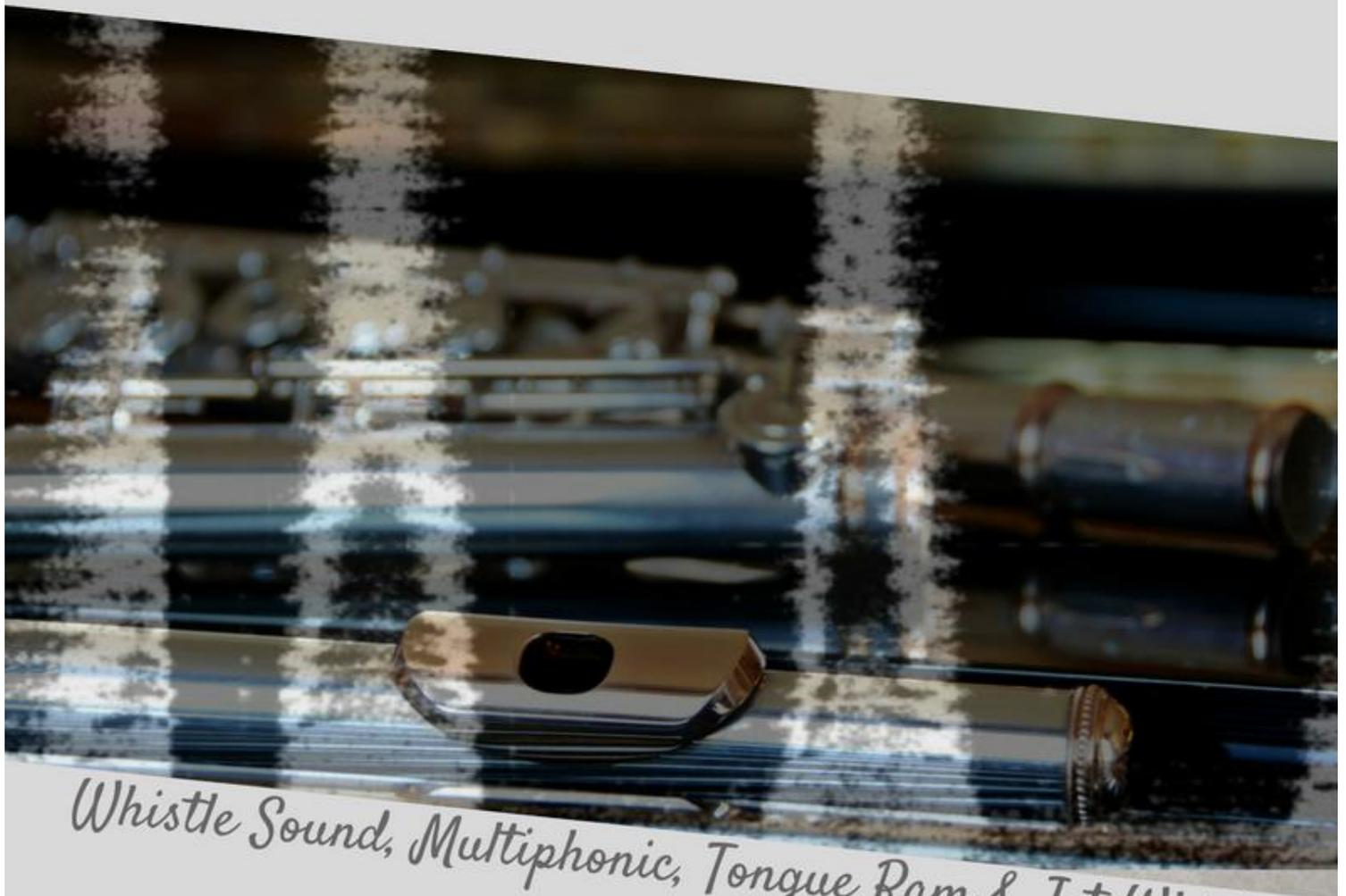


Artistic Research by Sofia Gantois
Flute class of Valerie Debaele

The influence of scientific
knowledge on extended flute
techniques and their execution



Whistle Sound, Multiphonic, Tongue Ram & Jet Whistle



Fontys School of Fine and Performing Arts

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SUMMARY

The topic of this research paper are four contemporary flute techniques; whistle sounds, multiphonics, tongue ram and jet whistle. I wanted to understand these techniques from a scientific point of view and see if this knowledge can then help me improve their execution. There have been few studies done on the acoustical characteristics of these techniques and they have intrigued me for a long time. I am convinced that it is important to understand how something functions in order to be able to correct or improve it and I think this knowledge can help a lot of flutists understand their instrument better and make them more aware of the physical processes involved in executing these techniques.

First, I had to gather information about the scientific and acoustical functioning of the techniques, but this turned out to be difficult. There are few sources that deal with these from an acoustical or scientific point of view. We can only find sources about how to execute the techniques and not how they originate and function. There are more sources about multiphonics because other instruments use this technique too.

I decided to investigate this problem from my own background in acoustics and physics. I studied the basis of flute acoustics and from there on formed theories for the techniques I wanted to investigate.

To help me with my theories I went looking for an expert in the field of acoustics. I contacted several acousticians and flute builders and eventually came into contact with Michèle Castellengo who was able to assist me in my work.

After this theoretical study I had to figure out what solutions or tips I could derive from this work for improving execution of these techniques on the flute. I tested the ideas I had and also worked through a number of sources devoted to the execution of contemporary techniques. With the knowledge I had gained from acoustics I was quickly able to predict which performance solutions would work and which would not. In this way I gathered insight into each of the techniques studied. As a result, I now understand why they function and how they can be performed easily.

It was a very intriguing journey and one that remains as of yet unfinished. In my search, I discovered a number of further issues that still have to be studied; similarities of mouth cavity for whistling and flute playing, new sorts of whistle sounds based on the functioning of the jet whistle and also throat tuning needs further investigating.

INTRODUCTION

In this research paper, my goal is to submerge myself in the world of contemporary or extended techniques on the flute. I love to play contemporary music and execute these techniques, because we learn to go so much further in our flute playing than we ever imagined, by adding this pallet of new sounds. Contemporary music and extended techniques can teach us to go much further in our performances and thus also influences the way we play the standard flute repertoire.

I noticed that teaching and learning extended techniques is very hard. In my eyes this is because we approach these techniques in a purely sensory-based way, our teachers try to describe what they feel and do whilst performing these techniques and then ask you to search for the same sounding result. Phrases such as “maybe you can try this” or “wait, let me see how I do that” are very commonly heard when learning contemporary techniques. There is no real thinking involved, just feeling and listening. In instrumental studies and teaching we often learn through these sensory-based methods, but for the study of extended techniques this did not strike me as enough. I was able to learn them, but I felt that having more information on how these sounds are conceived, how they are scientifically possible and explainable, would lead to more efficient learning, for me and for other flute players.

In my search for information I discovered there are few sources that deal with these techniques from a scientific point of view. Most sources have a “do-it yourself” kind of approach and favour explanations of describing what one should do to be able to execute specific techniques. Multiphonics were the only techniques on which I found scientific studies. Because a larger group of wind instruments make use multiphonics there has been more research on this subject. Brannan-Cooper, a flute building company, has done basic research on multiphonics on the flute in order to facilitate the introduction of a new flute-system as an alternative for the Boehm-system; the Kingma-system. This system allows the flutist to play a complete quarter-tone scale in a much easier way than on the Boehm-flute. This Kingma-system also creates far more possibilities for multiphonics as compared to the Boehm-system.

On other techniques such as whistle sounds, the tongue ram and the jet whistle I have found little to no information from scientific sources. There are a number of sources explaining how to execute these techniques but I have found almost none explaining how they function. As a result of the lack of information available to me I have focused this research paper on investigating four common extended techniques, namely: whistle sounds, multiphonics, tongue ram and jet whistle. These techniques are well known in the flute world and there seems to be a general agreement about the way they “should” sound. There is of course room for personal interpretation, but there are some characteristics that must be present in each technique to make its sound identifiable as such.

My study contains two different parts, a theoretical aspect and a practical aspect. I wanted to see if I could use the knowledge that I gained by scientifically investigating extended techniques to improve the execution of these techniques. I formulated this in the following research question: “How does scientific knowledge on extended flute techniques influence their execution?”

These four techniques I decided to investigate, were introduced in the 20th century and are mostly found in music composed in the 1970’s and 1980’s through to today. For each of the techniques I asked to following questions:

- How is the specific sound conceived?
- In what way is the sound different from normal flute playing?
- How can I explain the difference in sound, compared to normal flute playing, from an acoustical point of view?
- Now that I understand how this technique works, what can I do to optimise its execution?

- How can training this technique help advancing in normal flute playing, in repertoire without extended techniques?

These techniques can be used in different styles of contemporary music, but the style of music doesn't influence the execution or end result of the technique. There is no absolute right way of doing them, but there are uniform standards for the sounding result. The standards are individually defined for each technique and I will talk about this more thoroughly in each chapter. Of course we must not forget that the composer or performer maybe wants the extended technique to sound differently than "expected", but even then it is good to be able to play the technique as it "should" sound, so the performer can consciously transform it. I put together a set of best practices or tips for executing these techniques based on scientific information.

I finish my research with a case study of a contemporary piece I played last year. All four techniques I investigated are in it and I had a regular contact with the composer, Edgar Guzman, who gave me 2 recordings by 2 different flute players. In the case study, I compare the execution of the techniques on the recordings and try to explain why they sound differently. The differences can of course be individual choices and I do not judge the correctness of the execution, I just state what I hear and analyse the differences.

METHOD

I started my search by collecting numerous sources from websites and books. The bulk of the information I was able to collect on contemporary flute techniques did not go further than explain on how to execute them. There was a lack of scientific sources that I had hoped to find and there was nothing left for me to do but to go back to the basics of acoustics and build up a theory myself.

I immersed myself in the basics of flute acoustics, with the help of the many sources that are available. I studied the acoustical bases of waves and sound and examined a good deal of source material on the acoustics of normal flute playing. From there, I tried to form theories about the four techniques I wanted to understand. I felt that I needed the assistance from someone with expert knowledge about acoustics and about flutes, to help me with my theories.

After contacting various flute builders and acousticians I was happy to come into contact with Michèle Castellengo. She is working for the LAM (Luthiers-Acoustique-Musiques) and is head of research at the *Centre National de la recherche scientifique* (CNRS), both in Paris. She is an amateur flute player and specialist in the acoustics of the flute, the human voice and organ pipes. She created a class of acoustics in 1989 at the *Conservatoire Nationale Supérieur de Paris* and a specialised master's degree, which she led from 1999 until 2004.

Madame Castellengo kindly received me in her office at the LAM in Paris, where she looked through my theories and together we were able to make sense of the various phenomena. she was very excited about the jet whistle in particular, because she never did any research on this technique. I would like to thank her for the collaboration, she has been very helpful to me throughout the process.

After formulating a theoretical basis for my work I studied the questions surrounding how knowledge influences the execution of the extended techniques. I started off writing down all the logical things I could think off that could help each technique based on the findings of the scientific research. I tested them and added more during the process. After this I took a look at the tips given in the literature on executing these techniques. I made an overview of the best of these techniques with the help of the theoretical knowledge I had gained and was able to eliminate impractical advice.

Throughout the process I used sound analyses and spectrograms, to confirm what my ears told me. The software used was Raven Lite 1.0 and Audiosculpt.

1 BASES OF FLUTE ACOUSTICS

1.1 THE FLUTE IS AN OPEN TUBE

Before examining the extended techniques on the flute, it is important to have some knowledge on the bases of acoustics and more specifically the bases of flute acoustics.¹

The flute does not have a reed nor is sound produced with a mouthpiece like that of a trumpet or other brass instruments. Acoustically the flute acts like a pipe, open at both ends. We say it is open at both ends because the embouchure hole is not covered while the flutist plays on it. The length of the tube can be adapted by opening or closing the holes in the tube.

We know that a tube, with a specific length, has a natural frequency at which it wants to vibrate. This is the fundamental frequency of that tube, the lowest frequency that it can possibly produce. We can hear this frequency by hitting the tube against something .

In normal tone production on the flute, we blow into the tube and a standing wave will be formed. For an open-ended tube the antinodes are always at the extremities of the tube. The first vibration mode has one node and two antinodes, as presented on the image below.



Image 1: first vibration mode

In this first vibration mode, the frequency of the source is synchronised with the natural frequency of the tube itself.

If we raise the source's frequency and this frequency synchronises at double the natural frequency of the tube, we find the second vibration mode.

