Modelling An(other) Aulos—

Assessing Modal Synthesis in the Reconstruction of Musical Instrument

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Abstract

This thesis examines Modalys, a representative tool of modal synthesis, in the context of musical instrument reconstruction. The evaluation is based on two aspects: 1) Modalys' accessibility when combined with Max makes it an intuitive and simple tool for music researchers without extensive programming skills, and 2) the ability to create abstract models of vibrating objects which are manipulable through physical and geometrical parameters, and thus makes it suitable for instrument reconstruction based on measurements. The Louvre Aulos, an Ancient Greek reed instrument, was selected for modelling, whose pitches and timbres were assessed. Modalys proved to be accurate and user-friendly. It is generally a viable tool for quick simulations and preliminary studies, producing acceptable sound quality despite some limitations.

Contents

Chapter 1 Introduction

1.1 Research Background

The progression of computing technologies has changed sound synthesis with physical modelling, a method diverged from traditional synthesis techniques[1]. From its origins to the late 1970s, physical modelling has evolved from early digital signal processing algorithms to sophisticated synthesis methods in the 1980s. It achieved commercial success by the 1990s[2] for its relatively realistic emulation of wind and string instruments.

This thesis aims to implement physical modelling to create an emulation model to reproduce a musical instrument with historical importance: the Aulos, originally from ancient Greece. The Aulos typically have a double-pipe design, including differing pipe lengths, pitches, and materials used for manufacturing. Its tonal quality is produced by vibrating reeds attached to the mouthpiece.

There are several reasons to choose Aulos: First, physical modelling should be of greater importance in the virtual reconstructions of ancient instruments since ancient instruments benefit more from digital copies, which is a non-invasive method. Second, my prior knowledge of Aulos makes it a fitting subject. Third, Aulos presents a suitable complexity for the research scope. The Aulos is just enough for this study, unlike the simplest instruments, such as a lyre that relies solely on plucked mono-strings.

In this thesis, I examine the performance of modal synthesis in reconstructing musical instruments. Modal synthesis is selected for several reasons. First, Modalys, the primary research environment used in this study, offers an accessible and highly reliable method for modelling musical instruments. Unlike other methods that rely on a massive degree of programming and mathematical calculations, Modalys requires significantly less programming knowledge apart from the physical properties of the modelled instrument. This accessibility

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[1] For an introduction to the development of physical modelling, see Chapter 16 from Mullan (2011), Smith (1991), Välimäki & Takala (1996). Section 2.2 of this thesis mainly provides a technical introduction.

[2] One of the most famous examples was the YAMAHA VLA, released in 1994 as the earliest commercialised synthesiser powered by physical modelling techniques. It featured factory-defined instrument definitions, enhanced by a plethora of user controls, modifiers, and effects. Unique features included mapping MIDI Controllers to various controls such as Pressure, Embouchure, and Vibrato, catering to both real and imaginative instruments. The VL1 also boasted modifiers like the Harmonic Enhancer, a dynamic filter, and a suite of onboard effects, all adjustable via MIDI Controllers.

could significantly benefit humanists who are not proficient programmers. Second, modal synthesis has been overlooked in music instrument reconstruction for the "abstractness of its foundation" (Laird, 2001), which will be mentioned in section 4.3.2. Therefore, it can be interesting to explore whether this abstract modelling method can fully reproduce a given musical instrument. This will potentially fill this gap in research and can also compare modal synthesis with other established reconstruction methods.

1.2 Thesis Objectives and Outline

The main objective of the thesis is to test Modalys' feasibility in reconstructing the Aulos. After building sounding models using Modalys, I will apply multiple evaluation strategies, such as frequency analysis and participant assessment, to compare the sound qualities. The final chapter will provide a comparison between Modalys, other programming methods, and physical copies. This research will be conducted within the Modalys for Max/MSP environment.

Chapter 2-3: A Theoretical Review

These chapters serve as an overview of physical modelling in sound synthesis and the structure of Aulos. Chapter 2 reviews various physical modelling techniques, including the finite difference method, waveguide synthesis, wave digital filters, and mass-spring networks, with an emphasis on modal synthesis. Chapter 3 introduces the history, structure, and acoustics aspects of the Aulos. It explains what this instrument is made of and its unique features.

Chapter 4: Modelling the Aulos

This chapter will explain the environment for building the Louvre Aulos in Modalys for Max. It will introduce acoustically relevant characteristics of the Aulos and then the Max patchers, including the structure of the Modalys workspace and related controlling mechanisms. Also, this chapter will focus on the accessible logic and the simplistic interface of Modalys and Max.

Chapter 5-6: Assessment and Discussion

Chapter 5 will evaluate the performance in accuracy and quality of the modelled Aulos. There are two steps to analyse the pitches. First, the produced frequencies will be compared with the calculated optimal frequencies to identify any deviation. Second, the frequencies will be analysed with Pythagorean Tuning and 12 Equal Temperament to examine whether they produce satisfactory scales. After the accuracy tests, several audio clips featuring four different playing techniques on two modelled variants will be recorded. These audio clips will be shared with several participants to assess their sound qualities. The two different variants using different modelling methods will be compared according to their spectral features.

The final chapter will discuss Modalys' performance in modelling the Aulos and in a broader context of reconstructing historical musical instruments. I will compare Modalys with other methods to summarise its advantages and limitations. Moreover, this chapter will also reflect on the limitations of the current research and propose plans for future studies for more comprehensive results.

Chapter 2 Modelling Musical Instruments in Sound

In scientific terms, a "model" is a simplified representation of complex systems, objects, or phenomena that aids in understanding foundational principles through two critical stages: construction and manipulation (McCarthy, 2005). This process is crucial in natural and social sciences fields, where computational modelling techniques allow for exploring model parameters and forming new theories (Scheller et al., 2022).

In musical instrument modelling, mathematical frameworks and algorithms can simulate the movements of instrument components (Giordano & Chatziioannou, 2021). Physical modelling in musical instrument synthesis uses these mathematical frameworks to replicate the acoustic behaviour of real musical instruments (Tzevelekos et al., 2007). the sound source and the resonant body are combined for a unified approach, including excitations, resonator characteristics, and soundboard resonances (Välimäki & Takala, 1996). However, despite its realism, physical modelling faces many difficulties, including the fact that system models have been impossible to obtain in full, so simplifications had to be made here and there that may give rise to unnatural sounds. In addition, an elaborate system of turning these models into sound-generating algorithms at audio clock rates is required to ensure numerical stability and avoid perceptual artefacts (Bilbao et al., 2019).

This chapter categorises physical modelling methods from the comprehensive taxonomy, which was first presented by John O. Smith (1991) at the International Computer Music Conference. Smith’s taxonomy included various aspects of digital sound synthesis: Ruiz Strings Model, Extended Karplus-Strong Synthesis, waveguide synthesis, modal synthesis, Cordis-Anima Model, and MOSAÏC. However, some aspects of this categorisation have become outdated. Therefore, based on Smith’s output, this chapter also refers to a later categorisation by Välimäki et al. (2006) while updating relevant technologies.

2.1 Finite Difference Method

Sound synthesis has many different methods, with the FDTD (The Finite Difference Time Domain) model being one of them. This model uses the Linearised Eulerian Equations (LEE) to simulate wave-based sound propagation to capture the nuances of convection, refraction, and scattering of sound waves in an inhomogeneous and dynamic atmosphere (Tolonen et al., 1998). The FDTD model can deliver a comprehensive frequency response through a single time-domain simulation (van Renterghem, 2014). This process involves modelling a pulse-like source and applying a Fourier transform, thus enabling a detailed and dynamic representation of sound propagation (Bilbao, 2009). The finite difference method, which constitutes the main body of FDTD, represents a variety of possible numerical solutions that differ in degree from each other for partial differential equations. The method approximates derivatives by differences based on the requirements of a given problem and the available computational resources (Smith, 2005).

2.2 Waveguide Synthesis

The Digital Waveguide Model (DWG) for sound synthesis, originating from the Karplus-Strong Model developed by Kevin Karplus and Alex Strong in 1983, has been a significant advancement in synthesising sound (Tolonen et al., 1998). In the original Karplus-Strong method, a recursive comb filter is used on a wavetable, which starts with white noise and is processed through a low-pass filter. However, there were limitations with this process due to the fundamental frequency being inaccurately controlled. Jaffe and Smith (1983) rectified this in the same year by putting a fractional delay filter in the feedback loop and later developing linear and third-order Lagrange interpolators for use during feedback. Smith's development of the DWG, first introduced in 1986, built upon these early efforts. Initially designed for artificial reverberation, it was adapted to various sound synthesis applications. DWGs efficiently model physical systems as one-dimensional resonators using d’Alembert’s formula and delay lines (Smith, 1991; Tolonen et al., 1998).

2.3 Wave Digital Filters (WDFs)

Wave Digital Filters (WDFs) are a new approach to digital sound synthesis whose aim is to recreate the properties of their analogue counterparts, including passivity, stability, and losslessness. WDFs effectively address digital errors like numerical rounding off (Proverbio et al., 2021). Their design, based on passive analogue systems, ensures stability and maintains the integrity of the original analogue model. This makes WDFs skilled at retaining tone, texture, and timbre in sound synthesis. WDFs, when combined with DWGs, are suitable for modelling acoustic structures (Sarti & De Sanctis, 2009) and managing nonlinear interactions in instruments like pianos and violins (Petrausch et al., 2005).

