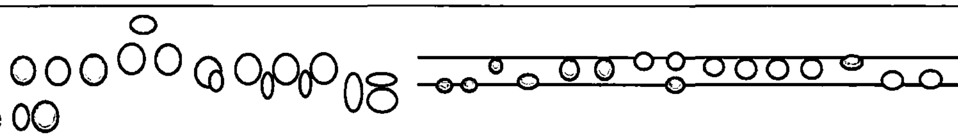

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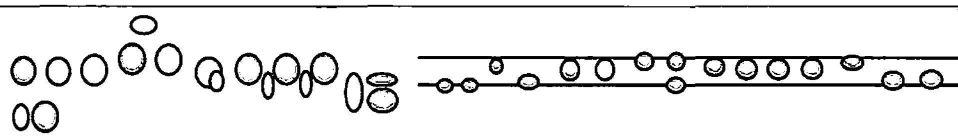

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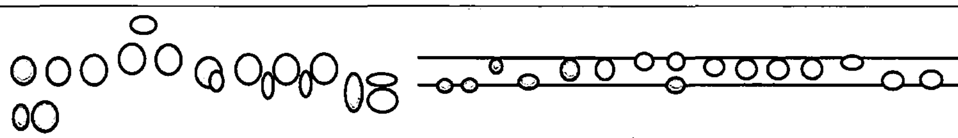

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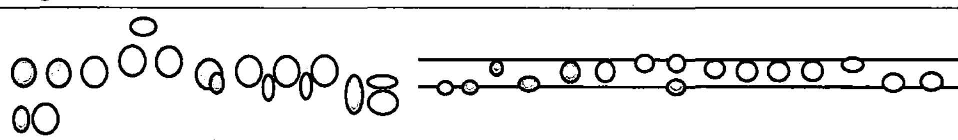

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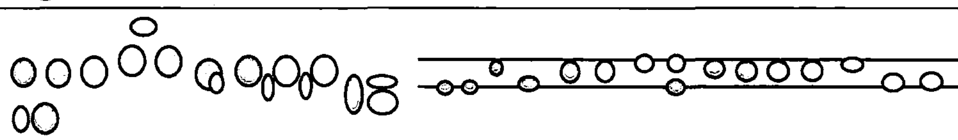

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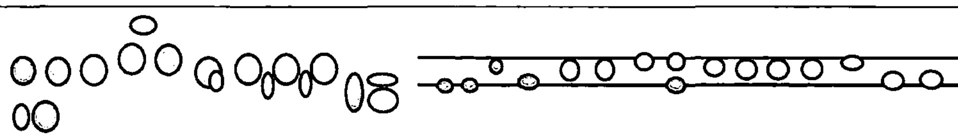

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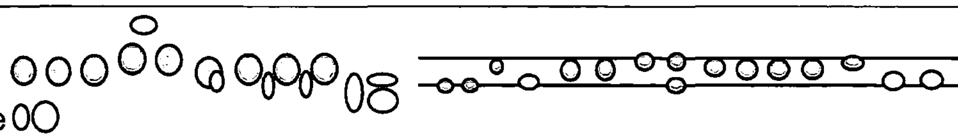

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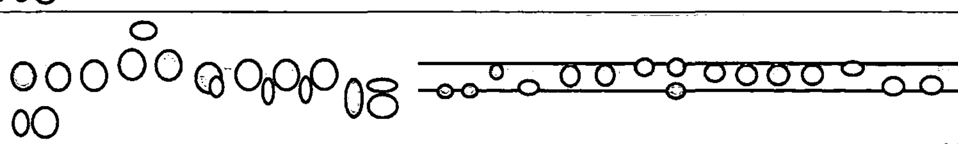

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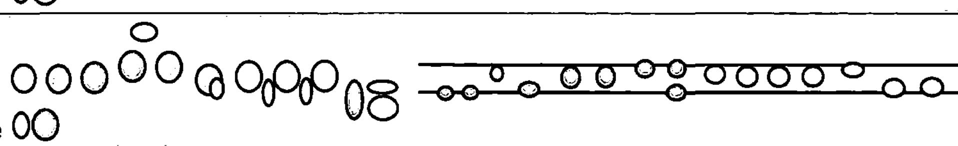

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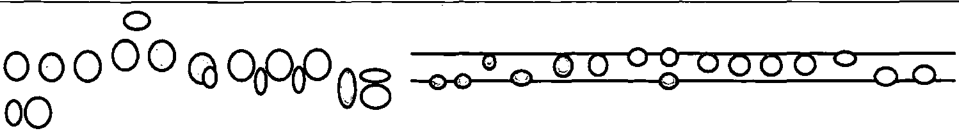

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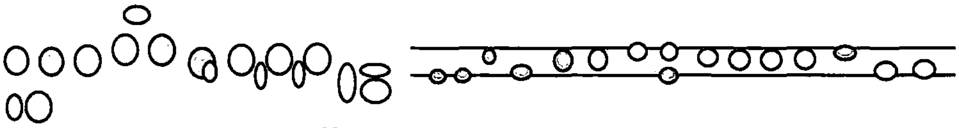

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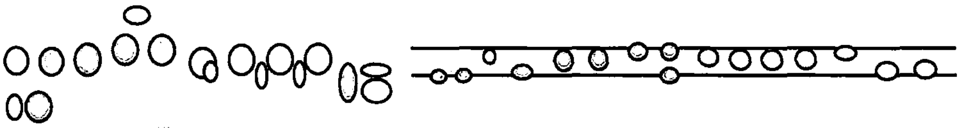

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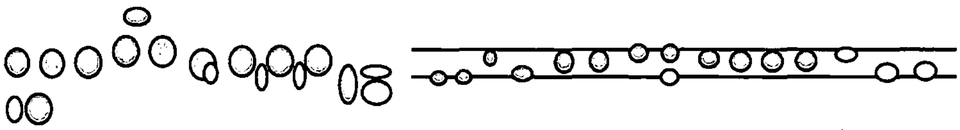

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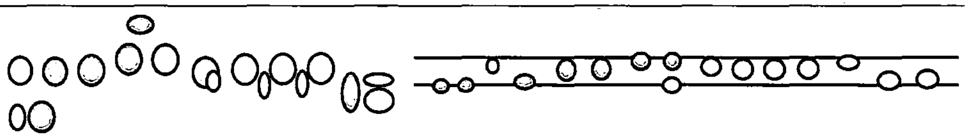

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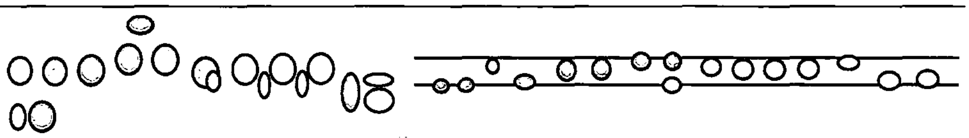

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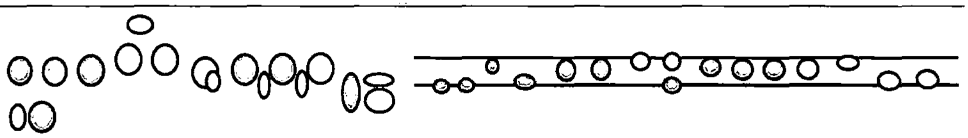

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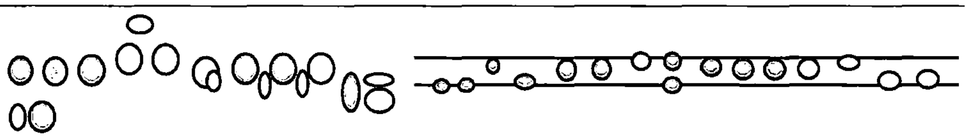

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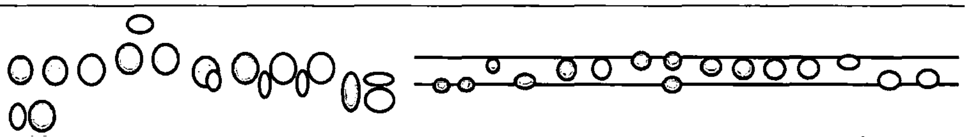

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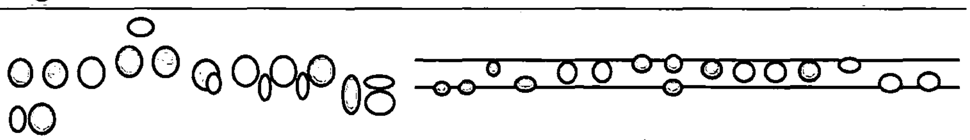

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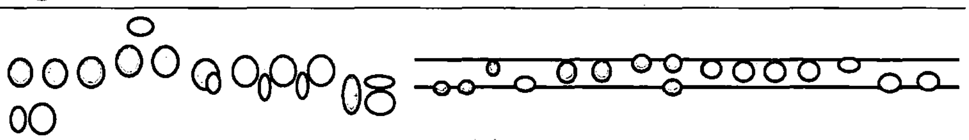

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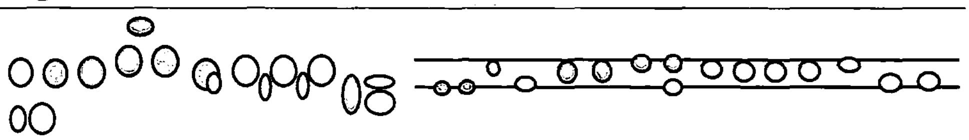

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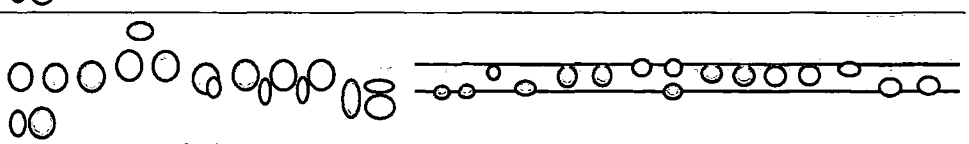