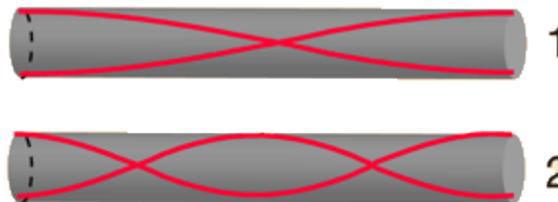
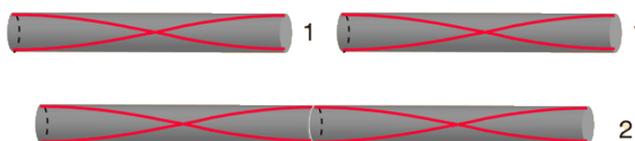


Image 2: first and second vibration mode

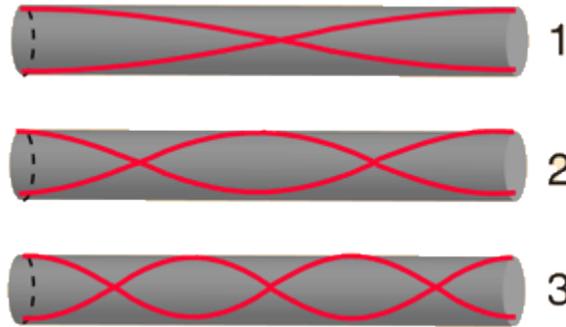
We now have two nodes and three antinodes. It is as if the first tube has transformed itself into two tubes of half its length.



Musically speaking the second vibration mode sounds an octave higher than the first vibration mode.

¹ Wolfe, J. (2016, august 7). *Open vs Closed Pipes (Flutes vs clarinets)*. Retrieved from UNSW Music acoustics: <http://newt.phys.unsw.edu.au/jw/flutes.v.clarinets.html>

If the frequency of the source synchronises at triple the natural frequency of the tube, we find the third vibration mode of the tube. Musically speaking the third mode sounds an octave plus a fifth higher than the first mode.



As we keep on augmenting the frequency of the source we find more and more vibration modes of the tube. They look like this:

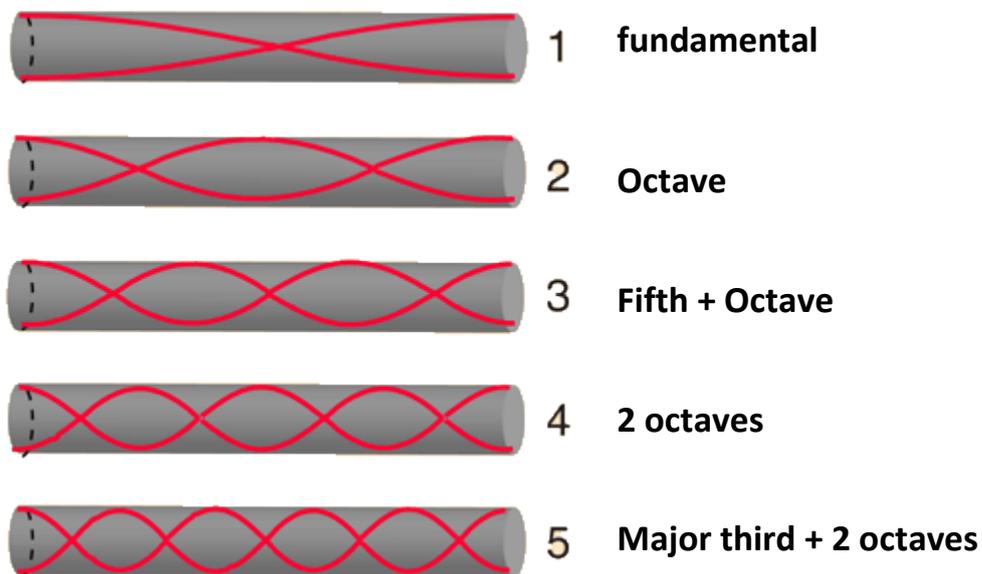


Image 3: vibration modes in an open end tube

A tube has one natural frequency, but multiple modes and their frequencies at which it can vibrate, depending on the frequency of the source. Because the flute is an open tube at both ends, the different modes are integer multiples of the fundamental. This means that we take the natural frequency and we multiply it by 2, 3, 4, 5, 6, etc. to find the frequency of the different modes. The different vibration modes follow the harmonic sequence completely. On this image you can see the natural harmonic series of a low C (with slightly to high A or to low B flat).

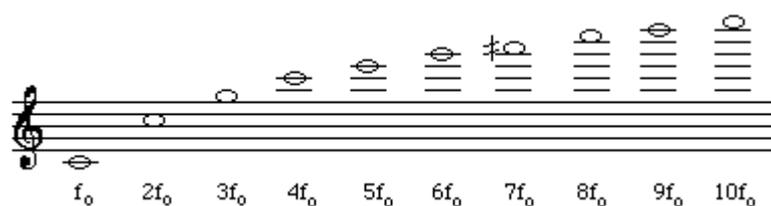


Image 4: harmonic series of a low C on the flute

For a tube closed on one side, this is not the case. A clarinet or oboe can only play the odd frequencies of the harmonic sequence, using only one tube length, thus without opening or closing keys.

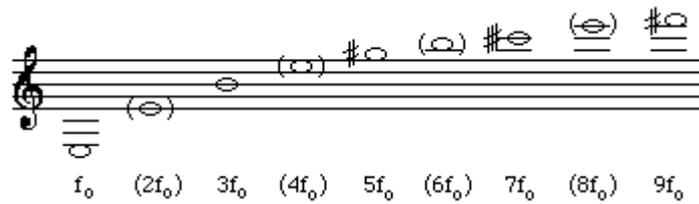


Image 5: harmonic series of a low E on a clarinet

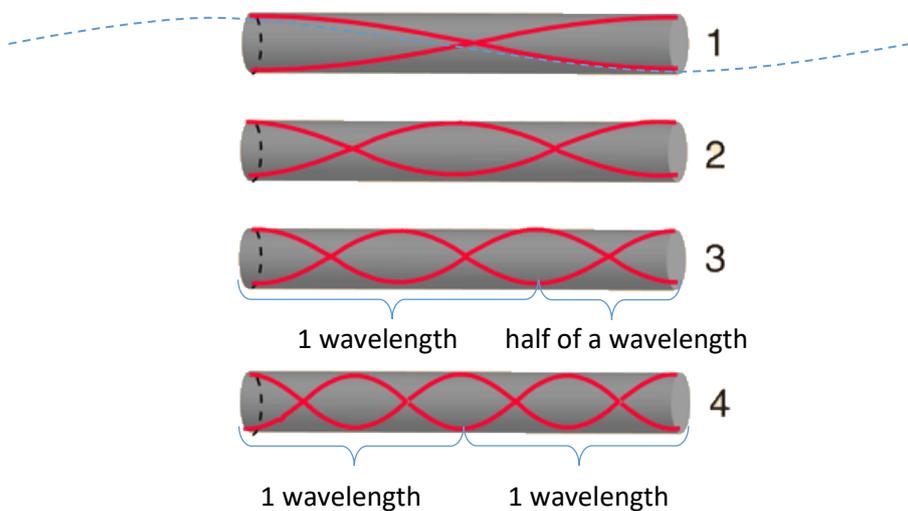
This can be explained by calculating the frequencies of the different modes that can be obtained within one tube of a certain length. The basic formula for frequency is:

$$F = \frac{v}{\lambda}$$

(F = frequency, v = airspeed and λ = wavelength)

The wavelength varies for each mode, so we are going to try to express it in tube length, which stays the same for the whole experience.

Let's take a look at the open end tube, the equivalent of the flute.



As you can see in the image, for the first mode, we only have half of a wavelength in one tube length.

The second mode has 1 wavelengths in one tube length.

The third mode has one and a half wavelengths in one tube length.

The fourth mode has 2 wavelengths in one tube length.

This means that for F1: $\lambda = 2l$ (with l = tube length)

F2: $\lambda = l$

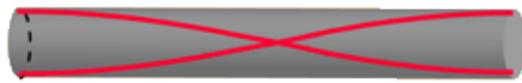
F3: $\lambda = \frac{2}{3}l$

F4: $\lambda = \frac{1}{2}l$

This gives us the following formula for an open end tube $\lambda = \frac{2l}{n}$ ($n = 1, 2, 3, \dots$).

Then we replace the wavelength in the formula for frequency.

$$\lambda = \frac{2l}{n} \rightarrow Fn = \frac{v}{\lambda} = \frac{nv}{2l} \rightarrow Fn = nF1$$



1 $\lambda = \frac{2l}{1} = 2l \rightarrow F1 = \frac{1v}{2l}$



2 $\lambda = \frac{2l}{2} = l \rightarrow F2 = \frac{2v}{2l} \rightarrow F2 = 2F1$



3 $\lambda = \frac{2l}{3} \rightarrow F3 = \frac{3v}{2l} \rightarrow F3 = 3F1$

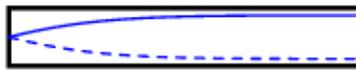


4 $\lambda = \frac{2l}{4} = \frac{l}{2} \rightarrow F4 = \frac{4v}{2l} \rightarrow F4 = 4F1$

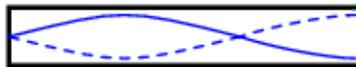


5 $\lambda = \frac{2l}{5} \rightarrow F5 = \frac{5v}{2l} \rightarrow F5 = 5F1$

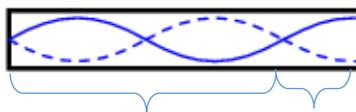
For a tube closed at one end, with the same tube length, this is different.



As you can see in the image, for the first mode, we only have a quarter of a wavelength in one tube length.

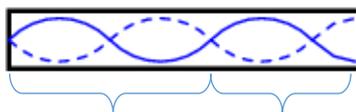


The second mode has 3 quarters of a wavelength in one tube length.



The third mode has one and a quarter wavelengths in one tube length.

One wavelength ¼ of a wavelength



The fourth mode has one and 3 quarters wavelengths in one tube length.

One wavelength ¾ of a wavelength

This means that for F0: $\lambda = 4l$

(with l = tube length)

F1: $\lambda = \frac{4}{3}l$

F2: $\lambda = \frac{4}{5}l$

F3: $\lambda = \frac{4}{7}l$

This gives us the following formula for a tube closed on one end: $\lambda = \frac{4l}{(2n+1)}$ ($n = 0, 1, 2, 3, \dots$).

Then we replace the wavelength in the formula for frequency.

$$\lambda = \frac{4l}{(2n+1)} \rightarrow F_n = \frac{v}{\lambda} = \frac{(2n+1)v}{4l} \rightarrow F_n = (2n+1)F_0$$

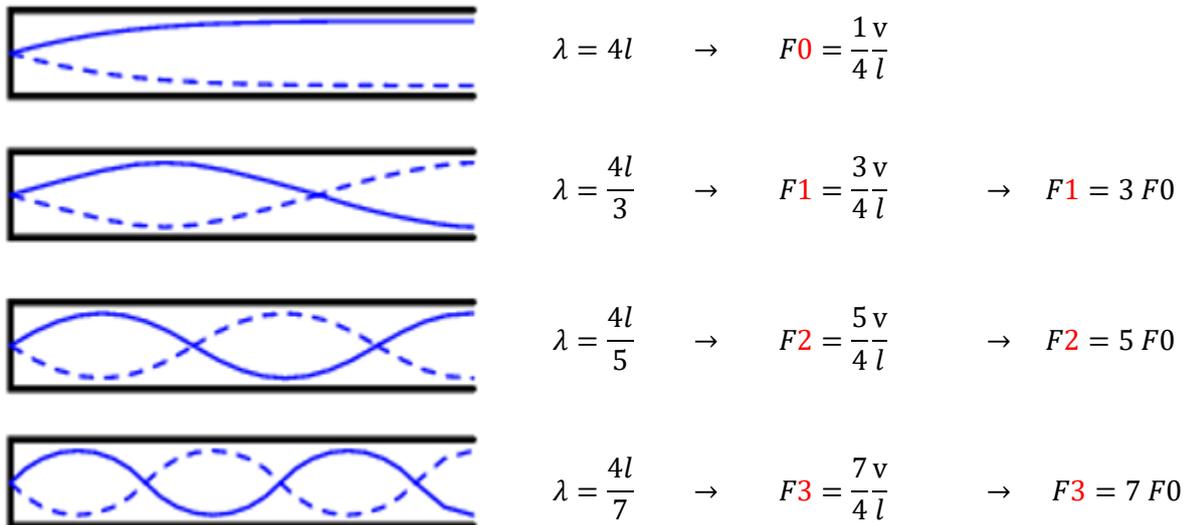


Image 6: vibration modes in a tube closed at one end

We can see that for a tube with one closed end, the frequencies of the different modes can be found by multiplying the frequency of the fundamental note with 3, 5, 7, 9, 11, 13, ... or else the odd numbers. This is why instruments closed at one end of a certain tube length, can only play the odd notes of the harmonic sequence.