2.4 Mass-Spring Networks

The Mass-Spring Network is another vital component of physical sound synthesis. It focuses on an object that produces sound rather than the actual sound production itself. This model uses masses, springs, and dampers, discretised with finite difference methods, to simulate motion in detail. The behaviour of these networks depends on their structure and the specific physical equations of each component (Morgan & Qiao, 2009; Szilas & Cadoz, 1998). Nevertheless, problems such as frequency warping and numerical damping can occur and affect sound pitch and resonance (Incerti, 1997).

Two notable implementations of the Mass-Spring Network are the CORDIS-ANIMA and TAO systems. CORDIS-ANIMA, developed in the early 1980s, reduces the complexity of networks into manageable parts while focusing on immediate interaction and realistic mechanical responses (Kontogeorgakopoulos & Cadoz, 2007). The TAO system, created by Mark Pearson, uses cellular automata for sound creation. TAO is user-friendly, allowing the creation of virtual instruments with natural-sounding audio.

2.5 Modal Synthesis

Modal synthesis has a close tie with the physical properties of objects that produce sound and is notably different from traditional sound synthesis methods (Rausch et al., 2014), differing notably from traditional sound synthesis methods. The development of modal synthesis began in the late 1960s and early 1970s, marked by work by pioneers like Lejaren Hiller and his team at the University of Illinois. Their first attempts at simulating sounds produced by various objects such as strings, rods, and plates laid the foundations for later applications of modal synthesis (Roussarie, 1999). Modal synthesis proliferated during the 1980s and 1990s at IRCAM in Paris, with Jean-Marie Adrien's work leading to the development of influential software like MOSAÏC, which later evolved into Modalys and acted as the primary environment of this research.

Modal synthesis is based on the principle that any sound-producing object's acoustic behaviour can be deconstructed into discrete vibratory modes. A mode has a specific natural frequency, damping coefficient and deflecting values. Each mode, in turn, contributes to the overall acoustic characteristics of an object (Dudas, 1998). This is generally done as a preprocessing step because it is computationally demanding to solve so many problems at once (Ren, 2013). Interestingly, it can be viewed as an extension of additive synthesis when the frequencies and damping coefficients are modified according to the specific physical properties of the modelled instruments (Trautmann & Rabenstein, 2003). The practical process of modal synthesis has three phases: first, it calculates the impact forces on the object; second, those forces need to be fed back into modes so that they will excite it anew; and third, sound samples are created for these excitations (Picard et al., 2010). The high-frequency sampling rate ensures that the phases between the impacting forces and the object's surface movements are accurately captured (Djoharian, 1993).

Another remarkable feature of modal synthesis is its ability to simulate complex objects with detailed geometries (Roussarie, 1999). Modal synthesis also allows us to recreate imaginary instruments that are no longer around and can produce sounds far removed from known copies.

As this section concludes, it’s clear that modal synthesis is a unique technique for comprehending and replicating the acoustic characteristics of musical instruments. The rest of the thesis will focus on the practical application of this technique, specifically on modelling the Aulos with Modalys, a representative tool for performing modal synthesis.

Chapter 3 Aulos as an Acoustic Instrument

3.1 What Makes an Aulos

The Aulos, originally meaning "tube" or "pipe" in Ancient Greek, was an iconic double-reed instrument, like modern oboes and bassoons. The Aulos is an instrument rich in timbres from deep and resonant to high and piercing. Various types of Auloi existed, each for specific purposes, such as national games or choral accompaniments (West, 1992). In Greek art and literature, the Aulos frequently appeared in vases, frescoes, sculptures, and the works of poets and playwrights like Sophocles and Anaxandrides. In this way, the instrument symbolised Greek society's ancient and wealthy cultural and intellectual inheritance and its reverence for music, art and the divine. (West, 1992).

Fig.1 A vase *(lekythos)* with a female Aulos player. (Source: Metropolitan Museum of Art, entry 130011977)

3.1.1 Pipes

The Aulos typically consisted of two cylindrical pipes, although single-pipe variants called "plagi Aulos" also existed. These instruments were made from various materials like bone, ivory or wood, with some featuring a metal case for durability and aesthetics. In its classic form, the two pipes can be each played independently and often attached side by side. These pipes varied in number of holes (and hence lengths), resulting in various pitches and sounds among ancient Greek Auloi from different regions. Marks on the instruments indicated the intended hand for each pipe, though archaeological evidence does not conclusively show that both pipes were interdependent for playing (Psaroudakes, 2008).

Ancient sources reveal numerous Aulos types for distinct musical purposes. These included *'Hemiopoi'* (half-hole Auloi), *'Paidikoi'* (boy-type), *'Bombykes'* for low-register tones, and gender-specific types differing in size and pitch. Other variants were *'Parthenioi'* (girl-type), *'Kitharisterioi'* (accompanying lyre), *'Teleioi'* (instrumental solos), and specialised forms for events like the Pythian Games and symposiums (West, 1992).

3.1.2 Reeds, Mouthpieces and Bulbs

Aulos reeds were mostly double, made from cane, with a cylindrical lower part for insertion and a flattened upper part that players can customise. Double reeds in the Roman Imperial period and Greco-Egyptian contexts typically had two parallel blades at the tip, so complex techniques like overblowing, pitch fluctuations, vibrato and staccato playing could be performed comfortably. This design allowed for extensive control and flexibility, like traditional Asian instruments like the *ciaramella* and *duduk* (Hagel, 2009).

The debate over the Aulos' use of single reeds was mainly about their different playing techniques and sound qualities. Slight differences in pitch and colour made single reeds, which were usually made by cutting a "tongue" out of cane, more stable when there was any time lag between one note and another when it did not correspond closely to what was expected. However, they had far less control than double reeds or less diversification in sound. Instruments like the *launeddas* and *arġūl* use single reeds. While some researchers still preferred single reeds in reconstructions, most artistic depictions and historical texts point to the predominant use of double reeds (Wysłucha & Hagel, 2023).

A reed stem and a bulbous section of the pipe form the mouthpiece of the Aulos in many extant vase paintings. The function of these components is not yet clear, but the choice of reed and the design of the mouthpiece are crucial for Aulos' musical character: it determines pitch, intonation, and tone quality (Howard, 1893).

Fig.2 A self-made double reed made by Barnaby Brown. Retrieved from doublepipes.info.

3.1.3 Fingerholes and Playing Techniques

The number and pattern of finger holes were crucial for sound production and musical range. Theoretically, a diatonic scale requires six holes, the bell-type pipe needed eleven, and some variants had up to twenty-four (West, 1992). Classical Auloi generally had five finger holes, with the second hole often cut on the underside of the pipe for the thumb. Over time, additional tools were required to make the Aulos more versatile. These could include collars that could be rotated for each set of holes, runners that could cover a note beyond reach and sleeves that would open or close finger holes, adding tonal possibilities for Aulos (Hagel, 2009). Due to a lack of surviving examples and difficulties in reconstructing its mechanics, however, this variant is not mentioned further here.

To play the Aulos, the musician should hold two independent pipes, each with its reed, in the hands and place them together in the mouth. To manage the pressure of continuous breath and control multiple finger holes, some players use a bandage (*phorbeia*) around the mouth and cheeks, which is necessary for ease of play and control with larger finger holes.

3.2 Existing Studies

This section explores various efforts to reconstruct the Aulos, from reconstructing scales and creating working replicas to digital recreations.

The Berlin Auloi 12461/12462

In 1894, the Egyptian Museum in Berlin acquired two wooden pipes, numbered 12461 and 12462, believed to be from Egypt. Hagel's 2010 study determines the structure and design of these Auloi. His original thought was towards some key mechanism along the pipes, but he later discarded the idea. He confirmed Howard’s hypothesis (1893) that the part called sýrinx was a speaker hole through detailed analysis of the reed inserts, bulb, ornamentation, and experimental archaeology. Hagel's later revised earlier assumptions about the Auloi's materials, theorised new functions for specific parts, and explored the use of a metal ring.

The Aulos from Argithea

Psaroudakēs (2002) conducted in-depth research on the fragments of an ancient Hellenic double pipe found in Argithea in 1991. These fragments underwent a comprehensive examination before being dated to the late 3rd-early 2nd century B.C. Psaroudakēs compared the Aulos with similar instruments to study their features and inferred from the nature of the fragments their construction and functionality. His research suggests a deliberate choice in parameters, like bore diameter, hole size, length, and reed selection when building the instrument, can achieve specific tonal patterns.

Similar explorations include several other notable reconstructions, such as the Aulos from Queen Amanishakheto’s Pyramid (Hagel, 2019), the Aulos from Pynda (Hagel, 2020; Psaroudakes, 2008), and two Auloi from Megara (Terzēs & Hagel, 2022). Although they are essential studies, they are omitted here. Instead, the focus here is on Auloi, which is under efforts at digital reconstruction.

The Louvre Aulos

Lynch's study of the Louvre Aulos, a historical relic nearly complete in Egypt and now preserved in the Louvre Museum, significantly contributes to our knowledge of ancient Greek music. Lynch's research provides archaeological evidence, historical documents and theoretical models to reconstruct the music of Aulos, then uses the scale and sounds of Hagel's measurements from 2014 apart from the surviving photographs to make 3D models which can be simulated musically. This places her work in the intersection of musicology, archaeology, and computer hardware.