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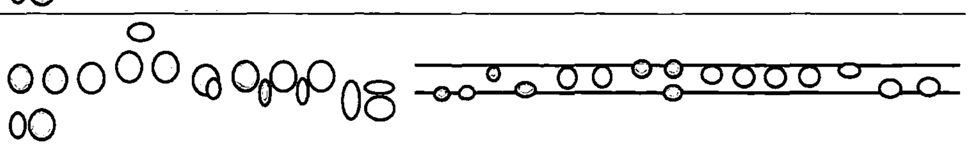

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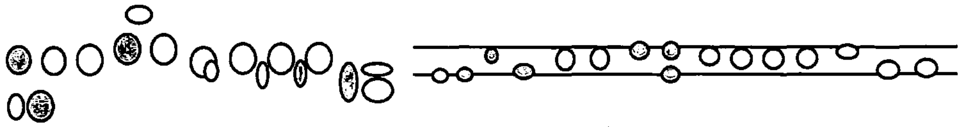

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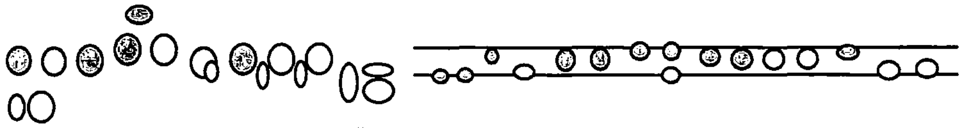

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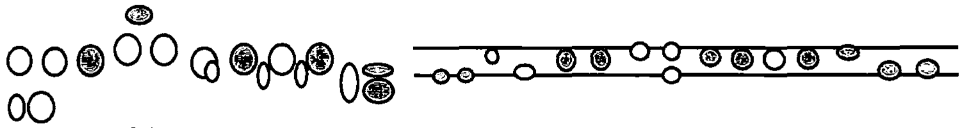

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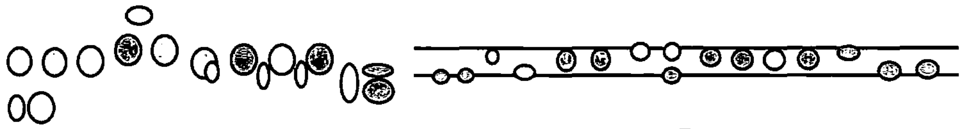

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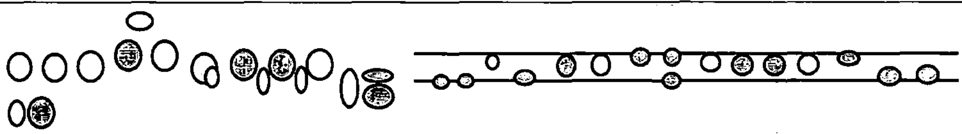

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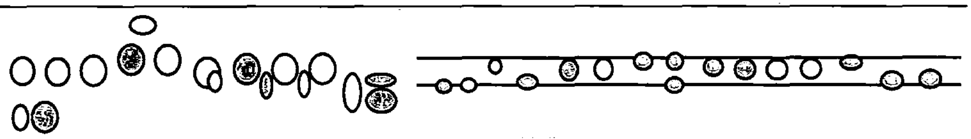

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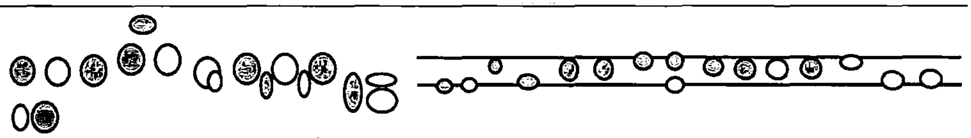

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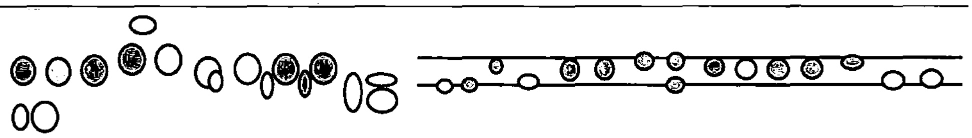

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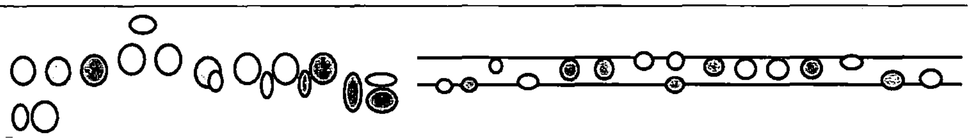

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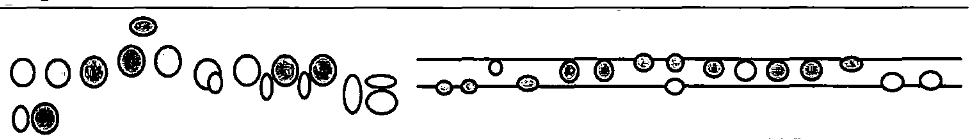

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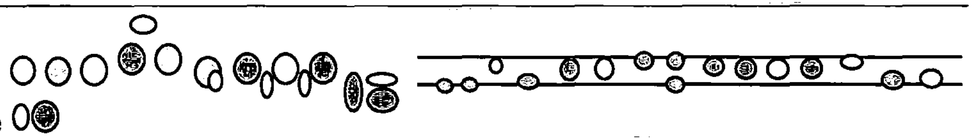
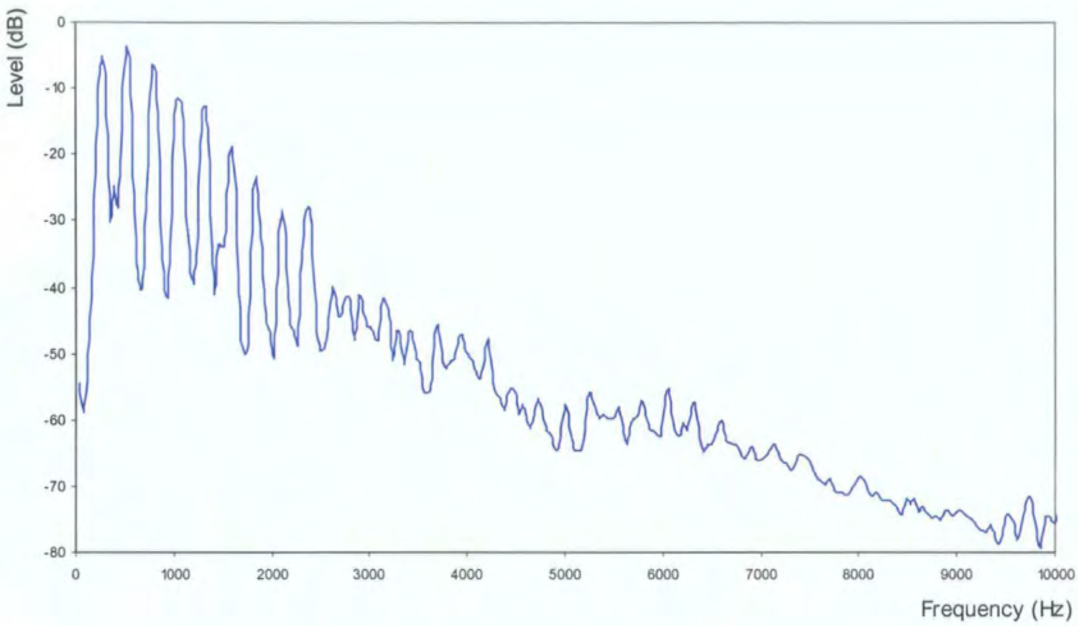
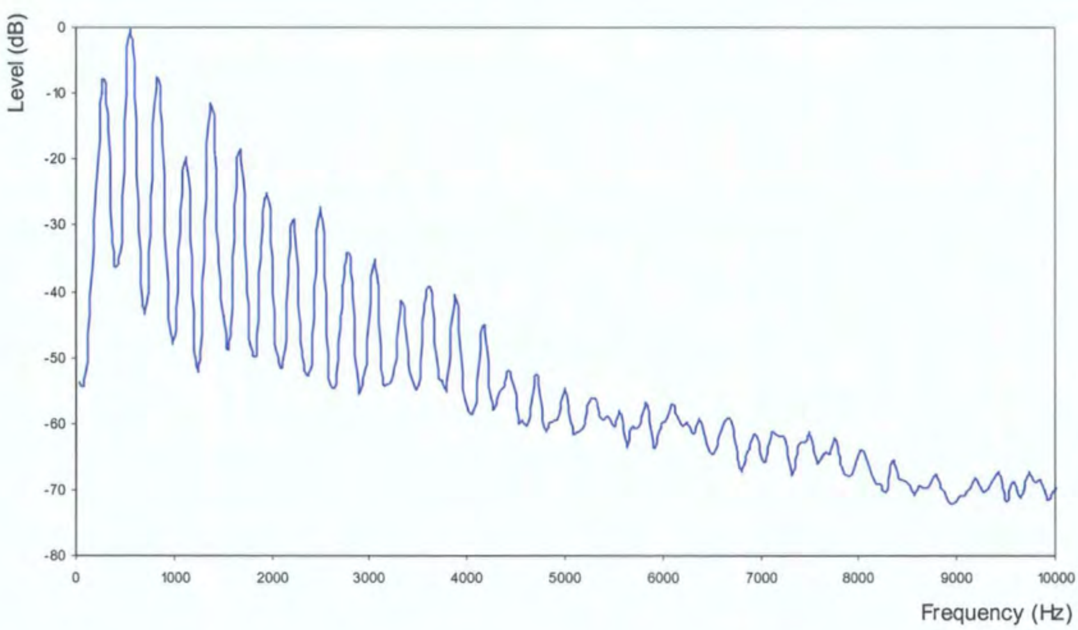