1.2 THE AIR JET - LABIUM SYSTEM

After figuring out how the tube works the next stage is to examine the generator or source of excitation. This system is the same for the flute as for the recorder. They are air-reed instruments.

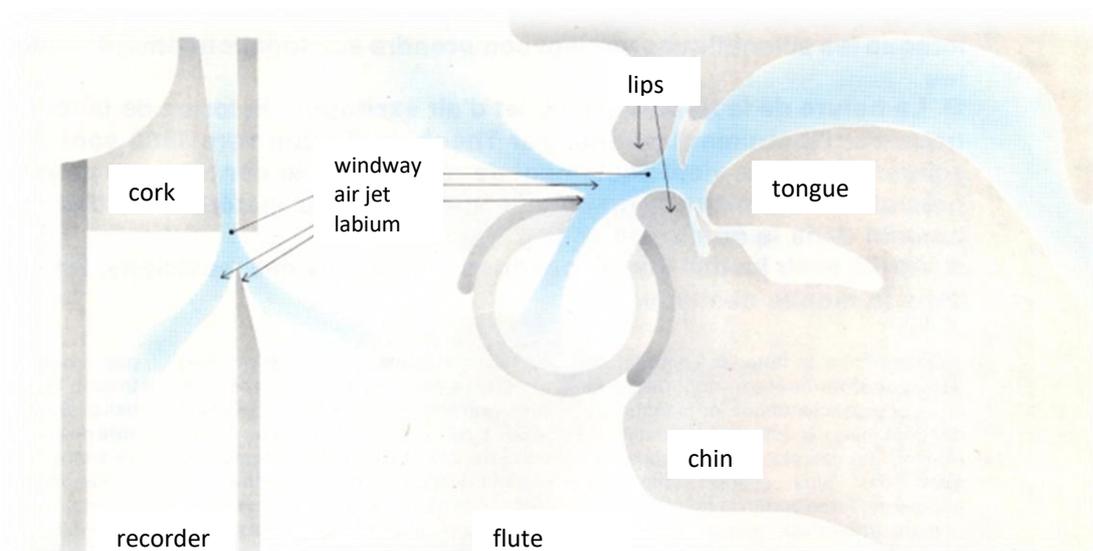


Image 7: the air jet - labium system, comparison between a recorder and a flute

This means the air jet is guided by the windway to the labium. For the flute the air jet is guided by the lips. What happens at the moment the air leaves the lips, is often incorrectly described by a lot of flute players. The statement that the air jet is divided by the labium is not correct. The air jet already starts oscillating the moment it leaves the lips and not only at the moment it touches the labium.²

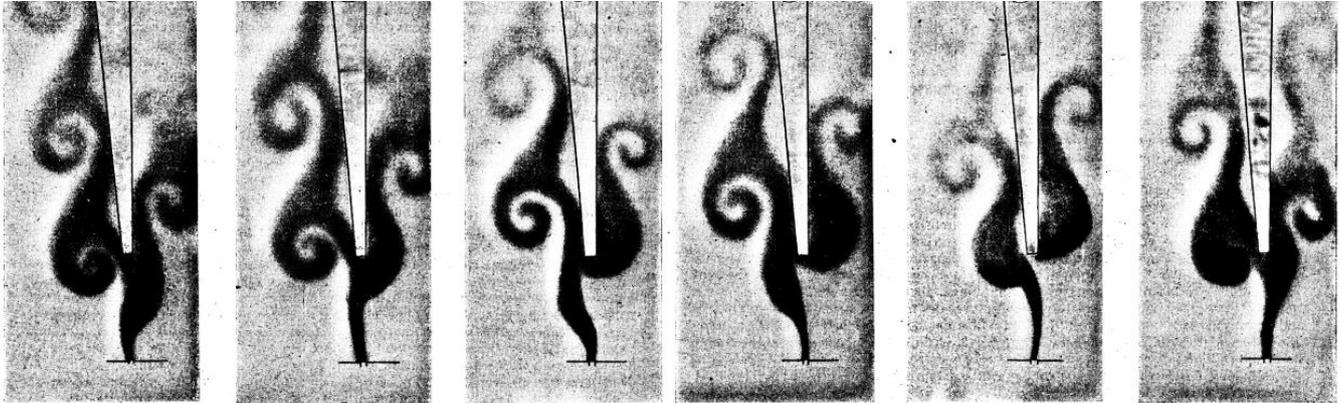


Image 8: movements of the air jet on the moment it leaves the windway

As you can see on this image, the air jet oscillates from the moment it gets out of the windway. You can see the movement even better if you cover the upper half of the image.

If the generator would be sounding without the tube attached to it, we would hear edge tones. These are the sounds produced by the air jet going alternatively from one side to the other side of the labium.³

You can hear these sounds very clearly with a nose flute, an instrument that uses the nose to push air to the labium using the mouth as resonant cavity. If you use this instrument without putting it against the mouth, you will hear a sound that gradually goes higher or lower, depending on the air pressure. The frequency augments very quickly when augmenting the pressure.



Image 9: nose flute

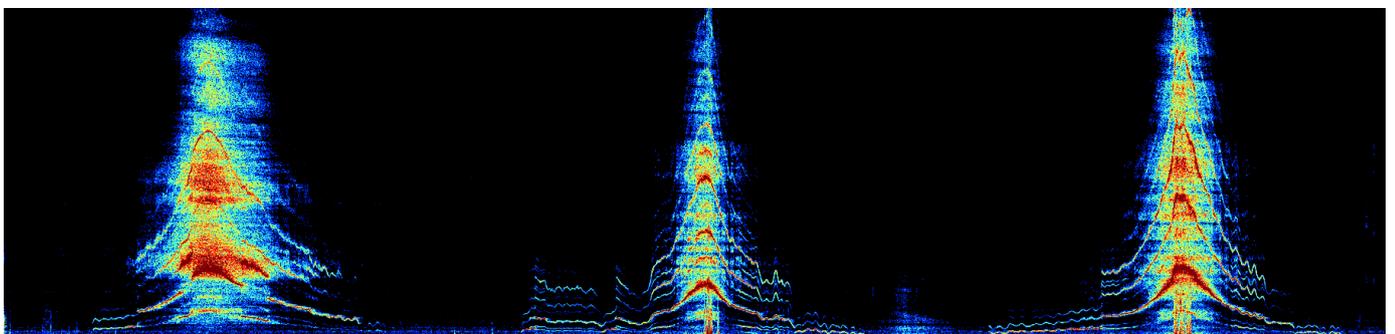
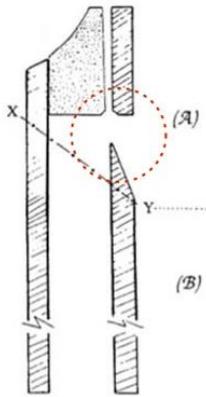


Image 10: spectrogram of edge tones produced with the nose flute

TRACK 1

² Carrière, Z. (1925). Phénomènes à l'embouchure d'un tuyau d'orgue. *Radium*, 52-64.

³ Castellengo, M. (1968). *La flûte traversière*. Paris: G.A.M.



The same thing can be done by cutting the headpiece of a recorder. In this way the air jet-labium system is disconnected from the tube and we can hear the edge tones.

If we associate the two systems we examined; the standing waves of the tube and the edge tones of the air jet-labium system, we see that in 'normal' playing, the frequency of the standing waves is dominant, because of the high air pressure. The air jet-labium system has the role of generator and gives the first impulse then the standing wave reacts to the generating system and imposes its frequency. In the normal functioning of the flute, the edge tones, will have almost no influence.

Image 11: separate the headpiece of a recorder

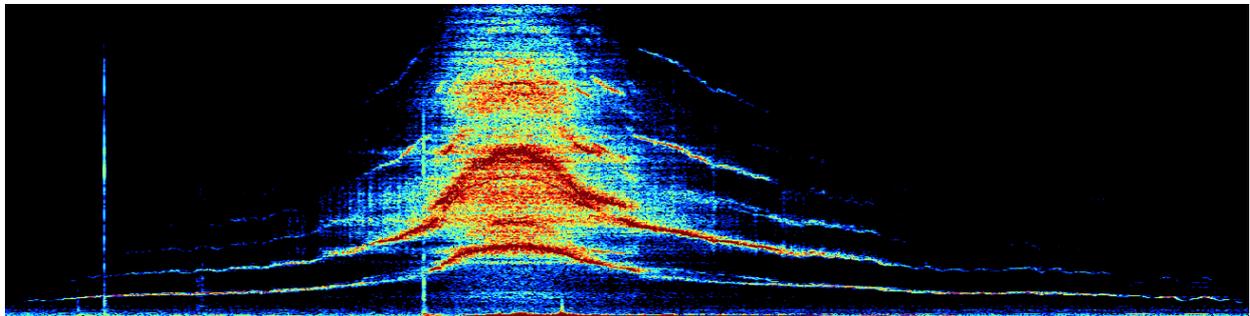


Image 12: spectrogram of edge tones, produced by the headpiece of a recorder

TRACK 2

2 EXTENDED TECHNIQUES

2.1 WHISTLE SOUND

While with normal sound production on the flute the edge tones do not have much influence, the whistle sound or whistle tones are heavily based on them.

By lowering the air pressure, the frequencies of the air jet-labium system become dominant. This is what happens when we play whistle sounds; the air pressure is low and so the frequencies of the edge tones become important.

When listening to whistle sounds we do not hear a gradually changing sound, like that of edge tones, but we hear unstable, individual pitches.

What happens is that the edge tones use the different modes of the tube and stabilise on them. We do not hear the gradually augmenting sound of the edge tones, but we hear a defined pitch every time that the frequency of the edge tone corresponds to one of the frequencies of the modes of the tube. The tube reinforces the frequencies of the edge tones that correspond to the frequencies of its own modes.

As a result, the whistle sounds follow the harmonic sequence, because the edge tones are stabilised on the modes of the tube. Although we will maybe not hear the lowest harmonics, because they are very hard to play, it is possible to play the harmonic sequence from the lowest note until pretty high (7th, 8th, 9th harmonic or even higher, depending on the note).

The low whistle sounds are difficult to play because very little air pressure is needed. The frequency of the edge tones augments quickly with the air pressure, so if we want the edge tone to stabilise on a low whistle sound we need a very stable airstream with almost no pressure.

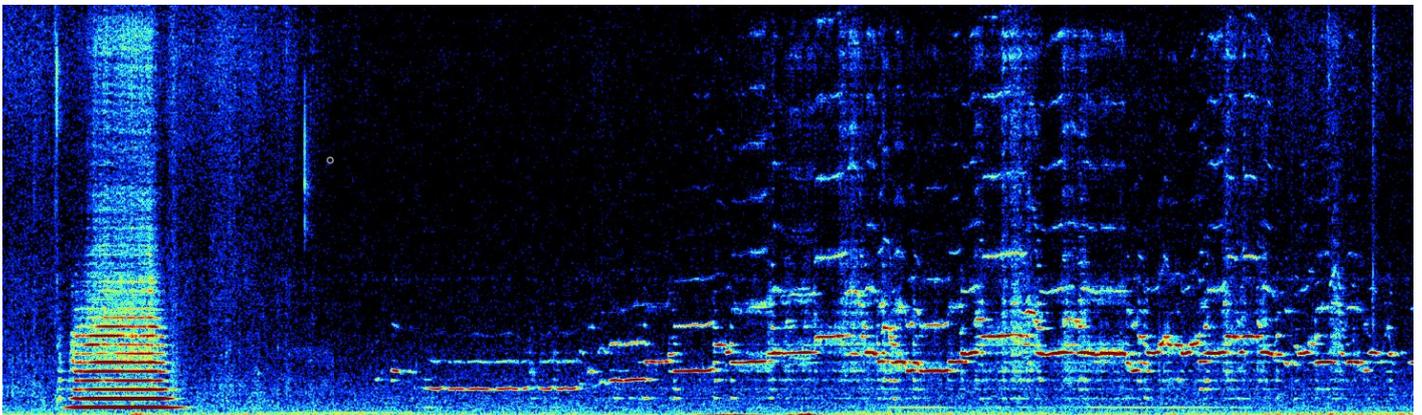


Image 13: Spectrogram of a low C and whistle sounds on a C fingering

TRACK 3

2.2 MULTIPHONIC

Another technique that has existed for a long time now, is the multiphonic. The *Sequenza* for solo flute by Luciano Berio, written in 1958 was the first work using this technique. It's a sound that is formed by multiple pitches sounding at the same time; often two or three. The flutist thus manages to make multiple modes of the tube oscillate at the same time. This is often made possible by using fork-fingerings, this means we have one or a series of closed tone-holes, then one or maybe two open tone-holes and then one or more closed tone-holes again. This results in two/three independent standing waves patterns⁴.