The Athenian Agora Auloi

Inspired by Landels' (1981) earlier attempts to reconstruct pitches, Andreopoulou et al. (2012) used waveguide synthesis to calculate interval relationships of the Athenian Agora Auloi, a group of fragmented Auloi found in the Agora in Athens. The study showed that physical modelling fully represents the Aulos' tuning, with various mouthpiece lengths suggesting its adaptability to ancient Greek tetrachord types.

The Posedonia Aulos

Found in the Tempa del Prete necropolis near Poseidonia in 1969, the Posedonia Aulos is a window into current research, as in the recently completed extensive digital analysis. Bellia and Pavone employed Computed Tomography (C.T.) for their 2021 study of how the Aulos were made. This non-invasive technique offers a thorough examination of the instrument's material density, surface, and internal structure.

Another study worth mentioning is the work by Polychronopoulos et al. (2019). Their goal is to recreate the Aulos' acoustic characteristics through digital waveguide synthesis. The model captures the instrument's double reed mechanism and acoustic resonator including the tone holes. Their model's accuracy is verified by comparing its sound with physical replicas. The comparison focuses on fundamental frequencies and harmonics, with only minor deviations within the threshold of perceptual insignificance. Their work possibly represents a milestone which can be modified to model different variants of the Aulos, as long as they have same structures. However, there are notable limitations: the model's source code and audio samples have not been released, and waveguide synthesis models demand considerable mathematical and programming skills and can be quite a problematic tool not just for professional musicians to build.

In the next chapter, I will build copies of the Louvre Aulos using Modalys. This process will include detailed, step-by-step explanations to highlight this method's accessibility and test its feasibility. I aim to engage with reconstructing ancient musical instruments, even for those without advanced programming skills.

Chapter 4 Towards a Working Model

4.1 Case selection: The Louvre Aulos

In this research, I will focus on the Louvre Aulos, a remarkable ancient musical instrument from the 3rd to 2nd century BCE, now housed in the Louvre Museum. Made of ivory, the Louvre Aulos consists of two pipes played simultaneously. Each pipe with several finger holes is connected to a mouthpiece with a double reed, like a recorder combined with an oboe. The Louvre Aulos stands out for its exquisite craftsmanship and well-preserved condition, except for the decayed mouthpieces.

There are several reasons for selecting the Louvre Aulos as the case study for this thesis. First, it is exceptionally well-preserved. Both pipes remain in perfect condition for detailed studies and measurements. Second, detailed measurements are available, including most physical properties. Third, extensive instrument studies have provided much information about its acoustic properties. For example, Stefan Hagel (2014) estimated the optimal pitches and scales for this instrument based on its measurements. It will then be helpful to access this body of resources when we compare the sound of the modelled instrument with a physical replica.

Pipe L		
length: 403.0 mm external diameter: 13.6–13.7 mm bore diameter: c. 7.7 mm, widening to 8.8 at exit		
finger holes		
nr.	size (mm) $Ø_l \times Ø_t$	distance from lower end of pipe (mm)
1	6.0 × 5.8	56.1
2	5.9 × 5.8	76.5
3	6.4 × 6.0	116.3
4	6.4 × 6.0	146.4
5	6.4 × 6.0	164.4
6	6.4 × 6.0	199.7
7	6.4 × 6.0	223.1

Pipe H		
length: 402.6 mm external diameter: 13.3–13.8 mm bore diameter: c. 7.5 mm, widening to 8.5 at exit		
finger holes		
nr.	size (mm) $Ø_l \times Ø_t$	distance from lower end of pipe (mm)
1	6.3 × 5.8	73.0
2	6.3 × 5.9	119.2
3	6.3 × 6.0	150.3
4	6.1 × 6.0	165.9
5	6.5 × 6.0	198.6
6	6.2 × 5.9	223.4
7	6.8 × 5.5	243.9
8	6.6 × 5.5	257.9
9	7.8 × 6.6	278.5

Fig.3 Measurements of the Louvre Aulos (extracted from Hagel, 2014)

The measurements of the two pipes from the Louvre Aulos were taken by Hagel (2014). It provides the basic information required to model the instrument. The Louvre Aulos consists of two pipes, which he identified as the L (Low) pipe and the H (High) pipe, differing from the traditional naming convention of pipes a and b by Belis (Hagel, 2009). Pipe L features seven tone holes in slightly elliptical shapes, while pipe H has 9. Since Modalys treats tone holes on wind instruments as cylindrical air columns, these elliptical tone holes must be approximated as circles. To achieve this, the diameters of the tone holes are calculated as the mean of the measured lengths of the two axes. The distances of the tone holes are measured from the open end of the pipe to the centre of each tone hole. Both pipes are of similar length and have a slightly conical shape. The tubes' lengths and the bores' diameters define the air column dimensions within the instrument, which is a key in the modelling process.

4.2 Environment

4.2.1 Modalys in Max/MSP Environment

Max/MSP, developed in the mid-1980s at IRCAM by Miller Puckette and later enhanced by David Zicarelli, is a flexible environment for real-time audio processing and multimedia production. Modalys, initially MOSAÏC created in 1987, stands out in simulating the physics of instruments. Modalys offers an intuitive and modular approach to sound synthesis, resembling "a luthier's workbench with an unlimited supply of virtual components" (Iovino et al., 1997), such as strings, air columns, and hammers. Users can assemble these objects into instruments by specifying parameters and connections, like plucking a string with a virtual pick. The platform allows for multiple types of interactions between modelled objects, controlled through a series of adjustable parameters. Modalys supports many working environments, including Lisp, MATLAB, OpenMusic, and Max/MSP, for different purposes.

The decision to combine Modalys with Max is based on Max's inherent simplicity and straigtforwardness as a visual programming language, where the flow of logic is plain to see. Therefore, this research aims to test the performance of this user-friendly workflow for modelling musical instruments. Both versions of Max and Modalys in this study are already at the latest stable release, 8.6.2 and 3.8.2, respectively.

4.2.2 Modalyser: An Early Attempt

An early attempt to create a graphic interface to simulate the "virtual luthier" more intuitively was Modalyser (Iovino et al., 1998). Modalyser A was meant to narrow the gap between complex sound synthesis techniques and the practical needs of composers who may need programming expertise. The core idea behind Modalyser was to provide a user-friendly interface that simplified the process of defining and manipulating virtual instruments and their performances. The patch-based notation of Modalyser allowed users to visually represent objects and connections for a more intuitive instrument construction process.

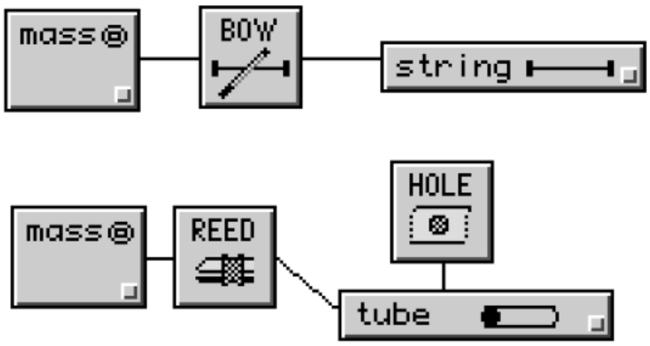

Fig. 4 A demonstration of building a bow-string and reed instruments with Modalyser (extracted from Iovino et al., 1998). The connection between different elements very much resembles Max's graphic programming interface.

However, Modalyser also has several usability challenges. Users must first build an instrument, then create a score, exporting them to Modalys files before final synthesis and playback of any sound is possible. Feedback during this process was limited to the information provided by Modalys during synthesis and the final sound output. While the technique editing area was somewhat effective, it lacked support for polyphony and sophisticated transfer functions in mappers. The score system, although functional, required improvements in visual features like dynamic zooming and scrolling. In contrast, Max provides a similarly intuitive graphic programming interface along with stable and powerful audio processing functions. The result is a combination of user-friendliness and real-time sound synthesis that can hardly be better.

4.3 Building the Louvre Aulos[3]

4.3.1 The Modalys Framework

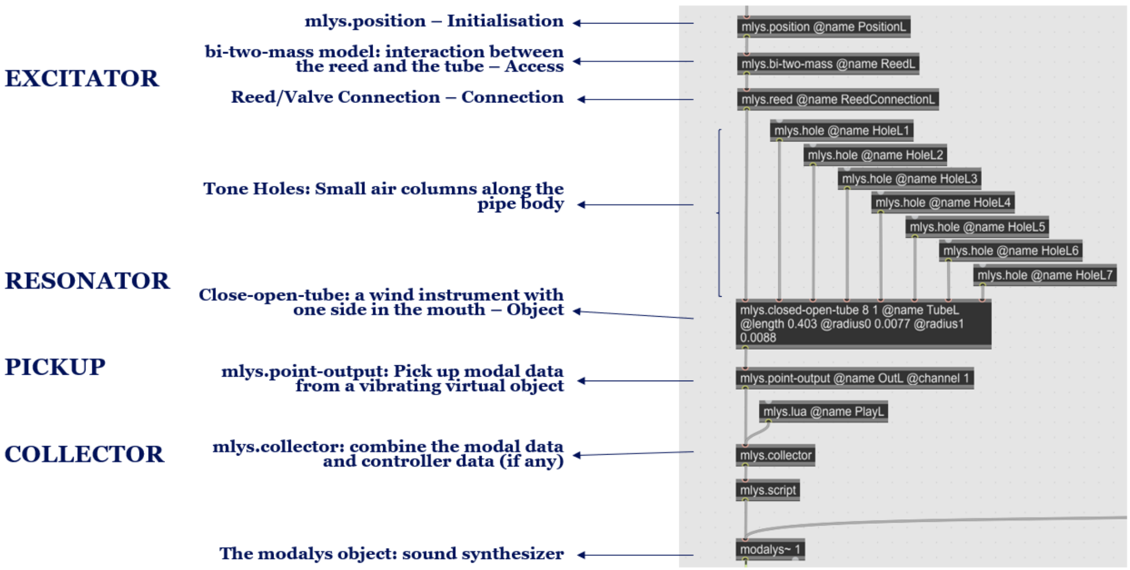

Fig.5 A scheme of the Modalys and Max workspace. The modelled L pipe is shown.