Appendix B

Spectrum of the Boehm flute



C4



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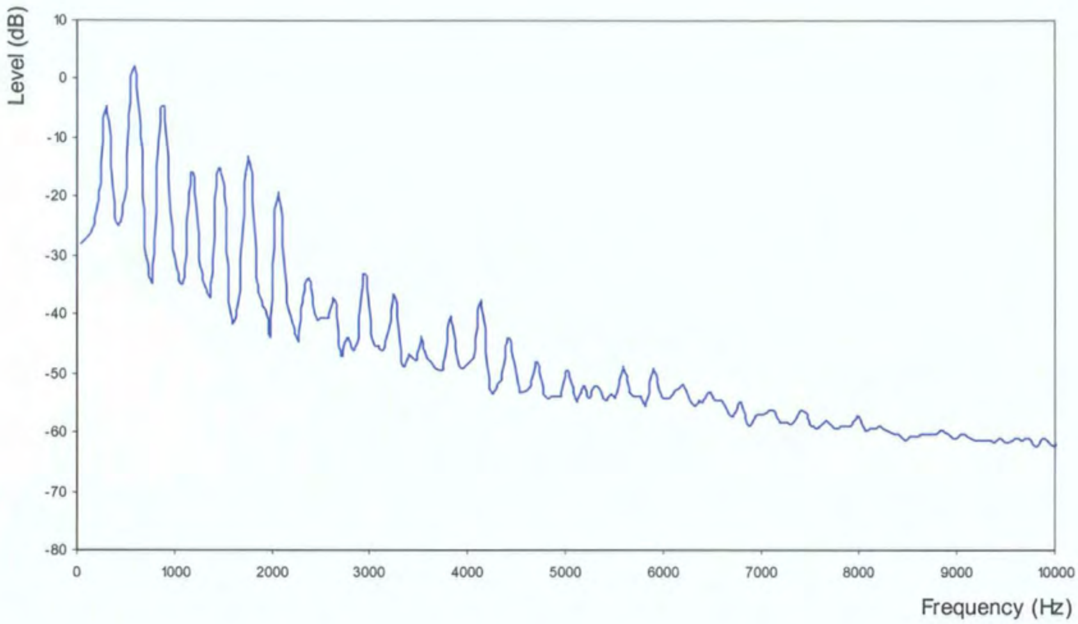
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8000
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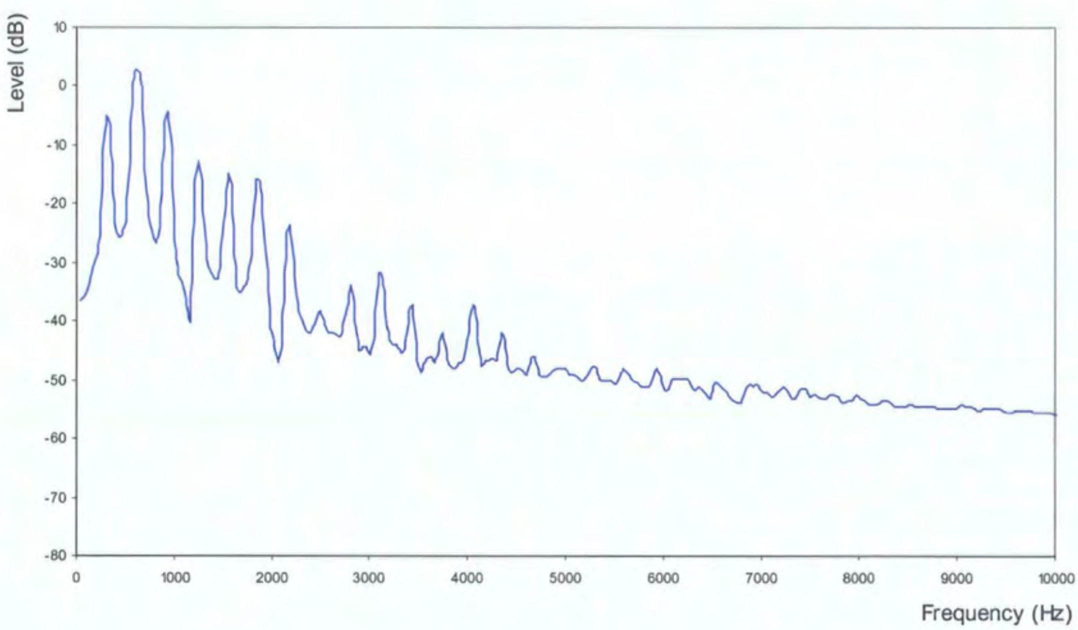
10000
Frequency (Hz)

D4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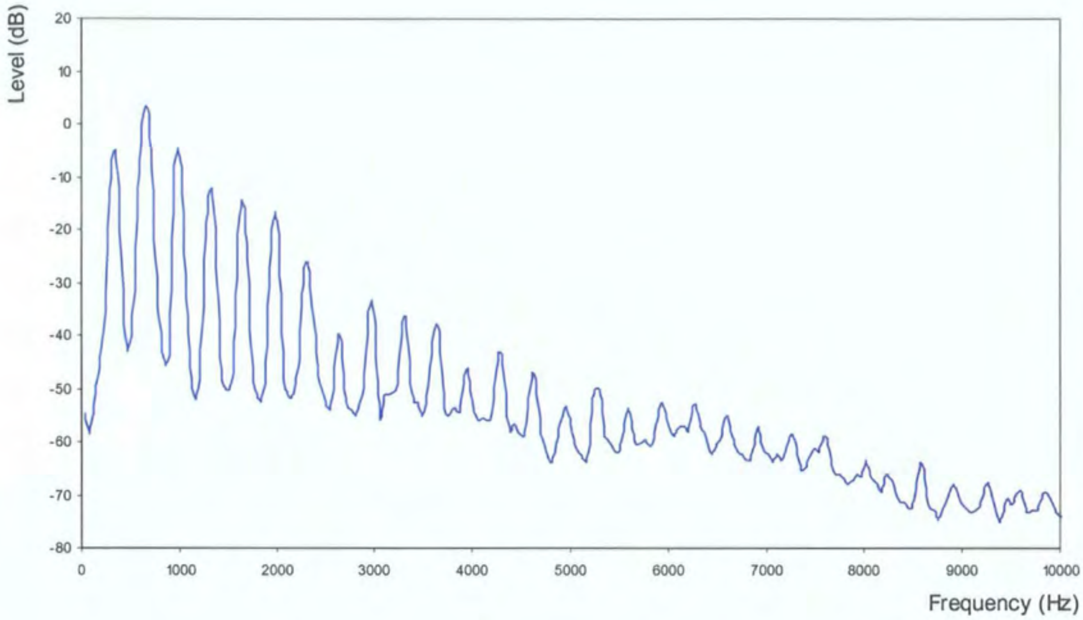
Frequency (Hz)

D#4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Frequency (Hz)

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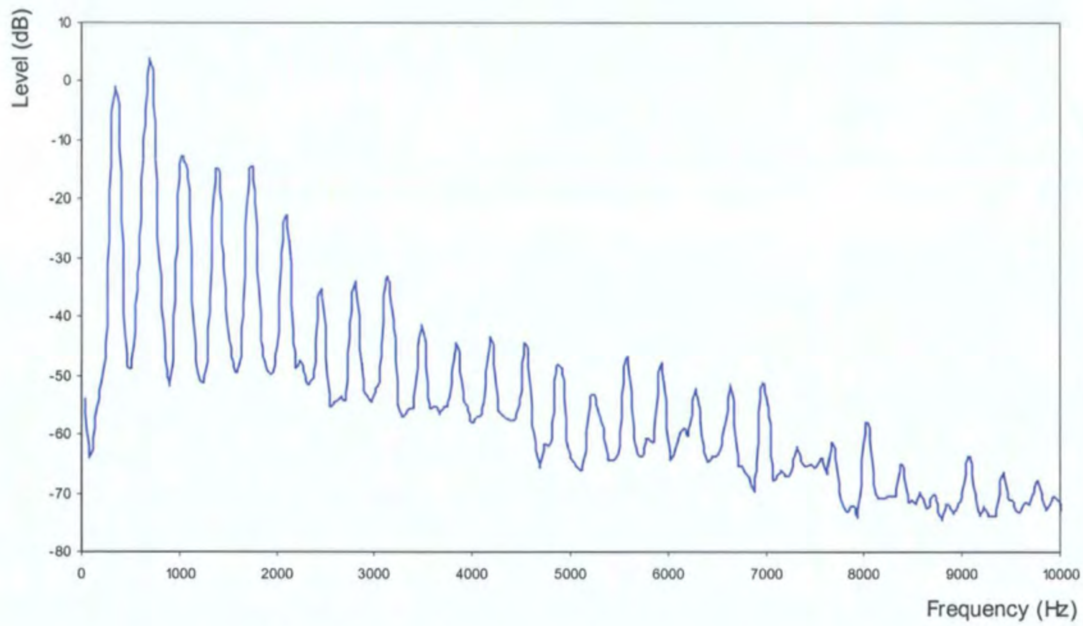
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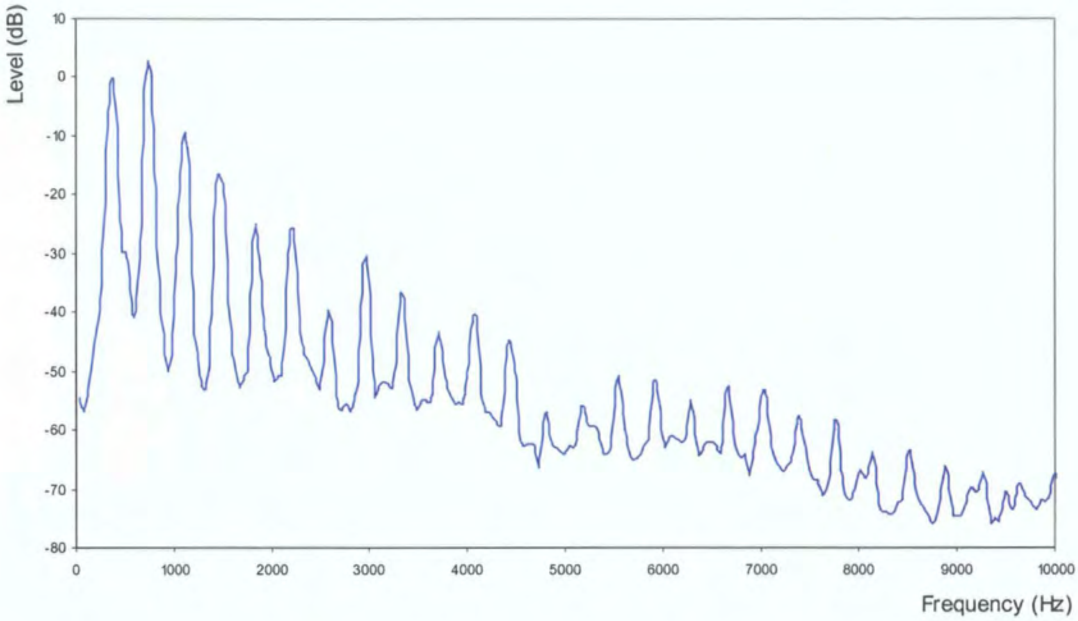
Frequency (Hz)