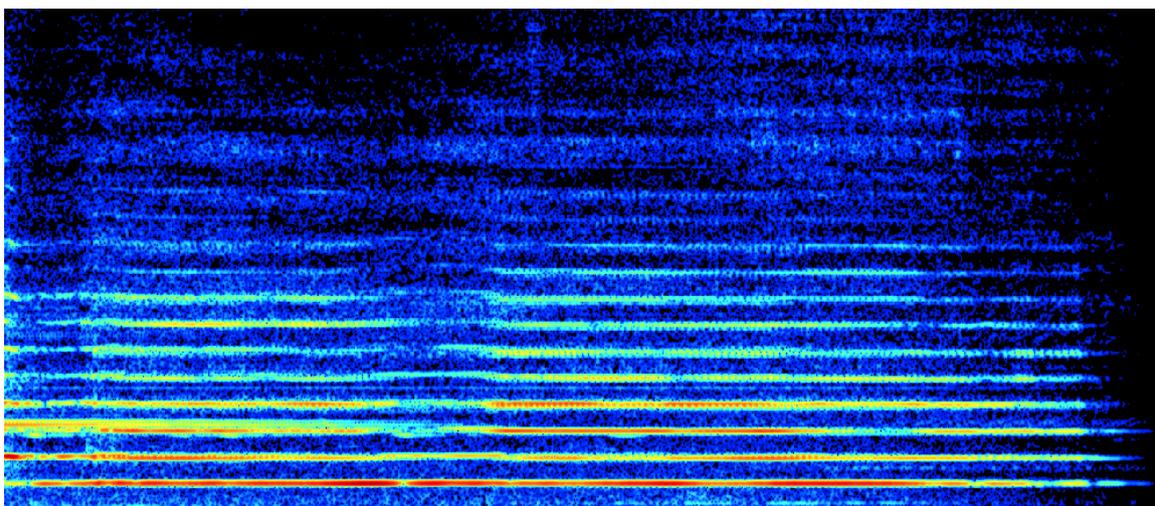


Image 14: spectrogram of a multiphonic

TRACK 4

To understand this better, it is necessary to explain the difference between the displacement pattern and the pressure pattern of a standing wave. The pattern I used in the previous chapter is what we call a displacement pattern. They show the areas where the air particles move a lot (antinodes) and the places where they do not move at all (nodes). A pressure pattern of a standing wave is a pattern that shows us the areas where there are big changes of pressure and the places where the pressure stays constant.

On the next page (image 16) you can see air particles in an open-end tube, the sound wave travels through them from the left to the right. If we observe individual molecules we see that some move a lot and others don't and we can see areas with great pressure and areas without pressure. The first pattern we see in each image is the displacement pattern and the second is the pressure pattern.

⁴ Shiung, C. Y. (2008). *the Brannen-Cooper Kigma system Flute: a resource thesaurus of multiphonic production capability*. New York: New York University.

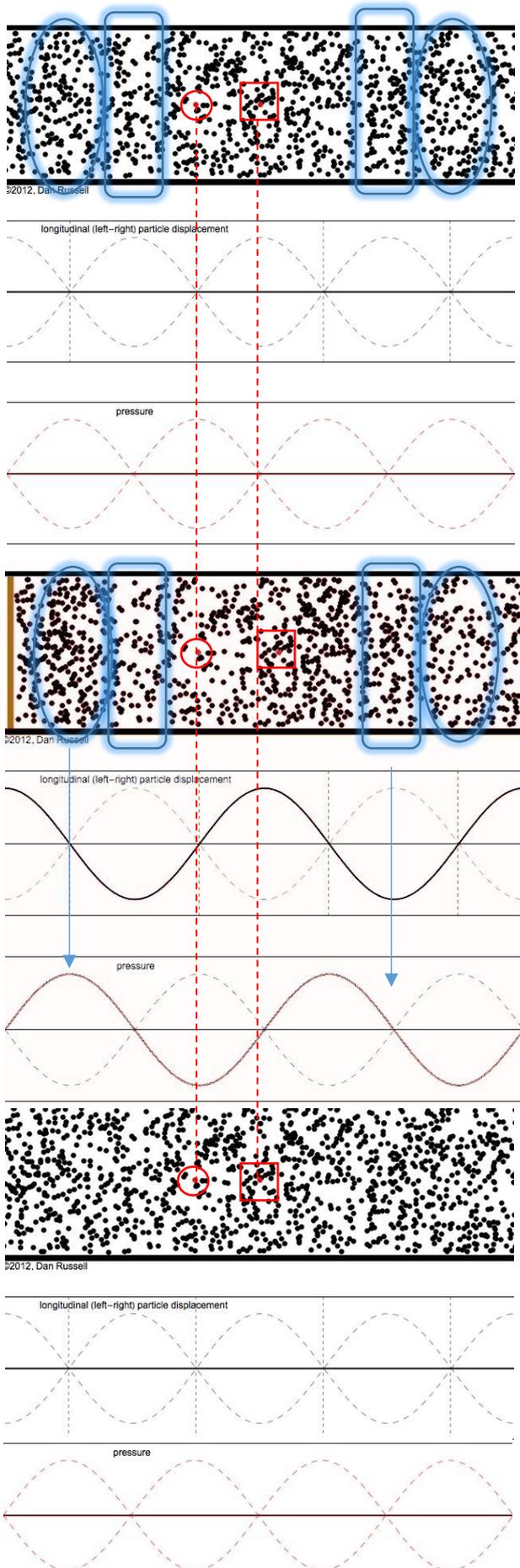


Image 16: displacement and pressure patterns

In red we observe two particles. The one in the circle does not move during the time the sound wave comes through. The one in the square moves to the right and then back to its original place. So in the displacement pattern we see a node corresponding to the place of the particle in the circle. The particle in the square is presented by an antinode on the displacement pattern.

Circled in blue we find the pressure changes. On the first image we have fewer particles in the first circle then on the second image. In the second circle we have more particles on the first image then on the second. The zones where the pressure changes correspond to the antinodes in the pressure pattern.

The blue squares indicate zones where pressure doesn't change. These zones correspond to the nodes on the pressure pattern.

As you can see, the pressure pattern has antinodes when the displacement pattern has nodes and vice versa. So in the pressure pattern of an open tube, like the flute, we will find two nodes at both ends of the tube.

On Image 15 you can see the different harmonics of one tube length, with the displacement pattern on the left and the pressure pattern on the right.

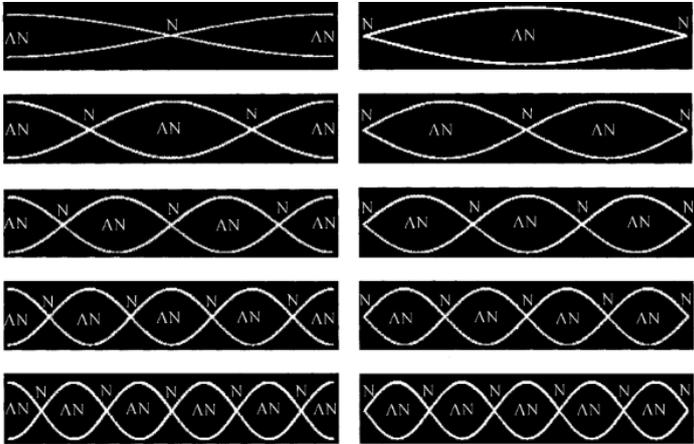


Image 15: displacement patterns and pressure patterns of harmonics in an open end tube

Closing and opening the tone holes on the flute changes the length of the air column that the standing wave can move through. The pressure node moves more to the left if we open the holes (starting from the right) and it moves more to the right if we close the tone holes. On image 17, you see the pressure pattern of a low C and the pressure pattern of a low E.

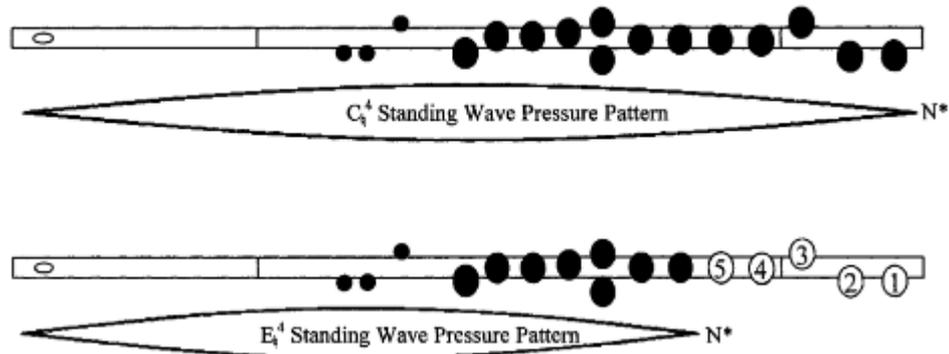
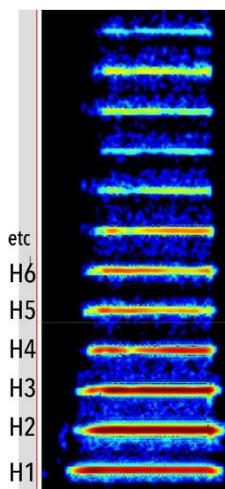


Image 17: pressure pattern in a flute



To understand how multiphonics work, one needs to be aware that a note on the flute is made up of multiple frequencies. If this wasn't the case, the flute would sound like a computer, playing one frequency. When we play a note on the flute, all of the modes of this tube-length are going to sound with the base frequency of the note. We don't hear the modes separately, but we hear a note that is rich in harmonics.

On the sonogram of a low C (Image 18), when we play this low C (bottom strip), up to 11 harmonics (stripes above first one) contribute to making this sound.

Since the naked ear cannot hear these different modes separately, playing this low C, we can say that the different modes fuse and form one sound.

Image 18: sonogram of a low C

If we now look at the pressure pattern of a low G, together with the first harmonics that sound simultaneously, we can start to understand what happens with multiphonics. On image 19, on the next page, we can see that the third node of the 3rd harmonic is situated in the exact same place as the little c-key on the left part of the flute.

If we open this c-key, it is no coincidence that we will find the fingering for a high D, the 3rd harmonic of the low G. But since there is a tone hole opened we create a second tube-length and we will also be able to play a note for which the standing wave stops at the hole. The frequency of this note will be a C.

The other harmonics on the low G will be impossible to play because we need to have a node at the tone hole, which is not the case for the other modes of this tube-length.

The player now has to adjust the air pressure in such a way that the two notes can sound simultaneously. We use a combination of open and closed tones holes to play the multiphonics C⁵-D⁶. This fingering has two independent and harmonically unrelated standing waves. As a result, there are two different tube lengths vibrating simultaneously.