To understand how Modalys produces sound, we first need a brief overview of its fundamental framework. Modalys' mechanism is intuitive, following an **Excitator-Resonator-Pickup-Collector** model.

Sound is created from vibrations induced by an applied force like a mallet striking a drum, a bow drawing across a violin string, or air flowing through a flute. In Modalys, excitation is the force applied to a resonating object to produce sound, consisting of connection and access. Modalys offers a variety of excitations; for this research, I will use both the reed and valve connections. The reed connection models a wind instrument reed, paired with a bi-directional two-mass excitation model, which simulates the airflow from the reed into the bore. The valve connection, a later addition to Modalys, simulates vibrating lips around the reed. In this research, I model the Aulos using both reeds and valve connections to determine if there are significant differences. The two-mass model, consisting of a small and large mass connected by a spring, can represent hammers, plectrums, fingers, etc. The small mass connects to the

[3] The patchers can be downloaded from the link below:
https://github.com/VLieuw/Modaulos/tree/main/Modalos/patchers

excited object while the user manipulates the giant mass. It is also worth noting that in the case of the wind instruments, while the two masses are air columns of different sizes (but no recognisable difference in weight), a bi-directional two-mass model can also be replaced with a mono-directional two-mass model, which will create similar sound effects while simplifying the parameters.

In Modalys, accesses are crucial for enabling objects to interact with each other. Whenever an object needs to exchange information, an access point is required. For example, to simulate a drumstick striking a drum, both the drumstick and the drum need access points to make contact, since they are essential for making connections and realistic interactions. Each access point has a specific location on the object and a defined direction or axis of movement, which is essential for accurate modelling and simulation.

Once air is blown through the reed, it enters the bore or main pipe, which resonates to produce sound. The instrument's main sounding part, the resonator, is modelled according to the measured dimensions of the Aulos' inner pipes. A closed-open tube model is used because the Aulos tube is open on one side and closed on the other (the mouth). The tone holes, which control the effective length of the air column and thus the pitch, are modelled as tiny air columns along the pipe. In later versions of Modalys, this process is simplified with the hole object that automatically creates small cylindrical air columns on pipes. The positions and sizes of these holes can also be adjusted interactively through parameters.

The point is to capture the sound produced by the instrument. The point.output object functions like a guitar pickup that captures the modelled objects' vibrating patterns or modes. The collector collects all captured modal information and optional controller messages and synthesises the sound signal in the sound processor, the modalys~ object.

Based on the introduction and demonstration of the Modalys patch, we can see the simplicity and accessibility of Modalys and Max thanks to the graphic programming interface and many pre-modelled sounding elements—just like a luthier assembling instrument components. This approach avoids the complexity of programming and thus is quite accessible for those who lack coding knowledge.

4.3.2 Important Concepts

To make the modelled instrument produce sound, setting up the instruments is just one part of the process; controlling parameters, or controllers, are equally essential. In this section, I will introduce the crucial parameters in this patch, using tube L as an example. Tube H is modelled in precisely the same way.

An Abstract Model?

Before diving into the details of the Aulos models, it is necessary to emphasise some foundational aspects of this modelling method. While searching through the online documentation of Modalys, I came across the following paragraph:

> "…Representation is independent of the spatial properties of the structure. This is especially useful since continuous transition from one instrument into another reduces the transition of modal parameters. "[4]

At first glance, one might infer that modal synthesis, independent of spatial properties, disregards all previously mentioned measured data, rendering them useless, or that it can only create imaginary, idealistic models. However, I must clarify that the "spatial properties" are closer to the specific physical properties of the instrument. For example, other modelling methods might consider the material and thickness of the pipes, as they need to calculate how air vibrates and reflects within the space. In contrast, modal synthesis abstracts this process by directly modelling the vibrating modes the air column should exhibit within the tube. Therefore, the model of the Aulos in this context is a tube excited by a reed, with seven or nine access points along the column. The pitch of the Aulos is determined by the distribution of the access points, which is based on the instrument's measurements.

Although Modalys provides an abstract modelling environment, its feasibility for reconstructing an instrument remains worth testing. Therefore, I will still faithfully represent the measured data during the modelling procedure, even if not all are acoustically significant in modal synthesis.

[4] https://support.ircam.fr/docs/Modalys/current/Introduction.html

The tube

The tube refers to the internal air column of pipe L. The radius0 (0.0077m) represents the radius of the closed side, while radius1 (0.0088m) is the radius of the open side. The tube object of pipe L has eight inlets: seven for the tone holes and one for the reed (see Fig. 5). To define the position of these inlets, the access-in-initial-position parameter must be modified, where the reed and the holes each act as an access point. This parameter consists of a string of numbers. The first number corresponds to the access closest to the closed side of the tube, which is the reed. Since the reed is connected to the tube rather than attached to its side, the initial number is 0. The tone holes are numbered according to Hagel's system, but the order of the distances is inversed. The parameters represent the proportion between the distances of the tone holes from the reed and the entire length of the tube (403mm). The calculated values are as follows:

0 0.861 0.811 0.712 0.638 0.593 0.506 0.447

The reed & valve

The reed is the main challenge, since both pipes' original mouthpieces and reeds are lost, so it would be impossible to duplicate an "authentic" one. However, Hagel (2014) has estimated the reeds' length to be around 4.1cm for both pipes.[5]. This estimated length will be input into the model, and the output will be compared to Hagel's estimations to ensure accuracy. The reed area is based on visual estimations from former works (e.g., Lynch 2023 & Rezanka 2014) and constantly adjusted, until the instrument sounds appropriate.

4.3.3 Controlling Parameters

Unlike most virtual instruments that can be directly played with MIDI messages, the modelled Aulos is controlled by two main parameters: air pressure and tone holes. The air pressure within the reed acts as an envelope and determines the instrument's volume and timbre, while the tone holes' opening and closing determine the pitches. The data from these two controllers are processed by the line~ and snapshot objects to simulate a continuous flow of input values.

[5] He further elaborated on how he used a Gaussian model to estimate the relationship between reed lengths and the frequencies of the scales in publications in 2020 and 2021.

Air Pressure

The sound of the Aulos is decided by the air pressure blown into the reed. I wrote an envelope that controls the air pressure with time. When tuning the values, I kept the air pressure in the reed within a reasonable range. Since the air pressure values are "connected" by the line~ object, the controlling parameters form a long string containing pairs of numbers representing pressure and ramp time. For long and sustained single breaths, such as a phrase played in legato, the function object is preferred due to its straightforwardness as it can be edited directly with mouse clicks. However, this method is unsuitable for more complex phrases, such as those with multiple staccato notes requiring constant envelope line changes.

On the other hand, the coll object primarily stores the envelope parameters for these complex phrases. It can store multiple data strings and capture them with tags, allowing quick switches between phrases. The main drawback of this method is that, since a phrase contains multiple notes and each note is represented by multiple pairs of values (which can be regarded as the two-dimensional coordinates of the points on an envelope line), locating each note becomes exponentially tougher as the phrase lengthens. For example, below is the envelope string for producing the staccato sample, which is a short melody with 15 notes:

0 40 2000 40 0 40 0 80 2800 80 2700 150 2250 70 0 50 0 50 1950 40 1850 30 0 40 0 90 2100 50 2000 30 0 50 0 70 2300 50 2200 30 0 50 0 70 2500 50 2400 30 0 50 0 70 2800 70 2700 150 2450 90 0 60 0 30 2100 40 2000 30 0 40 0 90 2600 40 2500 140 2300 100 0 60 0 60 2100 60 2000 30 0 40 0 70 2500 70 2400 150 2200 90 0 60 0 30 2100 40 2020 30 0 40 0 90 2400 60 2300 140 2180 100 0 60 0 40 2000 40 1900 30 0 40 0 90 2400 100 2700 100 2600 250 2100 200 0 50 0 150;

Tone Holes

Similar to the air pressure controller, the parameters controlling the statuses of tone holes are also pairs of numbers representing the diameter and the ramp time. The diameter value is zero when the hole is covered and matches the measured value when fully open. For techniques like glissando, the diameter fluctuates between zero and the fully open value.