F4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Frequency (Hz)

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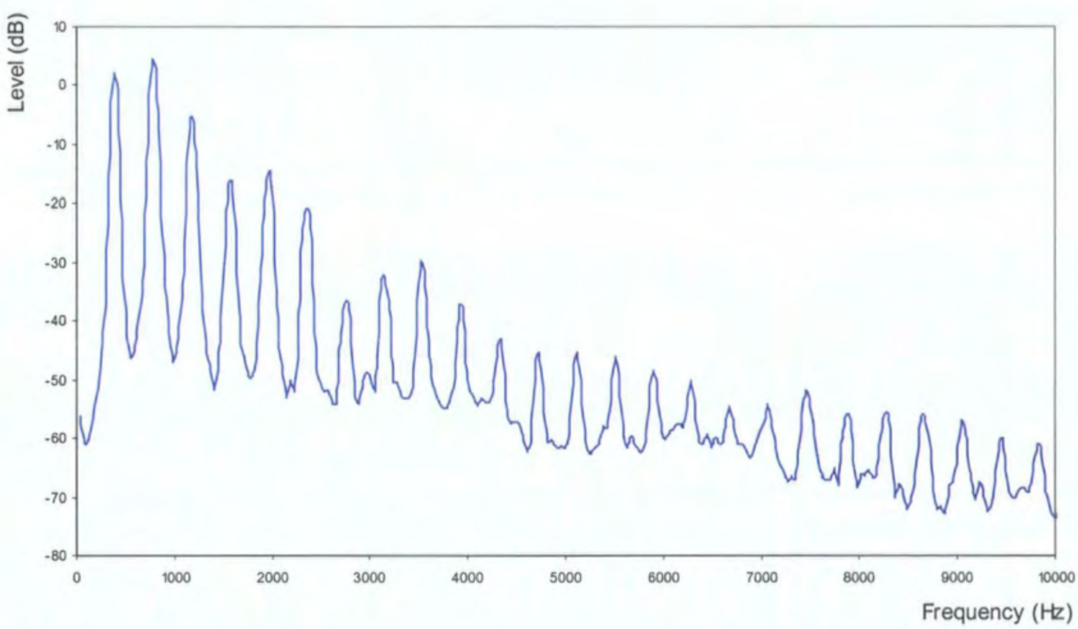
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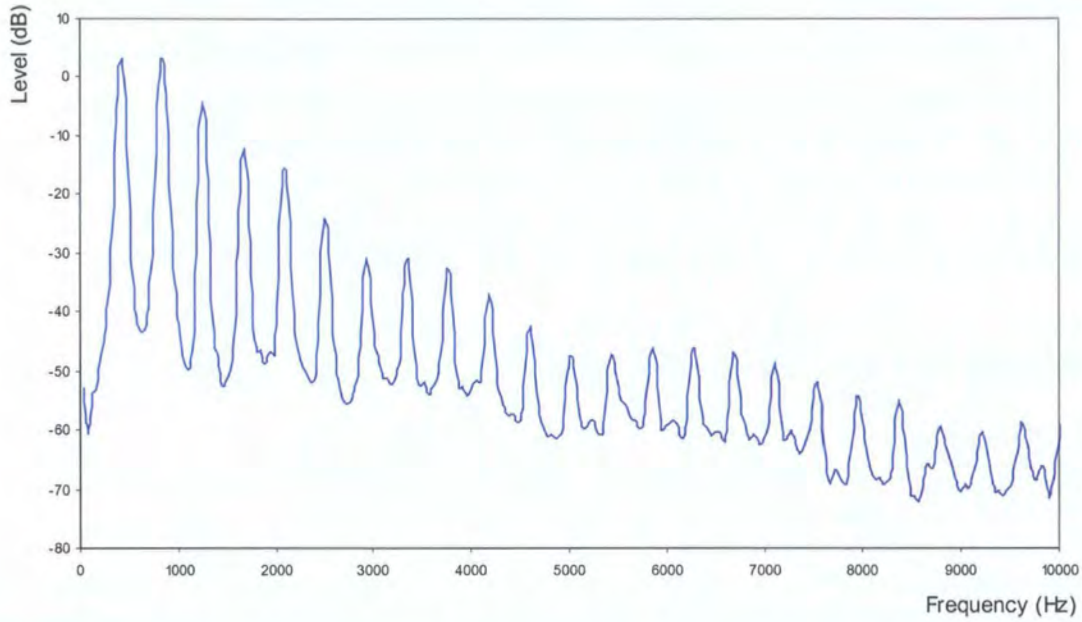
Frequency (Hz)

G4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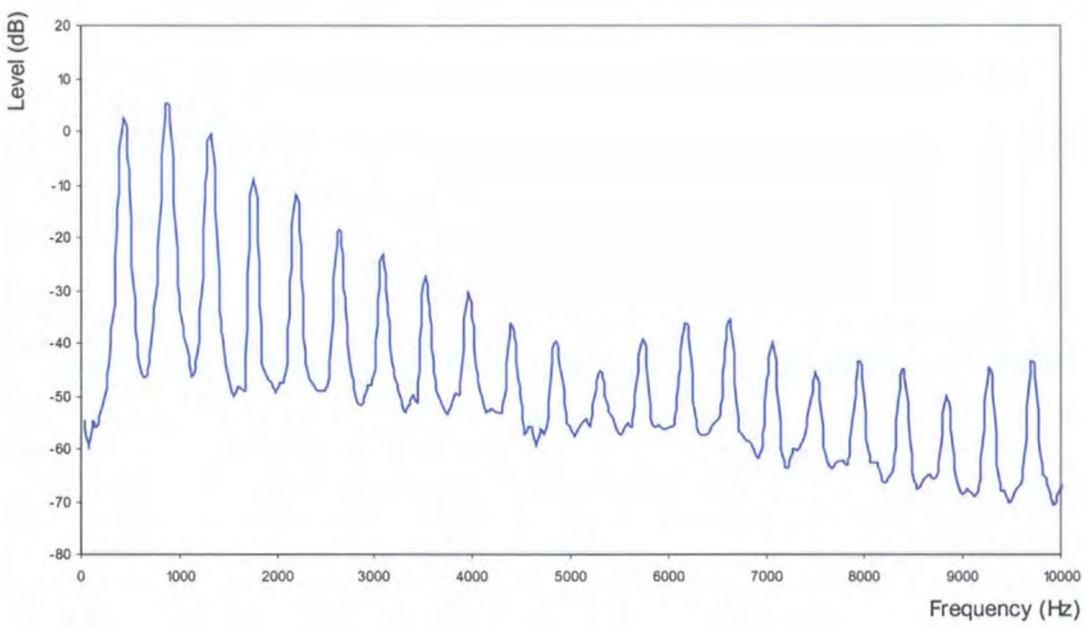
Frequency (Hz)

G#4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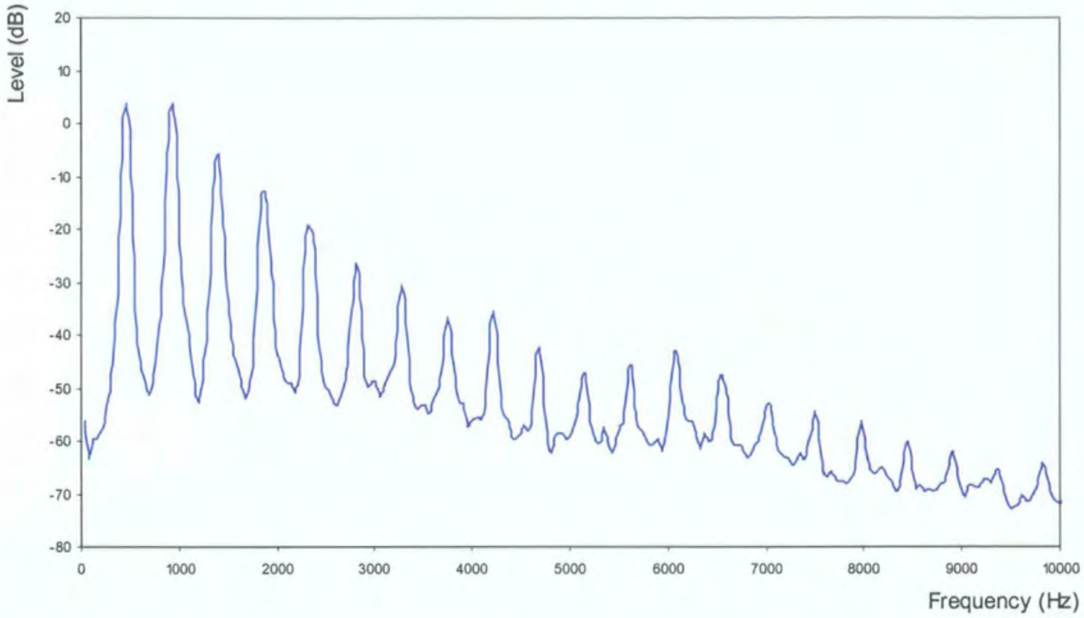
Frequency (Hz)