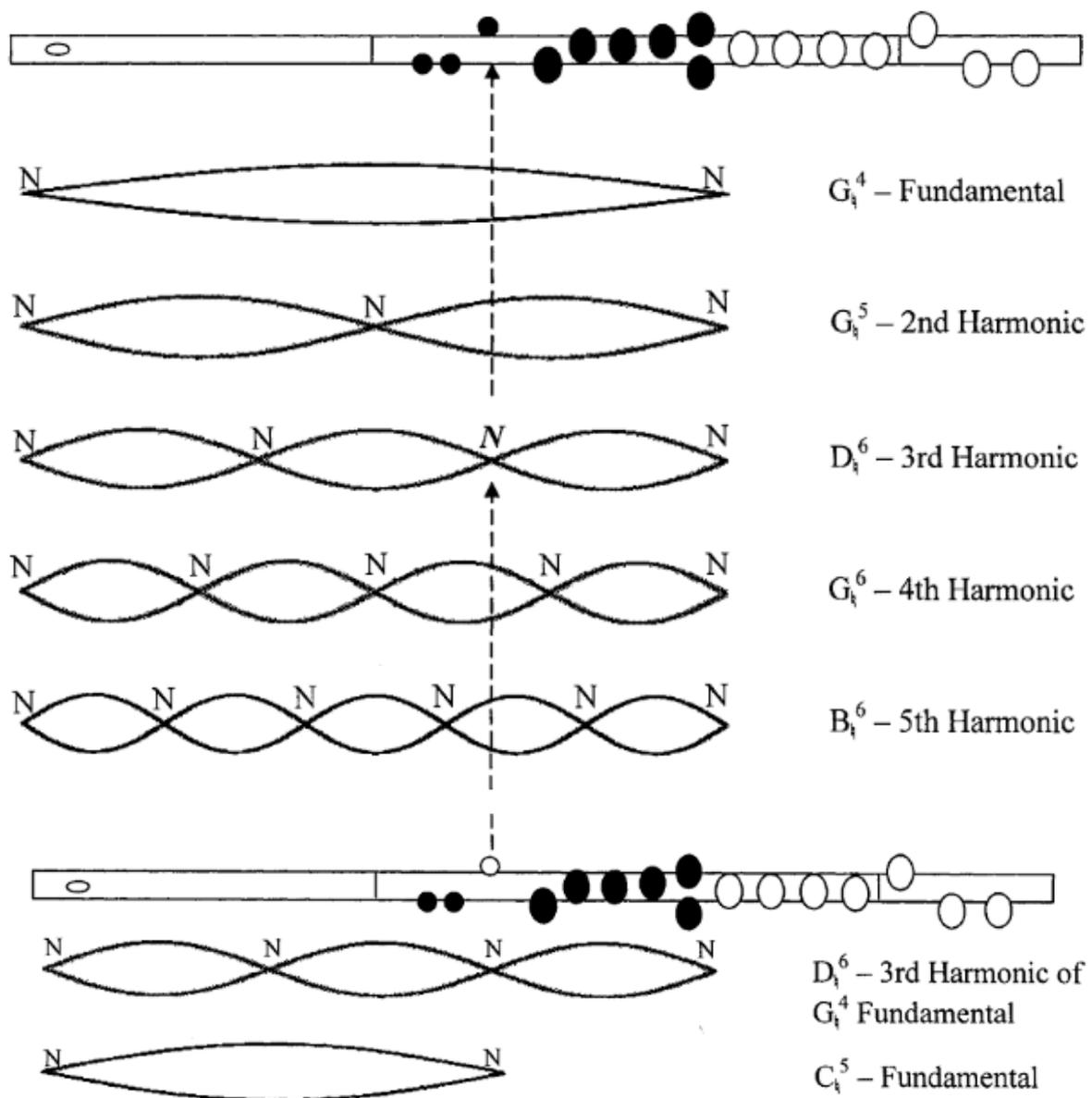
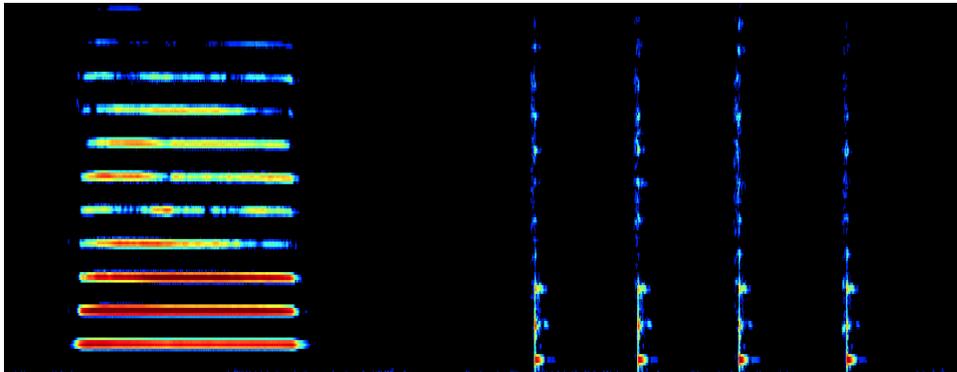


Image 19: pressure pattern of low G with harmonics and Multiphonic C⁵-D⁶

It is essential to have two harmonically unrelated standing waves. It is much easier to play multiphonics consisting of notes that are “out of tune”, taking the harmonic series as a reference. By out of tune, we mean that frequencies of the notes we obtain by overblowing or underblowing a certain fingering, do not correspond to the frequency we would expect, based on the harmonic series. In this case we have a C⁵, when we overblow this fingering, we would expect to find a C⁶, an octave higher (following the harmonic series), but instead we hear a D⁶. Thus the second note mode of this fingering is out of tune, taking the harmonic series as a reference. For a normal fingering, the modes fuse together to make one sound and we cannot hear them separately. If we use a fingering for which the overtones/modes are not multiples of the base frequency, the modes will not be able to synchronise and so we are going to hear them separately in the form of a chord or alternating as multiphonics with beat frequencies.

2.3 TONGUE RAM

The following section examines what is called the tongue ram or tongue stop. For this technique we take the embouchure hole in our mouth, between our lips, and we push the tongue against the embouchure hole with a high speed and a lot of pressure. The sound obtained sounds percussive, much like flute pizzicato (made by the tongue hitting the upper lip). If we compare both techniques, we can hear that for a same tube length there is a big difference in frequency between the two sounds.



TRACK 5

Image 20: spectrogram of a low C and tongue rams on a C fingering

If we analyse what happens, the answer seems easy; we cover the embouchure hole and so we create a closed tube at one end. This would mean that for this technique the flute would function as a tube with one open end. How does this change the pitch?

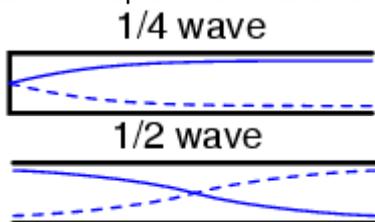
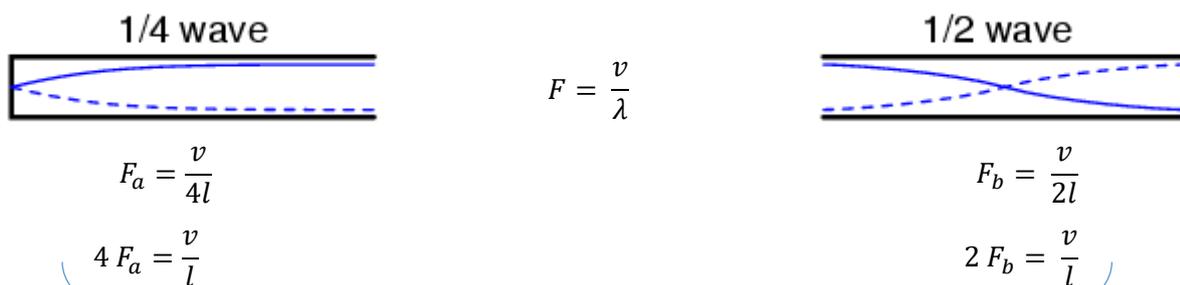


Image 21: tube closed at one end and open tube with first vibration mode

On image 21, you can see two tubes of the same length, the first one is closed at one end and the second one open at both ends. We can see their corresponding standing waves and notice that the open-end tube has a bigger part of a complete wave than closed-end tube.

In the case of the closed-end tube, in the first mode, the length of the tube corresponds to a quarter of a wave length. The length of the open-end tube corresponds to half a wave length. We also know that frequency can be found by dividing airspeed by wavelength. We replace the wavelength by tube length, which in both cases is the same.



$$F = \frac{v}{\lambda}$$

$$F_a = \frac{v}{4l}$$

$$4 F_a = \frac{v}{l}$$

$$F_b = \frac{v}{2l}$$

$$2 F_b = \frac{v}{l}$$

Knowing that the airspeed (v) and the tube length (l) is the same in both cases.

$$4 F_a = 2 F_b$$

$$2 F_a = F_b$$

We know that if you double a frequency, in musical terms, the note will sound one octave higher than the other. The difference in pitch between an open-end tube and a tube closed at one end, of the same length, will be an octave.

If we say that for example we have a frequency of 440.0 Hz for F_a , which corresponds to an A^4 , we will find a frequency of 880.0 Hz for F_b , which corresponds to an A^5 . The open-end tube will sound one octave higher than the tube closed at one end.

What we just showed is pure theory, if we listen closely to the difference in pitch of a note played on the flute and a tongue ram, with the same fingerings, we hear that the difference between them is not an octave. If we do a sound analysis, we can see that our ears are not deceiving us.

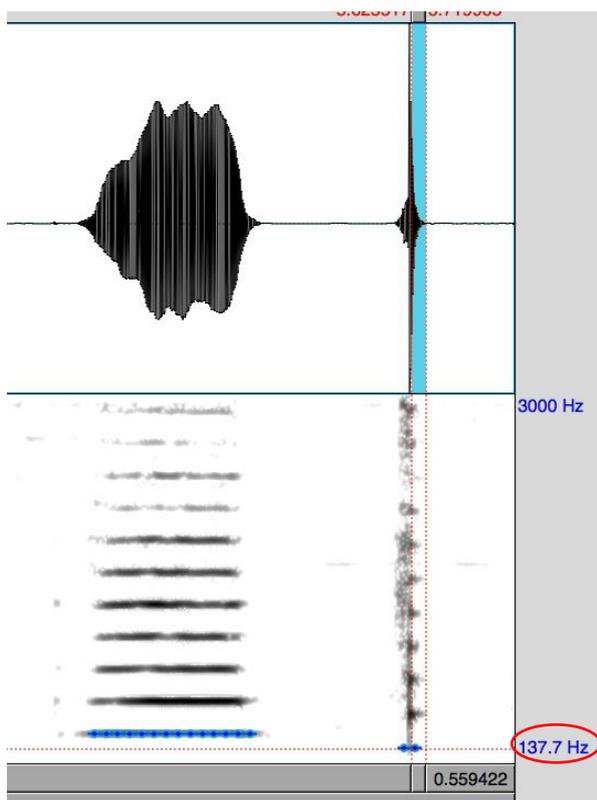


Image 22: sound analysis of a C played and tongue ram on a C fingering

On the left you can see the sonogram of a C^4 played on the flute, the frequency of this note is around 261 Hz. On the right you can see a tongue ram, played with the fingerings of a low C. we can see that the base frequency of this note is 137.7 Hz, which is much closer to a $C\#^3$ of approximately 138.6 Hz then to a C^3 of approximately 130.5 Hz.

The tongue ram sounds a major seventh lower than the original note, instead of an octave. Why is the tongue ram out of tune? Why does it sound a half-step too high?

The explanation is quite simple and I must say that in fact it is not the tongue ram itself that is out of tune, it is the flute that is out of tune! A normal note on a flute sounds in fact “one half-step too low”.

For acoustic science the flute is an open tube, however, in reality the instrument functions like an open tube, but the flute itself is not entirely open on both sides. As flutists will know, we cover up the embouchure hole with our under lip. Approximately one third of the embouchure hole

is covered up and this results in the flute sounding a semi-tone lower than if it would have been an entirely open tube.

This is because one end of the flute is not closed and yet not fully open. The frequency calculated in theory will always be higher than the frequency of the actual note played by the flute. The less the embouchure hole is closed off by the inferior lip, the more closely the played frequency will approach the theoretical frequency.

A tongue ram will thus sound a major seventh lower than the note fingered on the flute. This is true for the lower half of the flute, from the moment we go higher in the first octave of the flute, this interval will change. If we listen to a tongue ram on the fingering of an A^4 of 440 Hz, we remark that the interval isn't a major seventh anymore, but rather a minor seventh. The note we will hear, and sound analysis confirms this, is a B^3 and not an $A\#^3$. This means that when we normally play an A^4 on the flute, it actually sounds a major second too low and not a half step like we noticed with the C^4 . This can be explained by the fact that the tube length used when playing an A, is much shorter then when

playing a low C. The influence of the little part of the embouchure hole that is covered by the under lip, will therefore be much bigger in the case of the A.