The statuses of the tone holes for all pitches are stored in a single coll storage. Below is a demonstration of the pitch controller used to create the trill/tremolo effect. The musical phrase is measured by a timer (the clocker object), with different trill/tremolo patterns triggered at specific time points. The gswitch2 object makes it possible to rapidly flip between two outlets, which is perfect for this technique. Each note message triggers a list of sizes for all nine tone holes, which are then assigned to the respective holes using the unpack object.

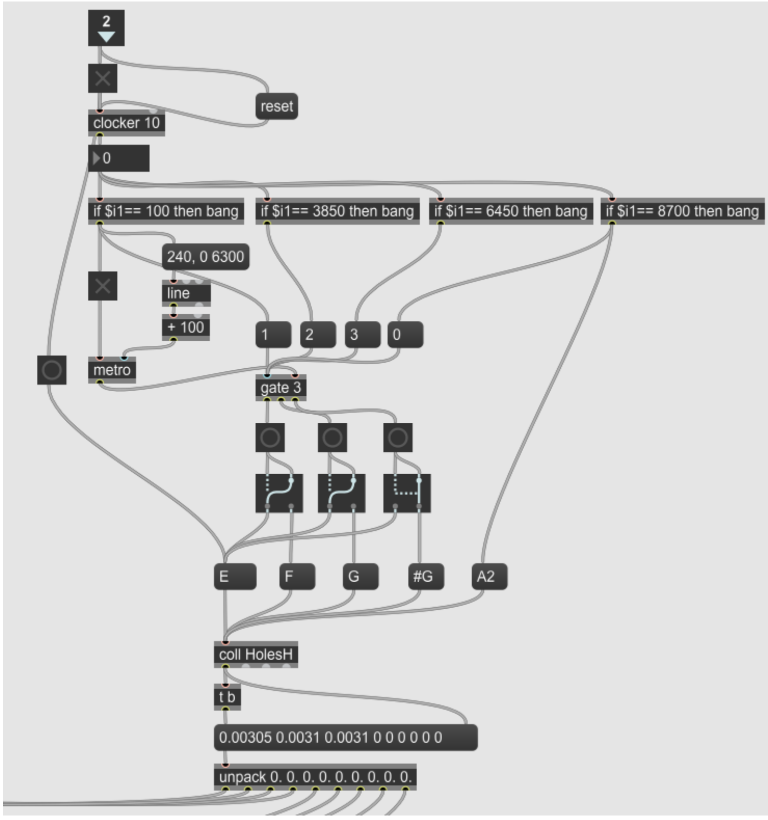

Fig.7 A demonstration of the trill/tremolo controller.

Mlys.Lua

Apart from the integrated messages from Max, the mlys.lua interface allows the use of Lua language to control Modalys' behaviour. Below is an example of the Lua controller of pipe L, with both controllers of airflow and pitches:

```
function blowInReed(dynamic)
  if dynamic == nil then dynamic ~=0 end
  -- Pressure envelope
  local pressure = {
    0.00, 0,
                0.10, 60,
                0.20, 120,
                0.30, 140,
    0.40, 130,
                1.60, 130,
                1.80, 110,
                2.00, 90,
                2.20, 70,
```

```
                    2.30, 0
                    }

   for i = 1, #pressure - 1, 2 do
      pressure[i + 1] = pressure[i + 1] * dynamic
   end
   apply_envelope(AirPressure, pressure)
end


function playPitch7(dynamic)
   blowInReed(dynamic)
   set_value(HoleL1Radius, 0.00295)
   set_value(HoleL2Radius, 0.00295)
   set_value(HoleL3Radius, 0.0031)
   set_value(HoleL4Radius, 0.0031)
   set_value(HoleL5Radius, 0.0031)
   set_value(HoleL6Radius, 0.0031)
   set_value(HoleL7Radius, 0)
end
```

Chapter 5 Assessment of the Models

5.1 Assessing the Pitches

Based on Hagel's measurement and calculation, the modelled Aulos will undergo some tests to examine whether it will perform as a functional instrument and whether Hagel's estimation of the pitches is correct. However, during the tuning process, the major problem of Modalys began to reveal. It seems that the tolerance of the reed object is marginal, with a tiny change in the geometrical parameters, even in the air pressure, will fail to produce sounds or produce high-pitch whistlers. The change of tone hole status to adjust the pitches is also pretty laggy. Since the reed connection has long been introduced and has proven stable, at least in simpler scenarios, the number of tone holes may add to the burden of calculating the sound of the reed. Therefore, as the variant using the valve connection as the reed works more stably, it will be used for the first section of the evaluation, which is how it reproduces the estimated scale. I believe the reed variant is capable of producing similar performance as the valve variant.

Before we proceed with frequency testing, we must have a clear picture of Hagel's calculated optimal pitches since our results will be compared against his findings. Hagel's results are valuable for their comprehensive detail and verification through various methods, including computational approaches (e.g., Bakogiannis et al., 2020) and physical reconstructions conducted by Hagel himself.

Hagel assessed the calculated pitches within two tuning systems: Pythagorean tuning and the equal-tempered diatonic tuning system, with a central note "*a*" at 363.8 Hz. Although 12-tone equal temperament (12ET) did not became historically significant until the Baroque era, it was proposed much earlier by Aristoxenus in his *Elementa Harmonica (Ἁρμονικῶν στοιχείω)*, where he suggested that an octave could be equally divided into 12 parts. Other significant tuning systems, like Ptolemaic tuning, were introduced much later than the estimated creation date of the instrument and are therefore not discussed. After reviewing and analysing the data from Hagel's 2014 research, I summarised his findings as follows:

- The two pipes cover a scale approximately seen as a major scale from A to d (seven whole notes and three half notes higher), with pipe H lacking the B note.
- Generally, all the notes except one from the two pipes fit into the scale in both temperaments, with no note deviating more than 1/10 of a whole tone. The exception

is the B note from pipe H, which is almost 1/6 lower than expected. This is due to the slight misplacement of the tone hole to accommodate better fingering for players, a feature also seen in other Auloi (Hagel, 2010).

To evaluate the pitches of the sounds produced under different conditions, the fzero~ object in Max was used to determine the base frequency of each sound clip. An air pressure envelope with a long and stable sustain time was applied. Multiple measurements were conducted to minimise the impact caused by the floating output by Modalys, and only the stable output values were recorded. The frequencies are kept to one decimal place. The results are presented alongside Hagel's calculations and the deviations between the two:

L:

NOTE	Modelled	Hagel’s Calculation	Deviation (in cents)
A	181.8	183.5	-16.1
B	205.4	206.4	-8.4
C	216.7	218.5	-14.3
D	243.4	243.9	-3.6
e	269.2	269.5	-1.9
f	287.3	288.3	-6.0
g	325.4	327.8	-12.8
a	363.0	363.5	-2.4

H:

NOTE	Modelled	Hagel’s Calculation	Deviation (in cents)
A	181.4	182.6	-11.4
B	N/A	N/A	N/A
C	214.2	214.6	-3.2
D	244.0	244.2	-1.4
e	269.8	271.2	-10.9
f	287.5	288.3	-4.8
g	323.8	324.7	-5.9
a	362.4	362.0	1.3
b	401.2	400.9	1.3
c	432.0	433.3	-5.2
d	488.5	490.0	-5.3

Tab.1 A comparison of frequencies between the modelled Aulos and Hagel’s calculation.

Overall, there is no significant deviation between the two modelled copies and the optimal calculations. However, the modelled Aulos produces slightly lower pitches than the calculated values. This discrepancy can be attributed to various factors, such as the inherent "instability" issue of Modalys[6].

However, we must understand that the deviations are within an acceptable margin, while on the other hand, focusing too much on the exact frequency values can result in biased findings. First, ancient musical instruments were crafted with a different pitch precision than modern instruments, which can be finely tuned; thus, pitch approximation should not be the highest priority. Second, in some cases, overemphasising pitch and interval accuracy could lead to unnecessary manipulation of computational parameters, which deviates from the reconstruction principles. As Hagel (2021) wrote, "…producing a higher number of nice intervals is therefore not necessarily a token of better methodology; it may be quite the contrary."

To assess the quality of the modelled instrument, we should focus on the comparison between the produced frequencies and the optimal calculations, Pythagorean Tuning, as well as 12ET. Initially, the Aulos was tested using Pythagorean tuning. Using the lowest common note as the foundation, I calculated a scale according to the Pythagorean tuning system. The frequency are as follows:

L:

NOTE	Modelled	Pythagorean	Deviation (in cents)
A	181.8	181.80	0
B	205.4	204.53	7.4
C	216.7	215.47	9.9
D	243.4	242.40	7.1
e	269.2	272.70	-22.4
f	287.3	287.29	-0.1
g	325.4	323.20	11.7
a	363.0	363.60	-2.9

[6] Modalys simulates the vibration of various objects instead of a static mathematical model. Therefore, changing parameters may result in a re-calculation, which may result in slightly different results. During the test, I also observed that the previous parameter would impact the output of the subsequent output, to which I haven't worked out a solution. Therefore, during the collection of the pitch data, the parameters were fine-tuned each time a note was changed to ensure stable output.

H:

NOTE	Modelled	Pythagorean	Deviation (in cents)
A	181.4	181.40	0
B	N/A	N/A	N/A
C	214.2	214.99	-6.3
D	244.0	241.87	15.2
e	269.8	272.10	-14.7
f	287.5	286.67	5.0
g	323.8	322.49	5.9
a	362.4	362.80	-1.9
b	401.2	408.15	-29.7
c	432.0	429.99	-13.3
d	488.5	483.73	17.0

Tab.2 Deviations of the modelled Aulos and a Pythagorean scale.