A4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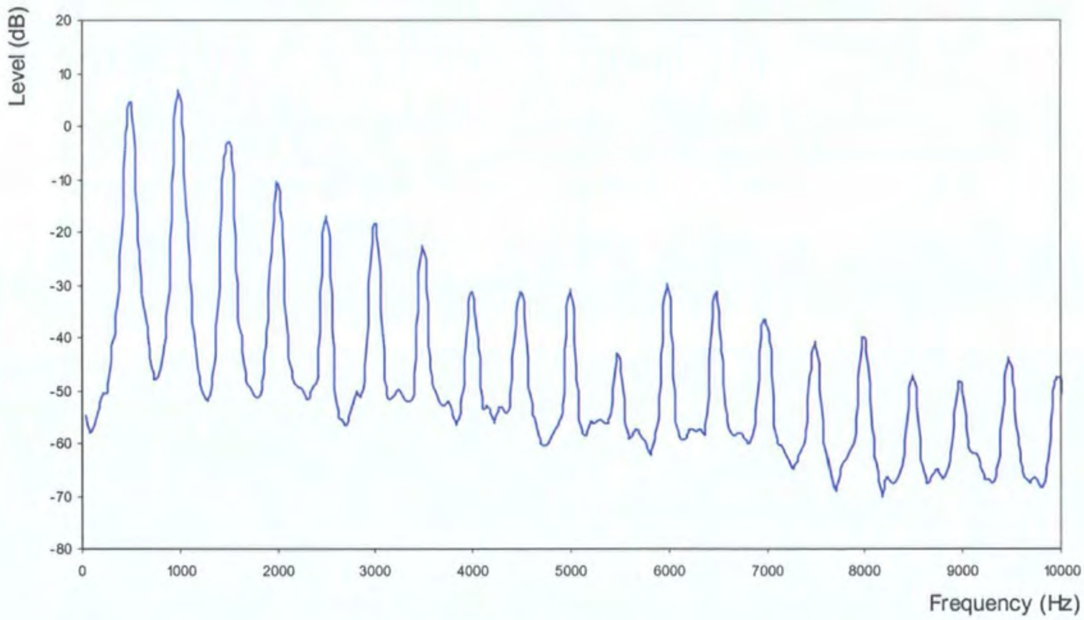
Frequency (Hz)

A#4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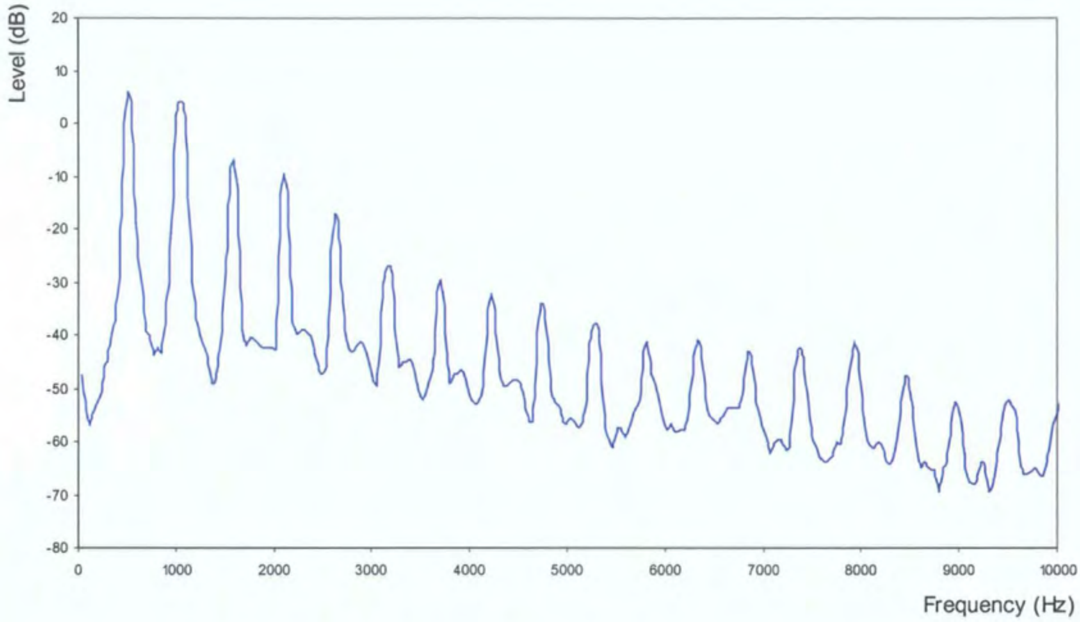
Frequency (Hz)

B4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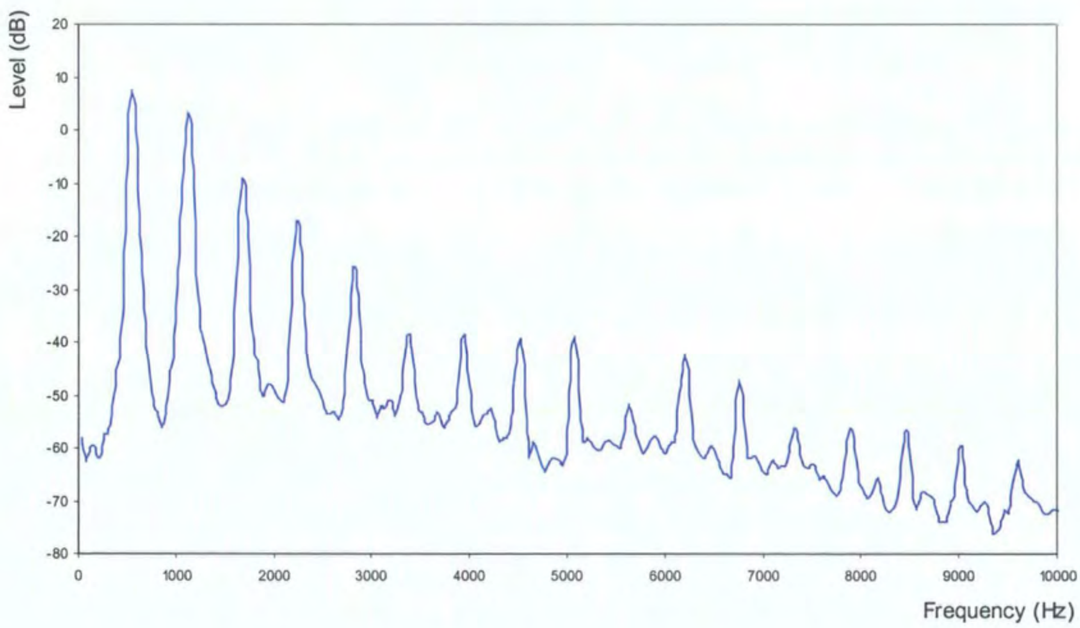
Frequency (Hz)

C5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Frequency (Hz)

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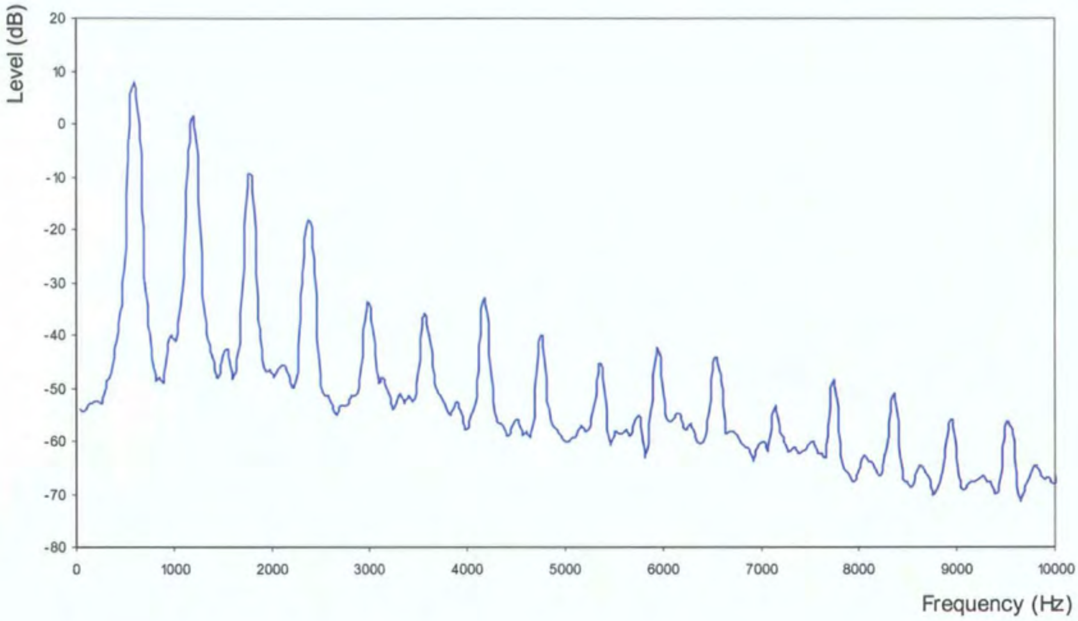

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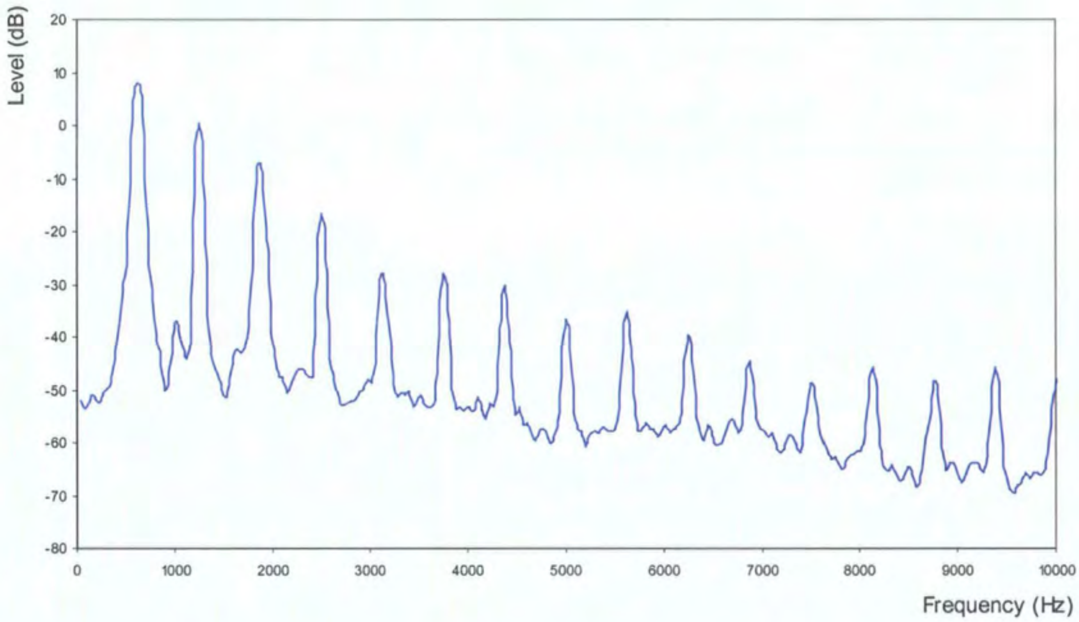
Frequency (Hz)