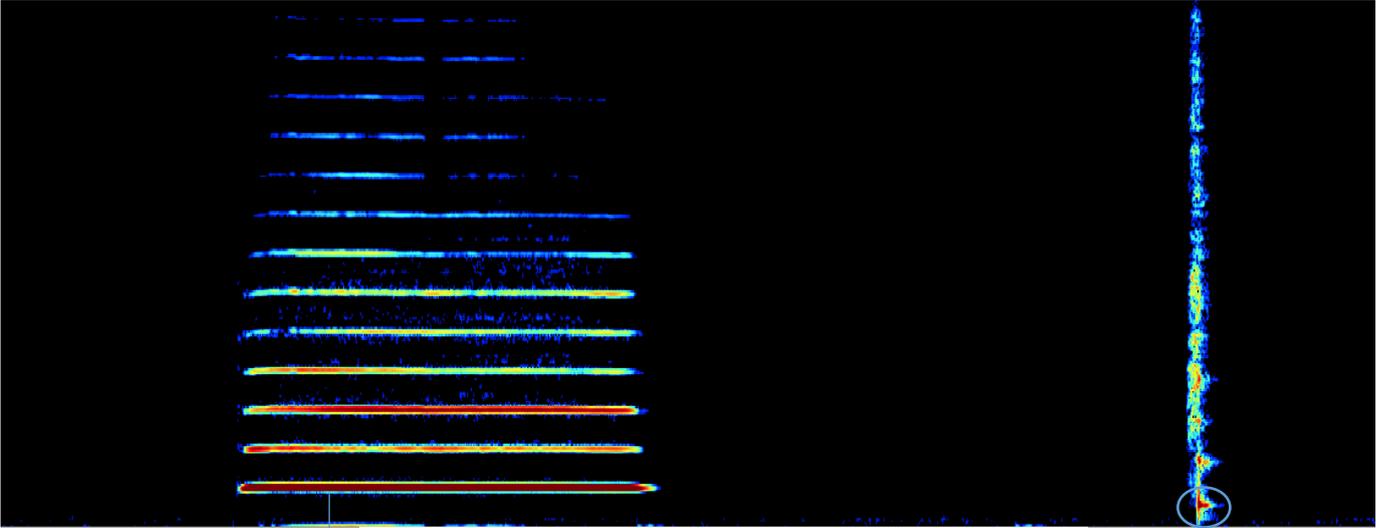


Image 23: Spectrogram of an A played and a tongue ram on an A fingering

A⁴: 440Hz

B³: 248 Hz

2.4 JET WHISTLE

The last technique that I have examined is the jet whistle. To execute the jet whistle, the flutist places the embouchure hole completely between the lips. Then, with a lot of power, air is sent into the embouchure hole.

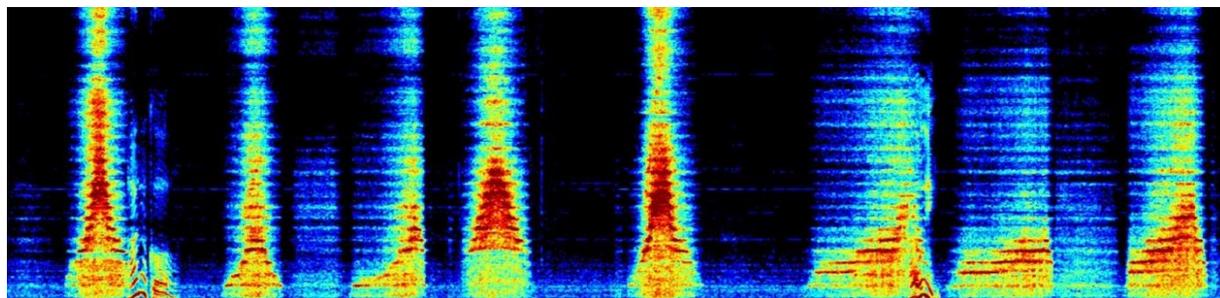


Image 24: spectrogram of a jet whistle

TRACK 6

When trying to figure out how this technique was acoustically explainable, I posited that the flute must function like a tube closed at one end again, just like for the tongue ram. The series of sounds that characterise the jet whistle, would then have to be in relation to the harmonic series of a tube closed at one end. This means that we should only find the odd frequencies of the harmonic sequence.

If we try to produce the different frequencies separately (which is rather hard), we can hear that this concept might not be correct. To verify the frequencies, I did a sound analysis of the jet whistle.

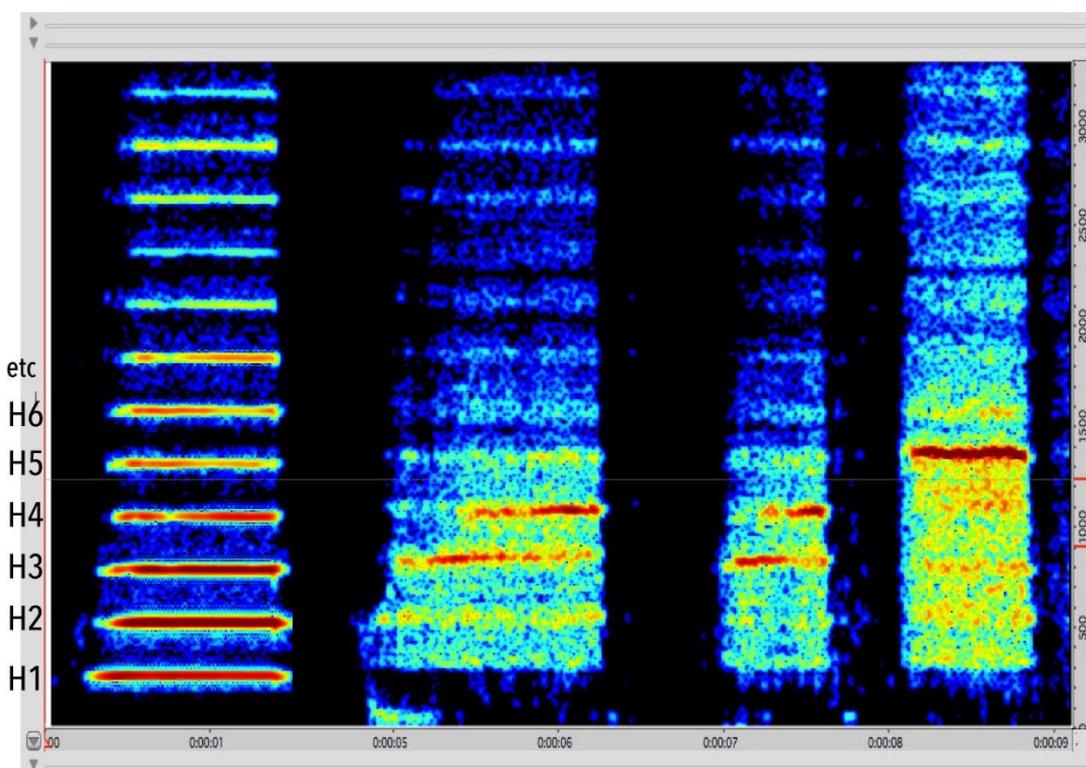


Image 25: spectrogram of a low C played and 3 jet whistle notes

TRACK 7

On the left in image 25, we see a low C with different harmonics sounding with it. On the right we see three “separate” jet whistle notes. The frequencies sounding follow the harmonic series of the flute. We do not hear the odd harmonic series, typical for the tube with a closed end. This means that, even though the embouchure hole is completely in the flutist’s mouth, the flute functions as an open tube.

This technique seems not to have been researched (not to my knowledge and not to the knowledge of Michèle Castellengo, acoustician at the LAM Jussieu and *directrice de Recherche* at the CNRS in Paris). As a result, we set about formulating an original theory ourselves.

What happens in the mouth of the flutist during a jet whistle, is not at all the same as during the tongue ram. While for the tongue ram, the embouchure hole is completely closed off by the tongue, for the jet whistle, the embouchure hole stays open in the flutist's mouth. The continual air-flow, that enters the flute during a jet whistle, prevents the embouchure hole from being covered. This is why the flute still functions like an open tube.

We also observed that all frequencies of the jet whistle are approximately one semi-tone higher than the harmonics of the normal flute sound, for the same fingering. So if we play jet whistles on a low C fingering, the frequencies sound like the harmonic sequence of a C#. On this spectrogram, image 26, you can see the difference in frequency between the played note with harmonics on the left and the jet whistle on the right.

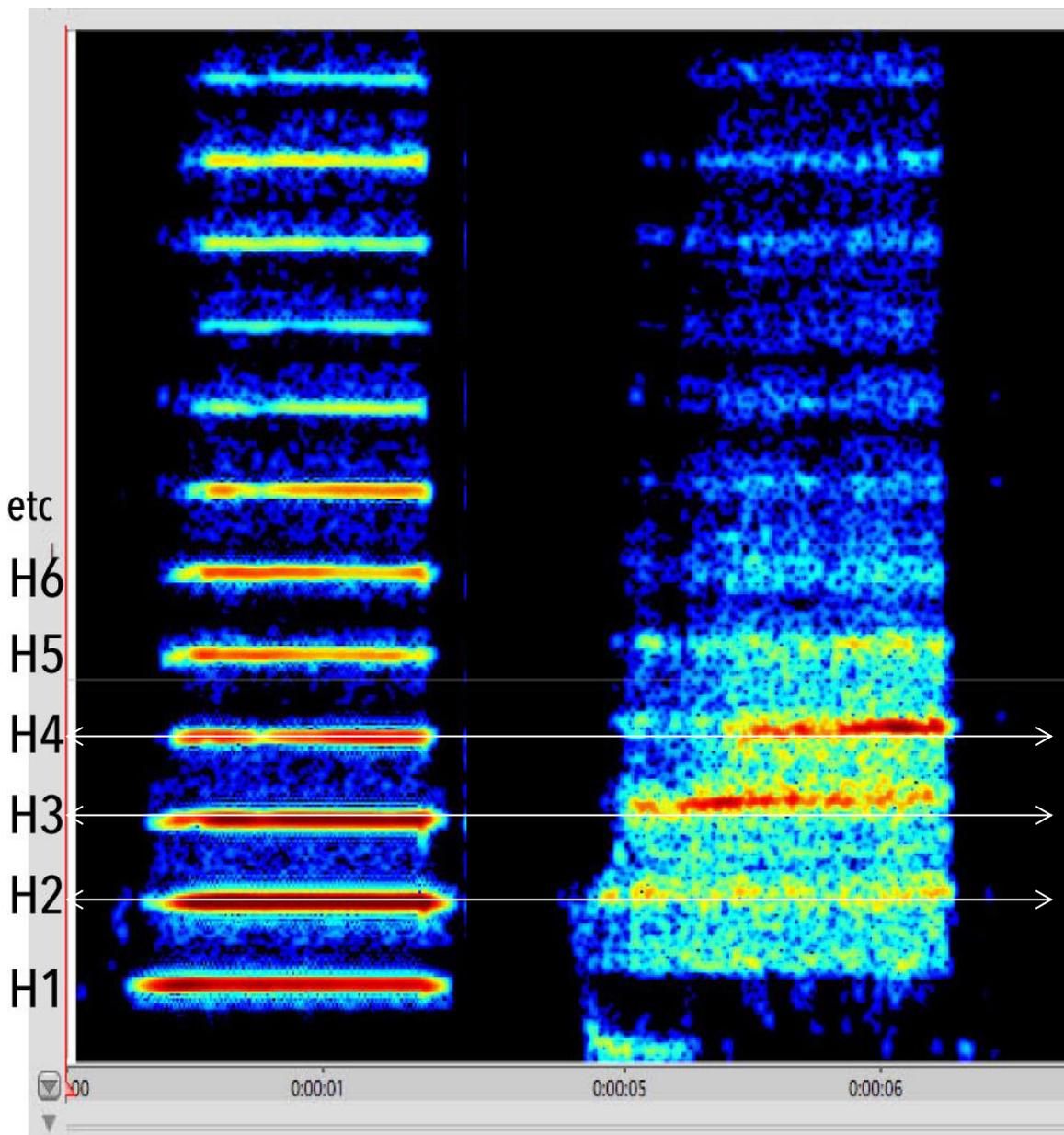


Image 26: comparison in pitches of the harmonics of a C played and jet whistle on a C fingering

The explanation for the difference of a half-step in pitch is rather simple, the embouchure hole between the lips of the flutist, is *entirely* open. This in contrast to normal playing of the flute, where the embouchure hole is covered by one third by the inferior lip. For once the flute not only functions like, but also is a *completely* open tube. That is why the jet whistle sounds half a step higher than the normal flute note.

3 APPLICATION

3.1 WHISTLE SOUND

3.1.1 What to do

We saw that pressure has a big influence on the edge tones, the pitch of the edge tones increases rapidly with an increase of pressure. Since the whistle sounds are reinforced and stabilised edge tones, this knowledge is important for their execution. If we want to play whistle sounds, especially low ones, we need to be able to lower the air pressure as much as we can.