Both pipes successfully simulated the pitches of the optimally calculated instrument within an acceptable margin and closely aligning with the Pythagorean scale. This included replicating the misplacement of the B hole from pipe H, resulting in a pitch nearly 30 cents lower than the standard. The only anomaly was the E tone from pipe L, which was slightly lower in the modelled instrument. Overall, the results suggest that the modelled instrument performs relatively well in accuracy.

Next, the pitch was evaluated using a 12ET scale. Hagel calculated a 12-tone equal temperament scale based on a centre note of *a*=363.8 Hz, which was not directly applicable here, since the centre note of the modelled scales are not certain. Instead, I applied non-linear regression to optimise the reference frequency based on the given frequencies and their corresponding semitone steps from the centre note in a 12ET scale. Assuming the frequency of the measured note as the centre note, I wrote a Python script using SciPy and Pandas libraries to perform the calculations. The script processed the number of pitches, their frequencies, and their steps from the centre note. The result was the optimised central frequency and the calculated standard frequencies of the input notes based on the 12ET scale.

```
Enter the number of notes: 8
Enter the frequencies of the notes (separated by space):
181.8 205.4 216.7 243.4 269.2 287.3 325.4 363.0
Enter the steps (positive for higher, negative for lower, separated by space):
-12 -10 -9 -7 -5 -4 -2 0
Enter the initial guess for the reference frequency (f0): 363
Optimized reference frequency (f0): 363.3303229875662
   Measured Frequencies  Steps  Fitted Frequencies
0                 181.8  -12.0          181.665161
1                 205.4  -10.0          203.912249
2                 216.7   -9.0          216.037503
3                 243.4   -7.0          242.493898
4                 269.2   -5.0          272.190197
5                 287.3   -4.0          288.375468
6                 325.4   -2.0          323.690519
7                 363.0    0.0          363.330323
Press any key to continue . . .
```

Fig.6 A demonstration of the script. The calculated scale of pipe L is shown.

Based on this calculation, the centre note of the scale of pipe L is 363.33Hz, while the centre note of pipe H is 362.59Hz. This is slightly lower than the optimal calculation. The detailed comparison between the modelled instrument and the 12ET scale is as follows:

L:

NOTE	Modelled	12ET	Deviation (in cents)
A	181.8	181.67	1.2
B	205.4	203.91	12.6
C	216.7	216.04	5.3
D	243.4	242.50	6.4
e	269.2	272.20	-19.2
f	287.3	288.38	-6.5
g	325.4	323.69	9.1
a	363.0	363.33	-1.6

H:

NOTE	Modelled	12ET	Deviation (in cents)
A	181.4	181.29	1.1
B	N/A	N/A	N/A
C	214.2	215.59	-11.2
D	244.0	241.99	14.3
e	269.8	271.63	-11.7
f	287.5	287.78	-1.7

g	323.8	323.02	2.7
a	362.4	362.58	-0.9
b	401.2	406.98	-24.8
c	432.0	431.18	3.3
d	488.5	483.99	16.1

Tab.3 Deviations of the modelled Aulos and a 12ET scale, each tube based on its centre note.

Generally, the modelled Aulos performed well in the 12ET tuning, with no significant deviations from the scale except for the misplacement on pipe H and the slightly off-note E from pipe L.

In summary, the Aulos modelled by Modalys closely resembles the original Louvre Aulos. The pitches produced by both pipes are marginally lower than the optimal values but not significantly so. Additionally, how each modelled pitch deviates from a standard scale differs marginally from Hagel's calculations. For instance, the C note from pipe H is lower than the C in the 12ET scale, whereas Hagel's calculation shows it as higher. These deviations are likely due to the preprocessing of measurement data, such as approximating access positions to three decimal places for tone hole locations (see section 4.3.2). Nevertheless, these differences are minimal and do not significantly impact the model's performance.

5.2 Assessing the Timbre

Hagel (2021), when mentioning the based concept of modelling the Aulos, wrote that:

> "A sound spectrum, on the other hand, can only be obtained from a replica, with all the uncertainties associated with the reed and not least the playing technique."

This undoubtedly serves as the basis for this thesis, since it aims to determine whether Modalys can accurately reproduce the pitch relationships of wind musical instruments, specifically in reconstructing the Aulos, rather than creating a fully playable copy. At the same time, physical modelling can replicate intricate details of musical instruments, which, however, goes too far beyond this research's scope. Despite this, the modelled instrument is still supposed to represent some key features of the Aulos instrument, if not all.

This section examines the sound qualities of the modelled Aulos. The distinction between the reed object and the valve object becomes crucial now, as they represent different (although similar) methods of sound production. Consequently, two variants of the modelled Aulos are analysed. Audio clips produced by the Aulos, recorded directly from Max, with representative wind instrument techniques, are used in this examination. Both human perception and computational analysis are performed to provide a clear assessment of the sound qualities.

5.2.1 Playing Techniques

Four representative playing techniques—Legato, Staccato, Vibrato and Trill/Tremolo—are considered when assessing the sound qualities, since they are the most played techniques of wind instruments. Legato, meaning "smoothly connected," means to play notes smoothly and without disjointedness. This technique requires steady and consistent airflow and smooth, coordinated finger transitions. On the contrary, Staccato means to play concise notes sharply detached from one another, with each note being short, crisp, and separated by short silences, which requires controlled bursts of air and precise finger movements. Vibrato is a technique with a regular, pulsating change in breathing pressure. Trills rapidly alternate between two adjacent notes, while tremolos are the repetition of a single note or alternation between two non-adjacent notes. Both trill and tremolo require rapid, alternating finger movements and consistent airflow.

A total of eight short audio clips[7] represent each of these four techniques played by the two variants. The lengths of these clips are constrained by the complexity of the controlling parameters (see section 4.3.3). Two short melodies represent legato and staccato, while the other two techniques each have an audio clip based on intervals to simplify the analysis. For Trill/Tremolo, only pipe H is used for simplicity, while the other techniques are recorded in stereo, with Pipe L in channel L and Pipe H in channel R.

[7] Download link:
https://github.com/VLieuw/Modaulos/tree/main/Modalos/TestFiles/Audio

5.2.2 Human Perception & Instrument Behaviours[8]

In this section, both variants of the modelled Aulos will play five short segments. I consulted four friends familiar with Ancient Greek music to listen to these clips and provide their opinions on the sound produced. Their feedback will be summarised for each audio clip.

Generally, there is a common agreement that the sound produced by the reed variant resembles a single reed instrument, such as a clarinet, rather than an Aulos. Conversely, the valve variant sounds closer to an Aulos but is described as "dryer" and "less resonant" than a real Aulos. Additionally, the valve connection in Modalys exhibits behaviours that do not accurately replicate those of a physical replica.

This section presents a summary of listeners' comments and an analysis of the instrument's behaviour based on the virtualisation of the audio samples. The five audio clips are visualised using IRCAM Partiels (v2.0.3), the spectral analysis tool in this research. All clips are peak normalised to -3dB for optimal visualisation. In the figures, the reed variant is displayed on the top, while the valve variant is shown below. The left channel (Pipe L) is on the top of the figure, while the right channel (Pipe H) is below. The purple line represents the perceived loudness of the audio, indicating the dynamic response of the instrument to blowing forces. The green line shows the estimated pitch generated by the full convolution network (FCN) plugin of Partiels.

[8] All the hi-res visualisations mentioned in this section can be downloaded from: https://github.com/VLieuw/Modaulos/tree/main/Modalos/TestFiles/Images

Legato

In this excerpt, both pipes play. The H pipe performs a simple melody within the range of a fourth, and the L pipe plays two lower notes to imitate a *basso continuo* effect.