D5



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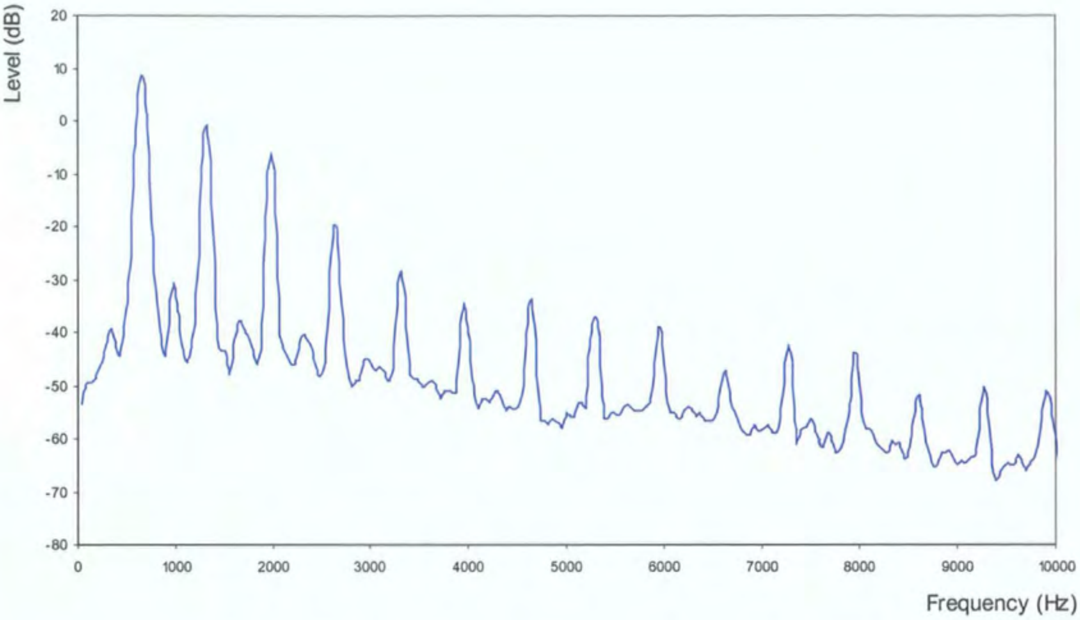

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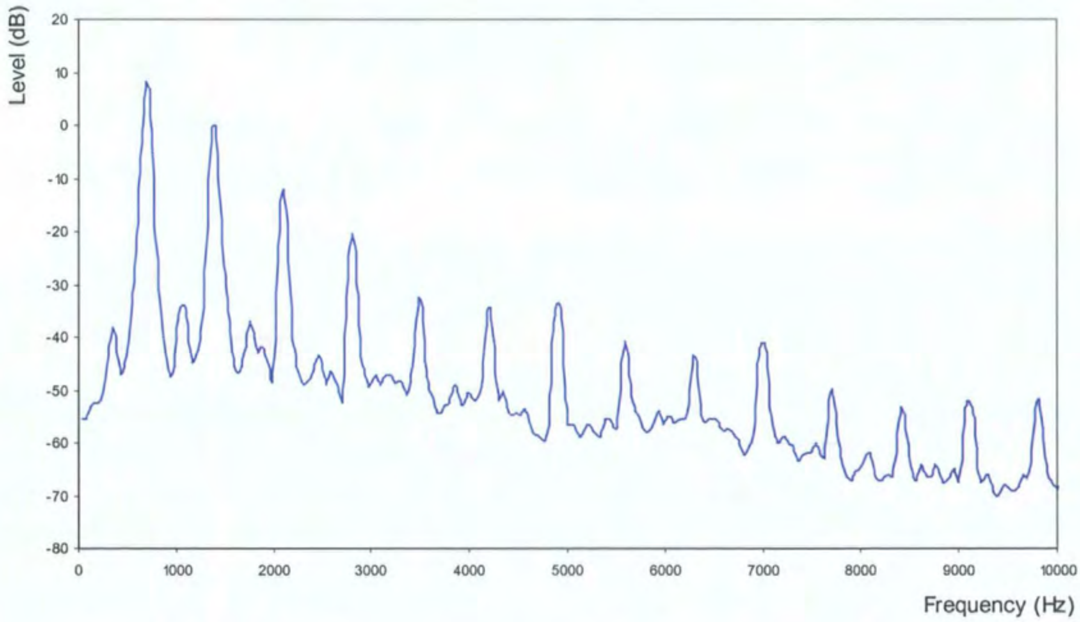
Frequency (Hz)

E5



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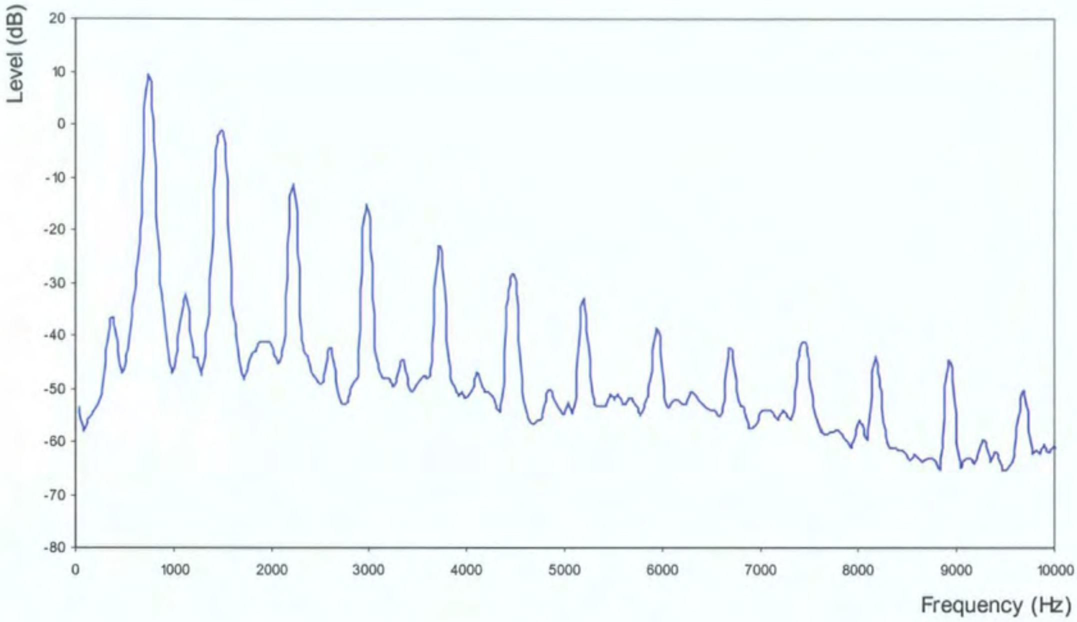
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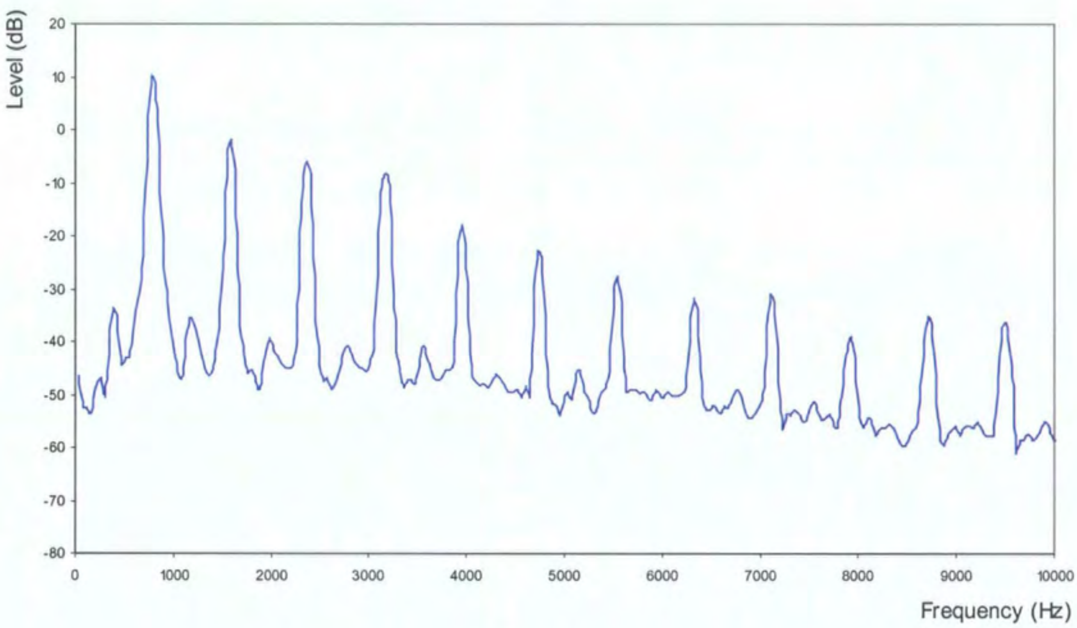
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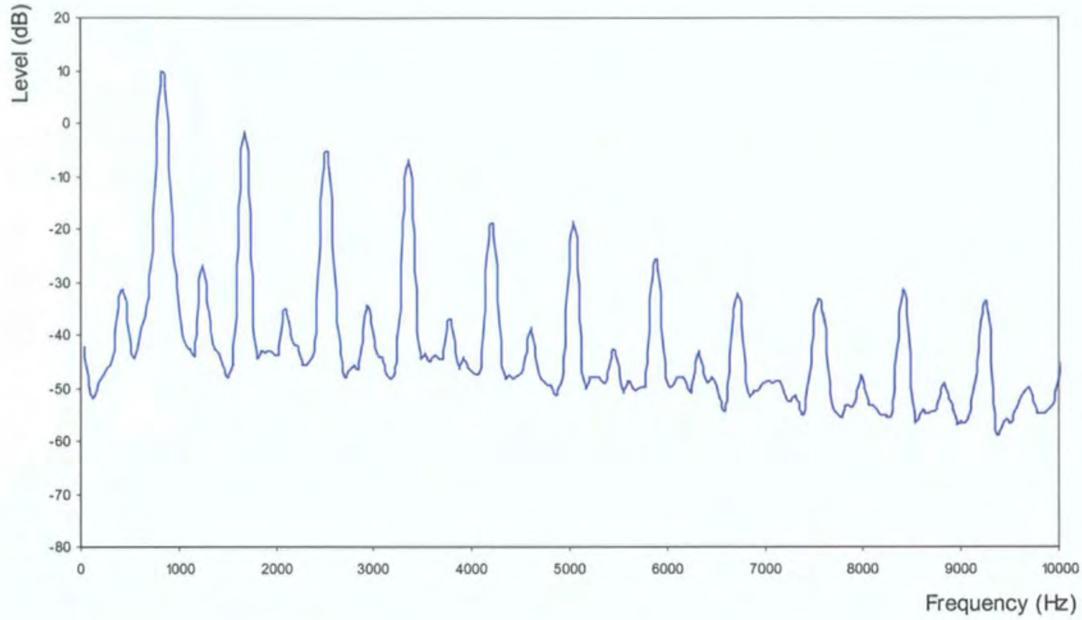
Frequency (Hz)