In order to execute whistle sounds we need two things, low air pressure and stable airflow. To play whistle sounds we will also try to “play a bit less into the flute”, when compared with conventional playing, the angle of the air flow will be slightly different. This is because we do not want a standing wave to originate. This is a matter of air pressure, but especially the low notes on the flute do not require a lot of air pressure and so aiming your airflow a bit higher will prevent the low note from sounding with the whistle sound. We can use the lower lip to aim the airflow higher, it will be a bit more forward to play a whistle sound when compared to a normal note.

It is important to think of ways to lower the air pressure, starting with embouchure. If we place the edge of the embouchure, where the edge tones originate, a bit further from the airway (the lips that form the air jet), the air jet is in open-air longer and outside air particles will interact with the jet, thus reducing the pressure of the air jet. We can try to achieve this by turning the flute’s head joint slightly outwards when we play. This will also help for the previous point discussed, the angle of the air jet. The labium, or edge of the embouchure, will be further down when compared to normal play. We can demonstrate this by blowing against the sharp edge of a sheet of paper, resulting in very high edge tones. As you move the paper away from the mouth the edge tones become lower.

For the lip embouchure itself we can posit that in general it has to be more relaxed to create whistle sounds. The less tension in the lips and the wider the “gap between the lips”, the lower the air pressure will be. We can try to make a rounder gap between the lips instead of the narrow gap we normally employ. As a result, the air jet is less compressed and so the air pressure will be lower.



Image 27: lip position for normal playing and whistle tone

The actions we can take inside of the mouth and in the throat are more complex. The position of the back of the tongue is important for determining the air pressure. If we look for different possibilities of making the mouth cavity bigger, we quickly end up taking a look at the different shapes made by the mouth when we speak. It can be helpful to see the inside of the mouth to understand why certain vowels can help us to control air pressure.

On image 28, on the next page, you can see the different vowels in English and the corresponding mouth shape for each of these vowels.

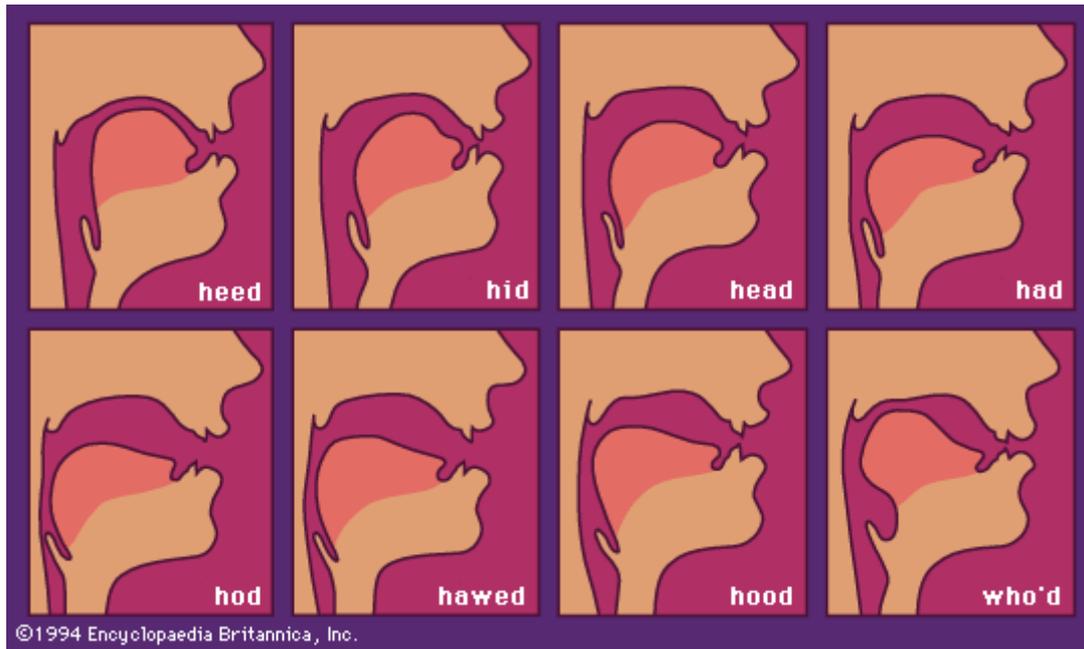


Image 28: mouth cavity for different vowels

We see that the mouth cavity is the biggest when using “o” or “a” and the smallest when using “ee” or “i”. When playing whistle sounds it is useful to think of saying “o” or “a”, this way the back of the tongue is lowered and more space is created in the mouth.

The last thing we can do to lower the air pressure it to open the throat. We can do this by thinking of yawning. When we yawn our throat is in its most open and relaxed state. Our goal is to imitate the physical action of yawning as much as we can when we play, especially when doing whistle sounds.

3.1.2 How this helps standard tone production on the flute

Whistles sounds are very useful for normal flute playing and they could be good technical exercises to practice daily. They encourage openness in the throat and mouth because to execute them the throat and mouth cavities have to be relaxed and open. For normal tone production on the flute this approach can help create a rounder sound and more volume, because by opening a relaxing the mouth and throat, we create more resonance. The knowledge gained about different mouth shapes of vowels can also help when creating different tone colours in normal flute playing.

Also airflow control can be exercised by doing whistle sounds. The airflow needs to be incredibly controlled to execute them, so that air pressure does not get too high, these are the same difficulties we face when playing very softly. Practising whistle sounds will thus help us extend our dynamic range.

3.2 MULTIPHONIC

3.2.1 What to do

In the previous chapter I showed that multiphonics are achieved by playing two (or more) different modes of the same fingering, at the same time. To optimise the execution of multiphonics we have to know precisely how the different modes of this fingering feel and sound. Then we have to find a compromise between mouth, throat and lip position as well as in air pressure, so that multiple modes can sound at the same time.

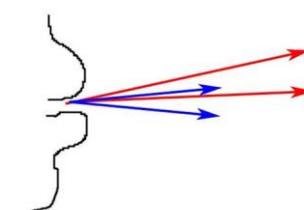
These instructions are meant to make the multiphonics more stable, so both notes are audible and as balanced as possible. Of course it can be a personal choice of the composer or musician to play these multiphonics unstable, but even then it's good to be able to execute them in a stable way. In this manner the unstableness will be a musical choice, rather than a lack of capacity of playing the multiphonics in a stable way.

To start, it is easiest to play the different modes of a same fingering separately and see how far we can go with dynamics. Often we have a weaker note, that cannot be played very loudly and a stronger note. The dynamics of the multiphonic should never be louder than the dynamic level of the weakest note, otherwise the weak note is not going to be sounding. This can be achieved by regulating the amount of air used in playing the multiphonic.

Regarding the mouth position, we will have to play the different modes alone again, and see what form the mouth has. In this case also we can think of the vowels. For a lower note, the mouth shape is going to be closer to an "o" or "a" and for a higher one more of an "ee". If we want to make both notes sound, we will have to try to find the middle position between the two notes. If we have a note with a position "o" and another with "ee", we will try to form "oy" (as in boy) to execute the multiphonics. The vowels are a very useful tool for a for understanding how the shape of the mouth should change for different multiphonics.

If we take a look at the lips, we will notice that lower notes on the flute are often "shaped" by the lower lip. You cannot play a low note if your inferior lip is in the position of a high note, you can however play a high note when your lower lip is in the position of a low note. To compensate for the lower lip being in the position of a low note, to play the high note, we will have to raise the air pressure and simply blow a bit harder.

The embouchure hole between the lips will normally be slightly smaller and the angle will be different when playing a high note, because of the lower lip going both forwards and upwards. This is why the pressure will be higher than with a low note with the lower lip in a "normal" position. For multiphonics, we need to leave our lower lip in a normal position so the low note can "fit in", therefore we will need to compensate for the difference in air pressure, if we want to be able to play the higher note at the same time. This is why big-interval multiphonics often sound "dirty" because we hear a lot of air. We need to find the correct angle and air pressure that will work for both notes.



The range of possible angles for the upper note
The range of possible angles for the lower note

Image 29: range of angles multiphonic

Finally, we need to adapt the position of the throat to optimise a multiphonic. Again we should feel the position of our throat for the different modes separately. Some flutists use a technique called throat tuning, which suggests that the player should try to tune their throat and vocal cords to the

note they are playing, the easiest way to achieve this is to think about singing the note ⁵. This means the vocal cords are constantly active and going into the position of the notes you are playing on the flute. I did not research this technique and cannot give any scientific explanation of it, nor can I confirm if it works, but it is a well-known concept and it makes sense if you think of the concept of resonance. If we don't use our body as a resonator, the flute will still sound, but less rich and there will be less sound projection. When we sing, we only have the body as a resonator; the chest, throat, mouth cavity and sinuses, the combination of their position and the vibration of the vocal cords creates and shapes the sound. If we combine these resonators with the flute, by throat tuning, the body will magnify the resonance of the flute itself.

Whether you use throat tuning or not, it is important to put the throat in the position needed for the weakest note of the multiphonic. This will help it resonate more and will help the multiphonic to be more stable.

Scientific knowledge about the different standing wave patterns when playing a multiphonics can help enormously in finding fingerings for multiphonics. Instead of searching for hours on the flute to find a multiphonic with two specific notes, we can narrow the search down a lot, if not just find the right fingering, by just sitting down and taking a look at the standing wave patterns.

3.2.2 How this helps standard tone production on the flute

Multiphonics are achieved mostly through embouchure control and air control. To execute multiphonics you have to be very aware of the position of your mouth and lips, which is something that can help improve regular tone production. This is somewhat analogous to doing complicated math exercises that result in basic exercises becoming much easier, because they were a smaller part of the more complicated exercises.

Making a multiphonic stable can be a difficult task and requires a lot of air control. This helps improve the stability of airflow and teaches airflow control.

⁵ Dick, R. (2016, september 20). *Throat tuning Part 1*. Retrieved from youtube:
<https://www.youtube.com/watch?v=FCxXc5p96YA>

3.3 TONGUE RAM

3.3.1 What to do

The most important thing for achieving the tongue ram is that the embouchure hole has to be closed off, with a sudden and energetic stop. The most common way to do this is by pushing your tongue in the embouchure hole. This research, however, made me discover two other possibilities for playing the tongue ram, I will explain these below.

We saw that the effect of the tongue ram resulted in a pitch a major seventh lower than the note fingered, this is because the instrument is functioning as a tube closed at one end. We noticed, with the jet whistle, that putting the embouchure hole in between the lips is not enough to make the flute function as a closed tube on one end. The flute can, therefore, only be closed off at one end if there is no continual air-flow. This means that we do not actually need to physically close off the embouchure hole with the tongue, we just need to abruptly stop the airflow. This led to two alternative ways of executing the tongue ram, that were not known to me before this research.

A way of closing off the air supply is by putting the front of the tongue on the hard palate of the mouth. For a tongue ram to work, we need to make this change quickly and with energy. We can do this by exhaling and cutting off air supply abruptly. This is not so much exhalation but rather an impulse to make the movement with the tongue. We can also do the opposite and inhale while stopping the air with our tongue. This almost feels by gasping a tiny bit of air before the tongue is stuck on to the palate.

These two alternative ways of executing the tongue ram are very effective especially if the tongue rams are placed within a series of other extended techniques and normal playing. Because there is no contact between tongue and embouchure hole, the lip plate stays clean and pleasant to play on.

The tongue ram can only work well, if the lips completely close off the surrounding air from the embouchure hole. Otherwise the effect will not work, because a split-second change in air pressure is required. To begin there is air in the mouth of the flutist as well as in the flute embouchure, then a fast replacement of air takes place. If the lips do not seal the embouchure hole off from outside air, this outside air will intermingle with the changing air pressure and the effect of the tongue ram will be lost.

3.3.2 How this helps standard tone production on the flute

The tongue ram helps to coordinate the tongue and the diaphragm. We give an impulse of air that has to be synchronized with rapid movement of the tongue.

3.4 JET WHISTLE

3.4.1 What to do

For the jet whistle it is important to close the lips entirely around the embouchure hole, this way we can ensure that no “outside” air interferes with the airflow that is sent into the flute.



It is again helpful to work with vowels in order to make the jet whistle go higher or lower. Many composers use the jet whistle in its “normal” state, to create a waveform by going up and then down again. We can obtain this effect by augmenting the amount of air sent into the flute and aid this with the mouth position, by going from an “o”-position to an “ee”-position and back again.

There are other cases where we will need to go from the highest sound possible and let it drop, or the other way around. To obtain the biggest difference possible between high and low in a short time, we need to work with the angle of the airflow. To get the higher notes in the jet whistle we can turn the flute a bit outwards. This combined with raising the diaphragm and making an “ee”-position in the mouth, will help to start from a high pitch.