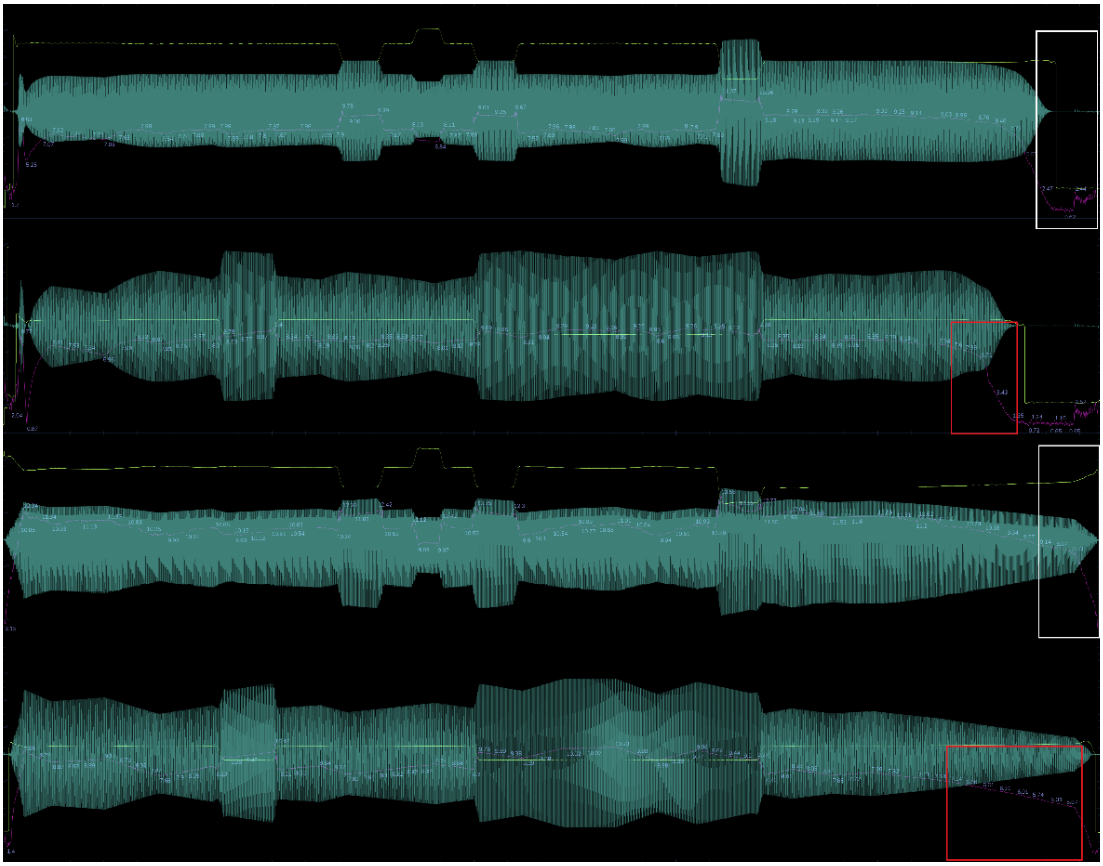

Fig.8 The visualisation of the legato playing technique.

Both variants can produce a smooth legato effect with relatively stable pitches. However, their behaviours differ significantly under low air pressure. All four listeners noted the "abnormal" behaviour of the valve variant at the end. When air pressure is reduced to zero over 600ms, the reed variant exhibits a clear "threshold" below which no sound is produced, which, according to the participants, resembles a real wind instrument. The valve variant, however, shows an almost linear reduction in volume until the end (see red frames for comparison). Additionally, the valve variant's pitch rises as air pressure falls below a certain level (see the white frames). The abnormal behaviours of the valve object may result from the properties of the valve object in Modalys. Unlike the more complex reed object, the valve model may simplify certain reed behaviours, which may lead to discrepancies. However, exploring the exact reasons for the valve behaviour is currently beyond this research's scope and could be planned in future studies.

Staccato

In this excerpt, both pipes play a short, simple melody consisting of 15 notes featuring staccato and sustained notes.

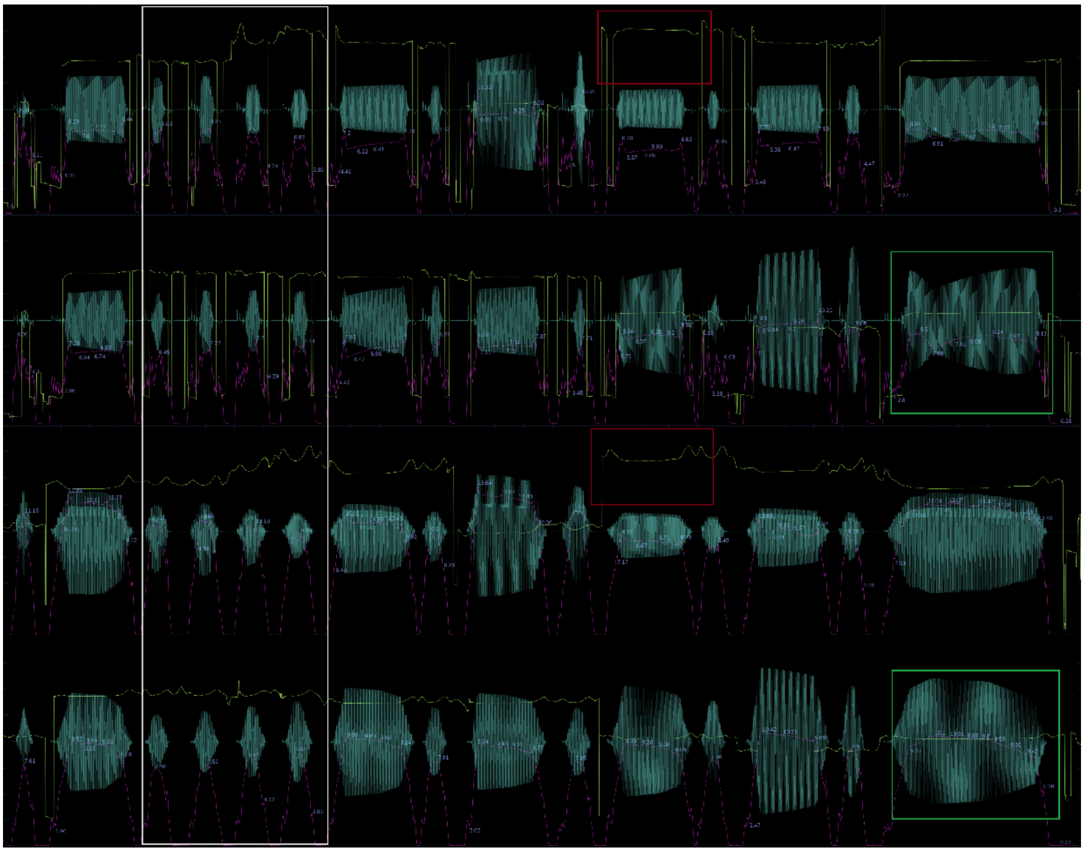

Fig.9 The visualisation of the staccato playing technique.

Both variants can produce short, staccato notes, though some details differ. Listeners indicated that the valve variant sounds closer to a physical Aulos playing staccato, despite being thinner and less resonant. In contrast, the reed variant sounds crisper and more like a pan flute.

Visualisation reveals further differences between the variants. The valve variant produces a more sustained sound for short notes than the reed variant, slightly lacking the crisp quality (see the white frame). Additionally, the H pipe of the valve variant reacts less stably to pitch changes, such as the pitch drop shown in the red frames. This instability may be related to oversensitivity to air pressure changes. Further evidence of the high latency of the valve in dynamic changes is seen in the last note, where the reed variant captures more details of the envelope controller than the valve variant (see the green frames).

Vibrato

This audio clip features a fifth interval between the two pipes, with an accelerating alternation in air pressure to create an increasingly pronounced vibrato effect.

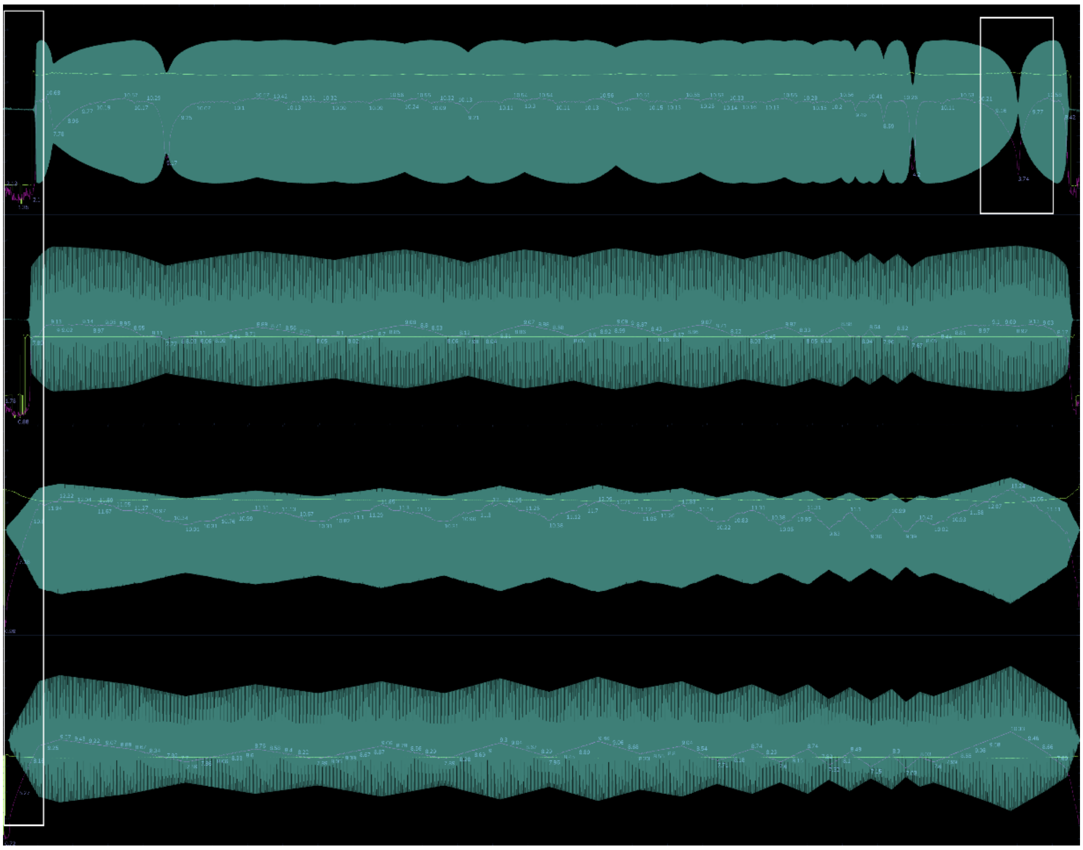

Fig. 10 The visualisation of the vibrato playing technique.