G5



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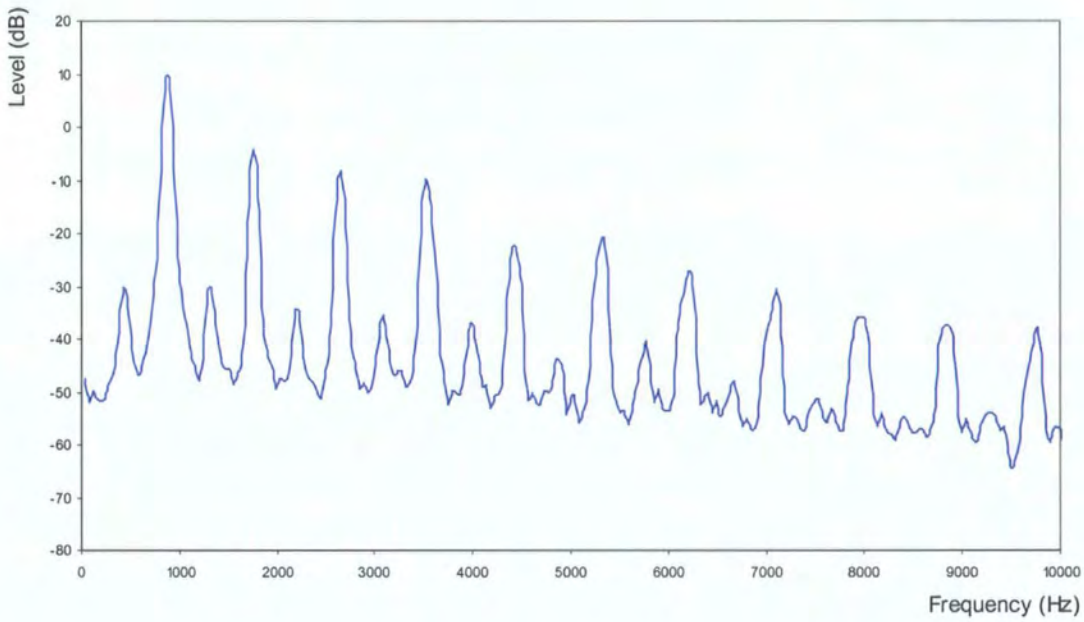
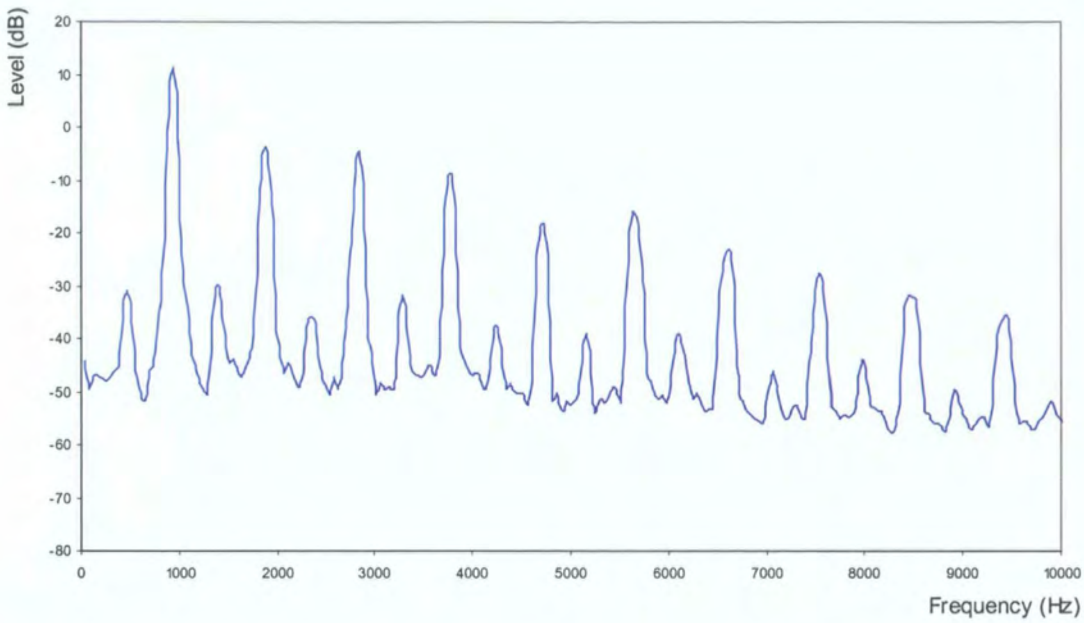
G#5

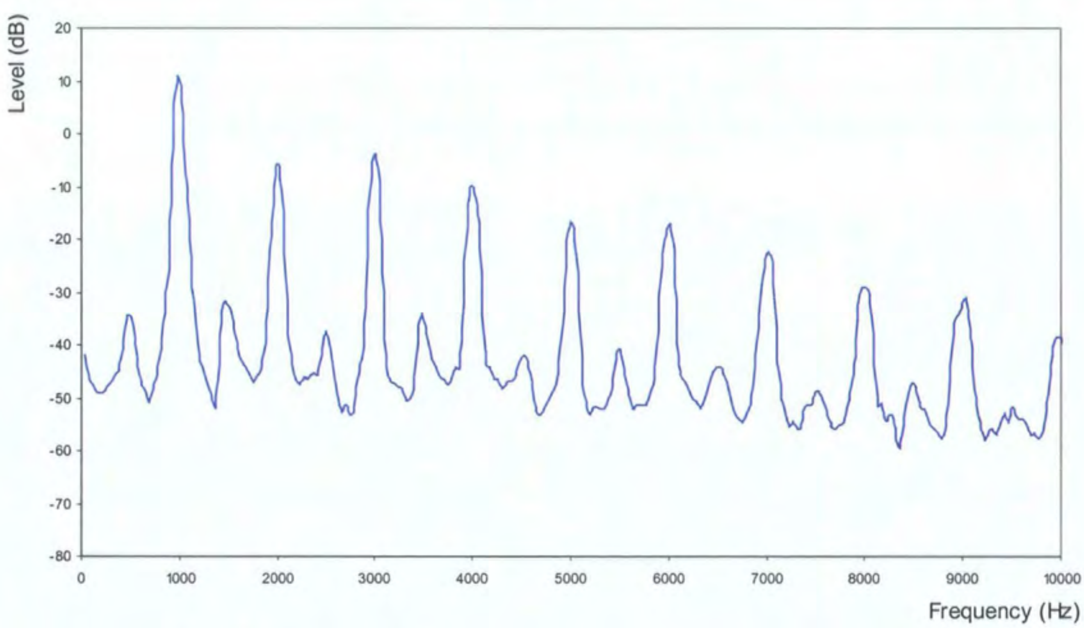


Level (dB)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Frequency (Hz)