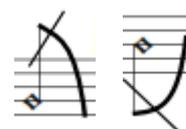


Image 30: jet whistle notation

If we need to go from low to high, it is important not to start with too much air, because we will run out of it before the jet whistle reaches its highest sounds. Making an “o”-shape in the mouth and turning the flute inwards will help in finding the lowest note.

If you cannot relate to the method of different vocal positions, normal whistling can help. When we whistle, we adapt our mouth automatically to make the sound go higher or lower. If you want to do a glissando-like whistle from low to high, you will notice that your mouth will start off in a very open position to make the low notes (“o”-position) and slowly the back of your tongue will rise to make the pitch go higher (“ee”-position). Whistling is a very natural way of adapting our mouth shape to obtain the corresponding pitches and I found that very often the exact position of my mouth I use when whistling a certain pitch, corresponds perfectly to the position of my mouth when playing that same pitch on the flute. Of course the position of the lips changes drastically, but the position of the inside of my mouth and throat remains the same.

If you play a jet whistle on the flute, you can imagine that you are whistling and doing a fast glissando. Your mouth will automatically be in the right position for making high or low sounds.

3.4.2 How this helps standard tone production on the flute

The jet whistle is really good for stimulating the diaphragm and abdominal muscles. Playing whistle sounds is very intense and can be tiring. It is best not to do this for long periods of time and it can help to be seated when starting to learn. It is possible that you feel weak or even start seeing stars or black spots. Because this technique is so physically intense, it is a very effective way to train extreme endurance, which is needed in all music but can be especially helpful in contemporary pieces that often connect many different extended techniques, without giving the flutist time to recover.

4 CASE STUDY

In this case study I will be looking at one specific piece; “Prometeo & Epimeteo” of Edgar Guzman, a Mexican composer. I played this piece last year and chose it because it has a lot of contemporary techniques in it, including the four techniques I investigated for this research. It is a work for flute and tape and has been played by different flutists over the world. I was able to work with the composer in my preparation of a concert and kept a good contact. He provided me with two other interpretations that were recorded by him. I will compare and discuss the execution of the contemporary techniques of these two versions and my own version, recorded last year in June. I am not judging the execution of the techniques, I am just stating the differences and explaining why they don’t sound alike. Every musician is free to make his or her own interpretation of a piece. As long as these techniques are willingly played “differently” and not as a lack of knowhow, this is a musical choice.

The three complete versions of “Prometeo & Epimeteo” are on the DVD, included at the back of the research. These are strictly for informational purpose only and cannot be distributed (version A: [TRACK 17](#), version B: [TRACK 18](#), version C: [TRACK 19](#)). To make the comparison easier, I cut out the passages with the techniques that I will use in this case study and made separate tracks of them on the DVD, I also added the corresponding passage in the score. The full score can be found appendices.

4.1 TONGUE RAM

As you can see on image 31, the piece starts with a tongue ram and is immediately followed by a whistle sound that starts off stable on a high E flat and becomes unstable, to then close off with a tongue ram again. Let’s talk about the tongue ram first.

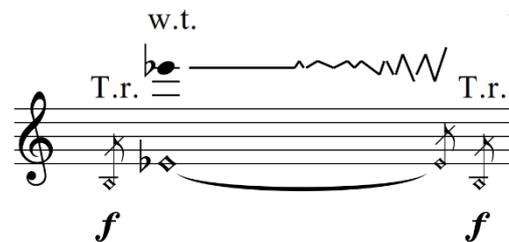


Image 31: excerpt "Prometeo & Epimeteo"

In version A ([TRACK 8](#)), we hear two times a very clear tongue ram, with a nice low note sounding (A sharp in this case). There is not too much air used before the tongue ram and the embouchure hole is nicely closed off, which gives it this clear percussive sound.

In version B ([TRACK 9](#)), the tongue ram is a bit “dirtier”, the flute player uses more air to execute the tongue ram and the sound of the effect is less clear than in the first version. It will help to remember that the sound of the tongue ram is made by a change in air pressure, we do not need much air for this. Just the fact of moving the tongue quickly against the palate of the mouth or embouchure hole is enough to make the change in pressure. This is because the sudden tongue movement, makes a lot of air particles move. We can use some air to give an impulse for the tongue to move quickly, but we do not actually need air for making the tongue ram sound.

In the last version ([TRACK 10](#)), we have two different tongue rams; the first one is very clear, the second one has almost no base note and sounds a bit dull. In this case the flute player didn’t cover the embouchure very well the second time. This is understandable because the change in mouth position between the whistle sounds and the tongue ram must be done very fast. The flute player has to go from an outwards turned flute to an inwards turned flute and make sure the embouchure hole is correctly sealed off for the tongue ram.

4.2 WHISTLE SOUND

If we now listen to the whistle sounds in the three versions, we notice that only in version C we hear first a stable E flat whistle sound before hearing unstable whistle sounds. We can see this very clearly if we put the spectrograms of version A and C next to each other.

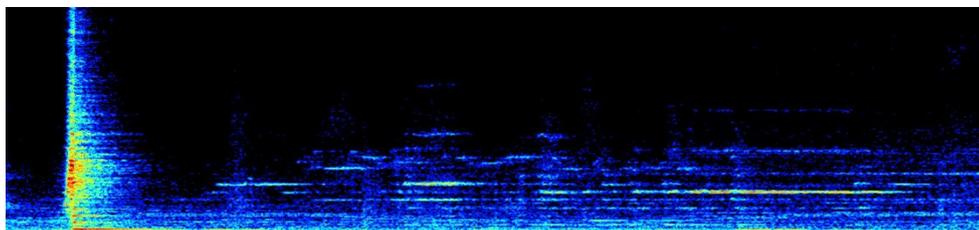


Image 32: Version A: Tongue ram + whistle sound

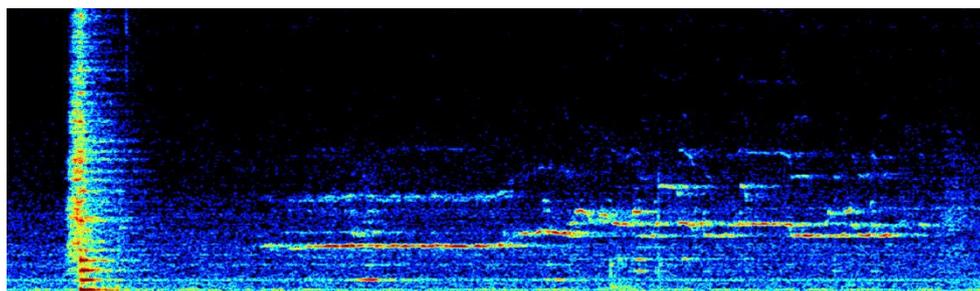


Image 33: Version C: Tongue ram + whistle sound

On these images we see that in version C there is a distinct line in the beginning of the whistle sounds, that stays stable for some seconds. This is clearly missing in the first version. We remark that the most stable whistle sound comes towards the end and is a G, a third higher than the E flat, intended by the composer.

Playing unstable whistle sounds is fairly easy, because you can just let the air flow as it comes and any pitch will do. Playing a stable whistle sound is another thing; you need to first find the pitch needed out of all the harmonics on the fingering indicated (in this case a low E flat) and then keep it stable. This means extreme control of the air pressure and the embouchure. If there is a little instability in the airflow or a minor change of the lip position, the whistle sound will find a new pitch.

The fact that the E flat is a relatively low whistle sound, only the 3rd harmonic in the row, makes it even harder to produce. The air pressure has to be low and mouth and throat as open as possible. Whistle sounds are very fickle and even if the flutist is very good at playing them in the practice room and rehearsals, the conditions of the concert can embranch the hours of practice and make the whistle sounds impossible to control. This will get better with every time you play whistle sounds on a concert.

Dynamics are very tricky to combine with multiphonics. As we discussed, when playing a multiphonic the flute player has to consider the dynamic ranges of all the notes of the multiphonic. If we want the two or three notes to sound simultaneously, the flute player cannot go out of any of the different dynamic ranges of each note. The flute player has to find a compromise between the different dynamic ranges of the notes and this leaves only a small margin. Because of this a multiphonic is often very limited in dynamic changes, composers should be aware of this.

4.4 JET WHISTLE

The last technique we're going to investigate in this case study is the jet whistle. I took the gesture just after the passage with the multiphonic, we analysed before, around minute 2:16 – 2:20. We see two jet whistles; one going from high to low, the other one going from low to high.

When we listen to the first version of this passage ([TRACK 14](#)), we can notice that there is not much distinction between the two jet whistles. The first one goes from high to low, but the second one only goes up in pitch a little at the beginning, and then drops again, which breaks the up going motion we need. The flute player maybe didn't have enough air to finish the last jet whistle and so the air pressure dropped and the jet whistle went down. It can help to make the up going movement with the diaphragm to help the air pressure increase at the end.

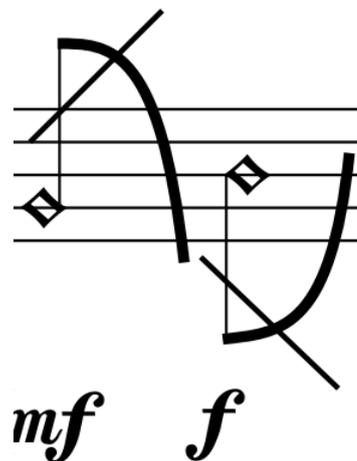


Image 37: excerpt "prometeo & Epimeteo"

In the second version of this passage ([TRACK 15](#)), the difference between the first and second jet whistle is much clearer. However, the second up going jet whistle could even start lower, this would make the motion bigger and clearer. The key is to start off with little air and turn the flute inwards, when starting. Then whilst augmenting the air pressure, turn the flute out.

The last version ([TRACK 16](#)) is the clearest of them all, if we listen to the down and up going movement. Also, the pitch range in this version is bigger than in the others, meaning that the difference between the lowest sound and highest one is larger. To achieve this result, the flutist probably combined an air pressure change with turning the flute outwards and inwards.

DISCUSSION

When I started this research, I was very surprised to find a lack of information in this domain. The extended techniques I researched exist for several decades, and it struck me as odd that there has been almost no scientific and acoustical research done. For this, I think that the theoretical subject on its own is very innovative and can inform a lot of flutists who are learning these techniques or who are teaching them to others. I understand that not everybody has the same learning process, but I am sure that there are other flute players like me, who like to understand how something functions when learning it.

In the practical part of my research, I discovered a lot of new things; other ways to execute the tongue ram, better ways to practise different techniques, tips for optimising the execution of certain techniques, etc. For myself this was of course very useful and I am convinced that other flutists will be more aware of why they have to do certain things when playing a certain technique, because they understand how it functions. They will be more conscious of how to execute the techniques, because they will know how the sound originates and which factors are important when forming it.

This manner of thinking and working will not be the best way of learning extended techniques for everyone. I don't think that everybody should work with this approach, but I do think that having the option is a good thing, especially for persons who have a hard time learning from a sensory-based method only. With the scientific knowledge of the techniques, even more progress can be made in developing more efficient ways of executing them. The more people have access to this knowledge, the more people will find ideas on improving the execution of the techniques.

The theoretical knowledge I wanted to obtain when I started this research is in this paper. All the questions I asked myself about the different techniques are answered, but throughout the process more and more questions came to the surface and there is still a lot of research that can be done in this domain. I have questions about throat tuning; this needs further investigation with professional equipment. Also the position of the inside of the mouth when whistling and playing the flute seems to me very similar, I would like to research if this feeling is correct. The technique that puzzles me the most is the jet whistle. The manner on which the sound is created is very intriguing. I think that research on this matter can even lead to the development of new extended techniques.

In order to do further research in this matter, a collaboration between acousticians and musicians is necessary. A lot of measurements with professional material need to be done, especially for throat tuning, for example medical scans that would allow us to see what happens in the throat and mouth. I hope to be able to be part of this research or conduct it myself, because it is a subject that intrigues me and that can help a lot of flutists and musicians around the world.

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APPENDICES

In the appendices you can find the complete score of “Prometeo & Epimeteo” by Edgar Guzman. I only provide this score for informational purposes, it cannot be used for concerts or distributed under any circumstances.

A DVD containing all the sound examples, used in this research, can also be found annexed to this paper. The three complete versions of “Prometeo & Epimeteo” cannot be played in public spaces, nor distributed on the internet.

The appendices can be found online also. Digital appendices:

<https://drive.google.com/drive/folders/0B7auiS3CqrD1ckt3QTB0cENTWW8?usp=sharing>