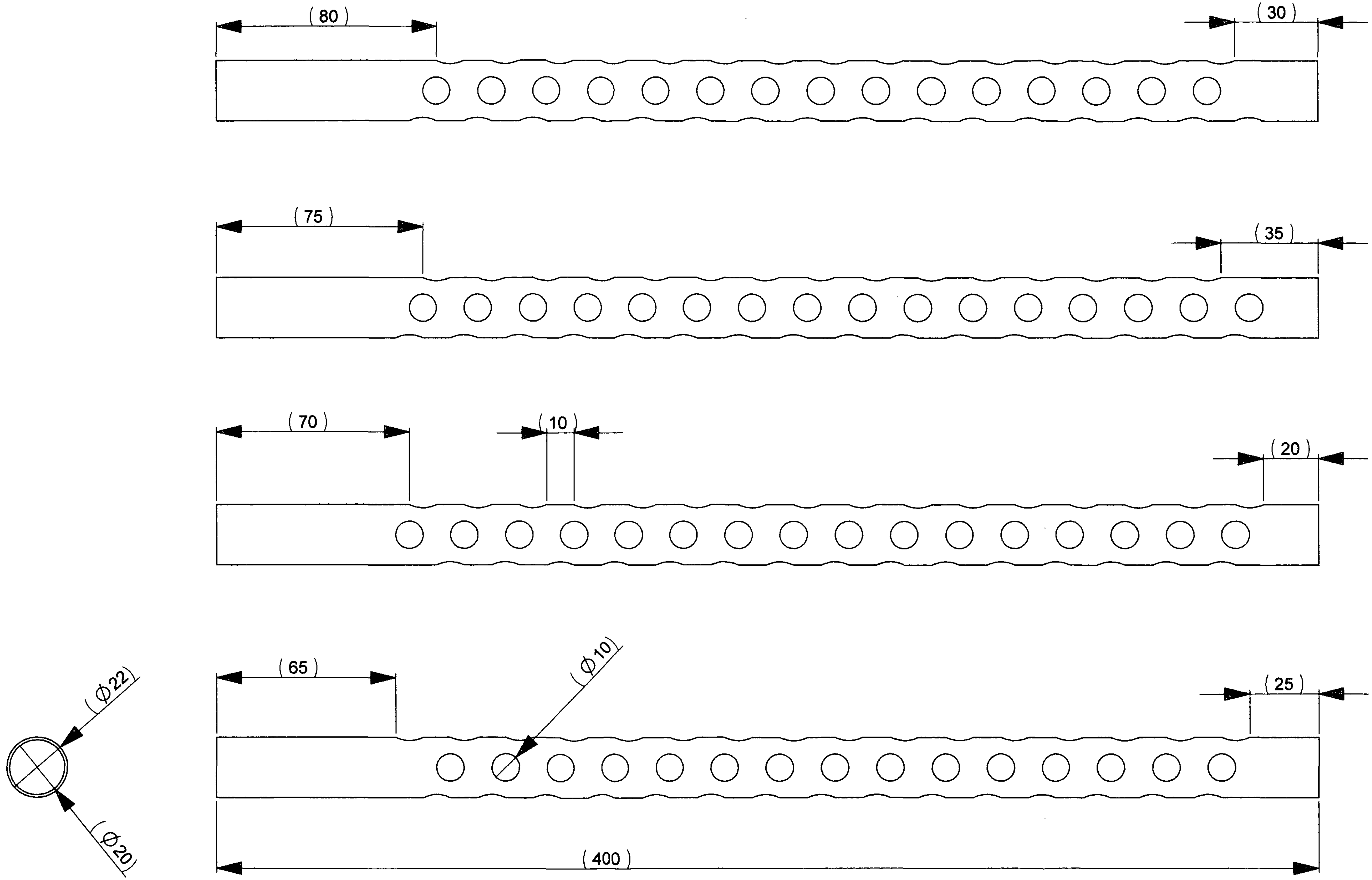
A5


Level (dB)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Frequency (Hz)

A#5


Level (dB)
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Frequency (Hz)

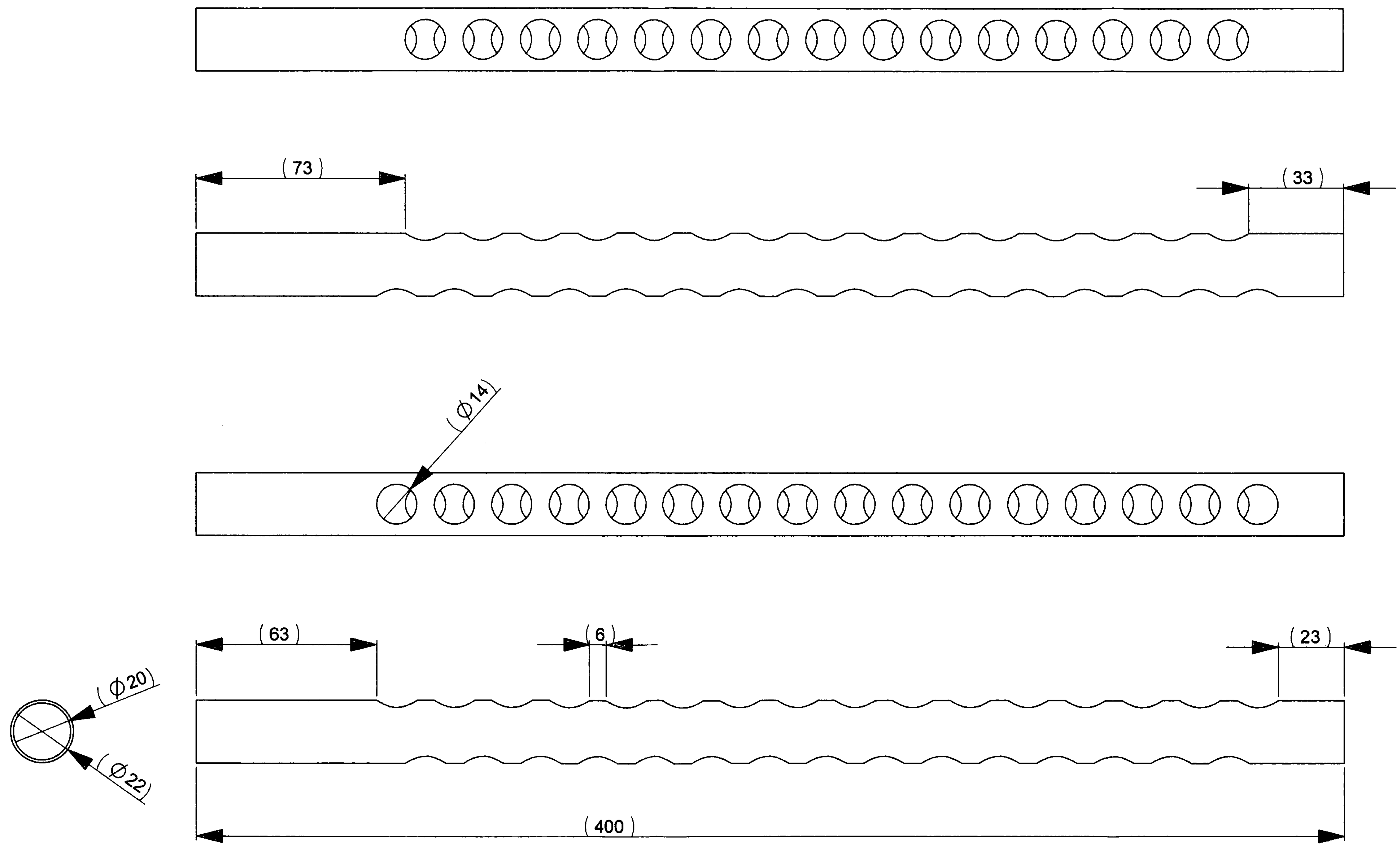
B5



10mm Sieve Flute

Scale 1:1.5

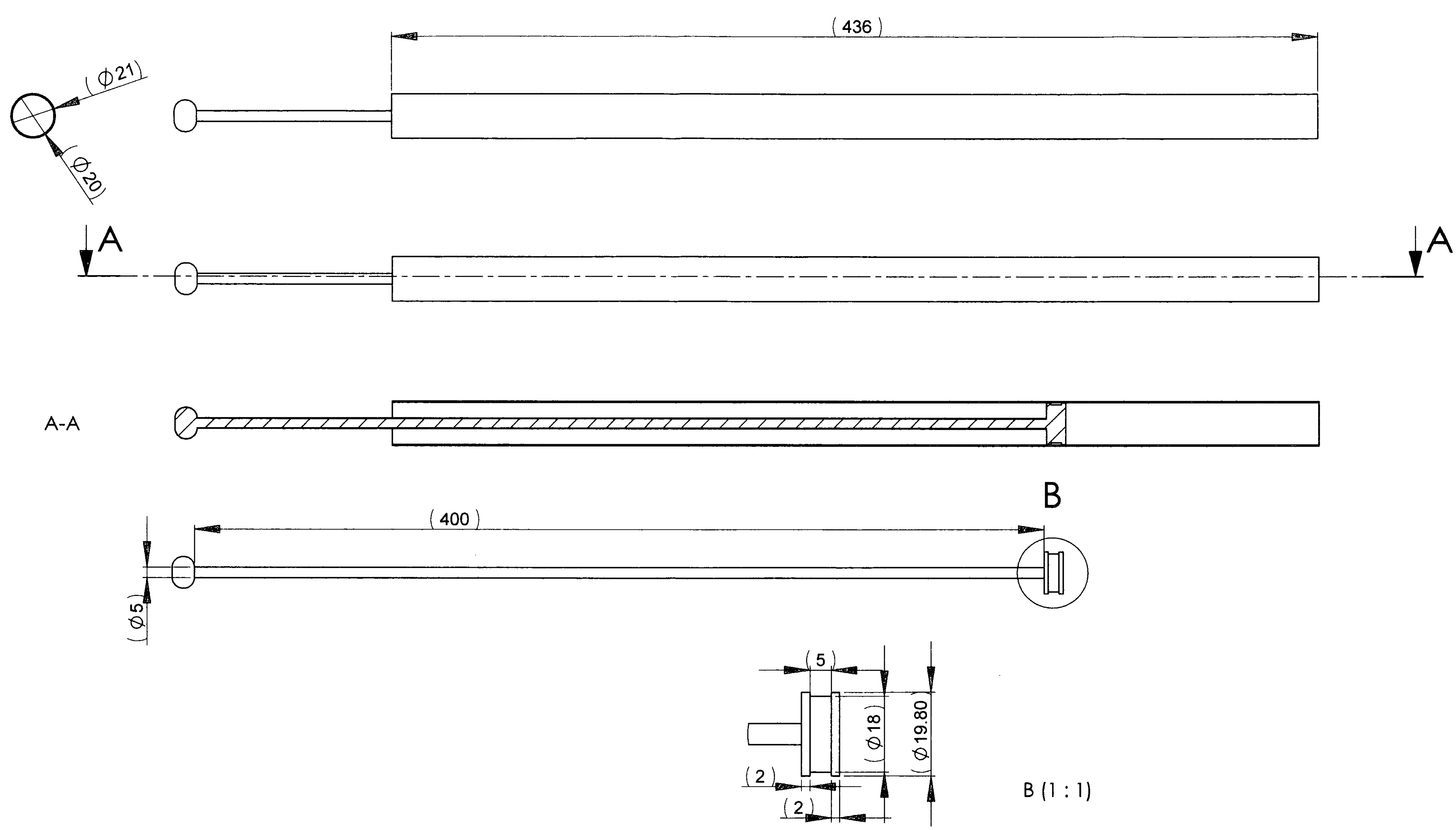
All measurements are in millimetres



14mm Sieve Flute

Scale 1:1.5

All measurements are in millimetres



Plunger Flute

Scale 1:2

All measurements are in millimetres