The "threshold" effect of the reed variant is demonstrated, as shown in the white frames: when the breathing force drops below the threshold, the pipe ceases to produce sound. In contrast, the valve variant fails to simulate this characteristic and instead produces a near-linear dynamic response. However, this sensitivity produces a more audible vibrato effect than the reed variant.

Trill/Tremolo

Only pipe H is used for this excerpt to analyse the instrument's behaviour. It starts with a trill in a minor second, then progresses to a minor third, a major third, and finally ends with the higher note a.

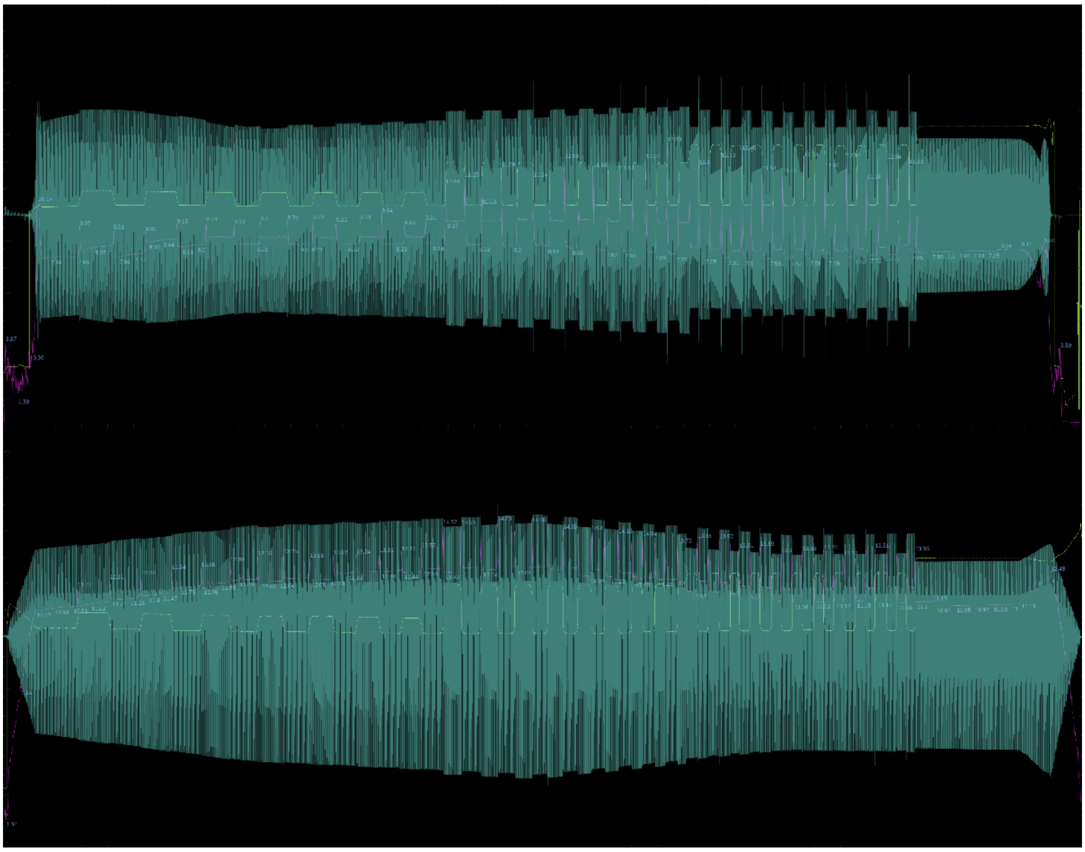

Fig. 11 The visualisation of the trill/tremolo playing technique.

Both variants can produce the trill/tremolo effect smoothly, though the valve variant exhibits the common issues previously noted. The sound quality differs notably between the two variants. Listeners agreed that the reed variant sounds like a clarinet, even with simulated tiny noises from the opening and closing of buttons. Conversely, the valve variant was described as "dry" and "reminds me of a saw wave synth," which suggests poor performance under a long, sustained breath.

5.2.3 Comparison of Timbres between the Valve and Reed Variants

Based on feedback, we can summarise the following differences between the two variants of the modelled Aulos:

- The reed variant sounds more like a single reed instrument, while the valve variant sounds slightly more like a physical Aulos replica but lacks the rich, resonant timbre.
- The reed variant exhibits a threshold for air pressure to produce sound, whereas the valve's reaction to airflow is somewhat unrealistic.
- The reed variant produces a more detailed sound than the valve variant, which performs poorly in long, sustained phrases.

To distinguish the timbre quality between the two variants more clearly and quantitatively, the following four descriptors were selected for analysis:

Sharpness is the high frequency part and is also associated with perceived brightness and harshness. It is computed by a weighted sum of spectral components. Higher frequency components contribute more to the result than lower ones do. For the Aulos, sharpness helps to determine what effect the combination of valves and reeds has on the high frequency components of the instrument's sound.

The spectral centroid indicates the "centre of mass" of the spectrum which is associated with the brightness of a sound. It is calculated as the weighted mean of the frequencies in a signal with spectrum magnitudes as weights: a higher spectral centroid value means more energy at higher frequencies, hence a brighter sound, while lower values produce the opposite result.

Spectral roll-off indicates the frequency below which a certain percentage of total spectral energy lies. This parameter helps to learn something about how the energy is distributed in a spectrum, and particularly whether it is biased towards high or low frequencies. The roll-off point is calculated by summing the magnitudes of Fourier transform bins until the desired energy percentage is reached.

Spectral spread, or spectral variance, measures the distribution of spectral components around the spectral centroid. It indicates how spread out the frequencies are, or how complicated or rich a sound is. A higher spread stands for a richer timbre, while a lower spread indicates a purer or sometimes drier tone.

Two audio samples represented different playing styles—legato for long, smooth airflow and staccato for short, sharp airflow. Only the sound from Pipe H was analysed for simplicity, as its melody is more complex than Pipe L. The four audio clips were converted to mono, normalised to -3dB, and analysed using IRCAM Partiels.

Legato

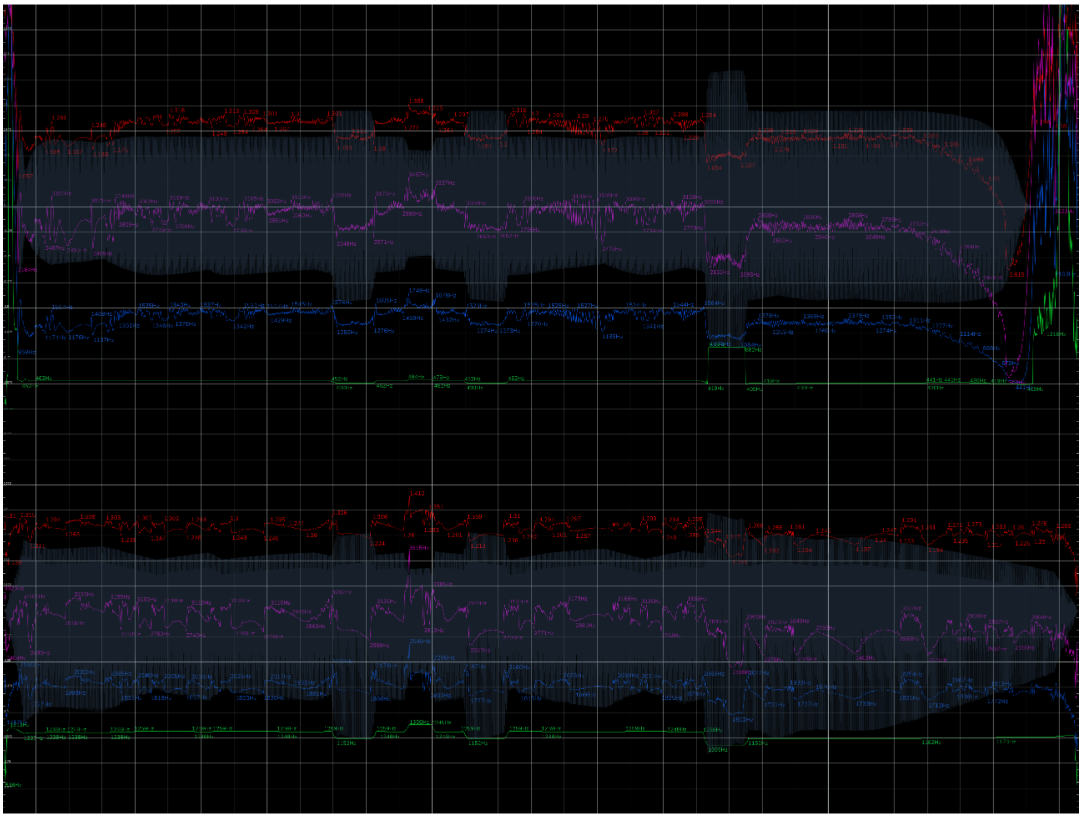

Fig. 12 A comparison of descriptors in legato playing between the two variants.

Some abnormal values appeared at the beginning and end of the audio clip, as displayed by the visualisations. Broadband noise from sharp changes in amplitude and frequency content during the attack and release of notes is thought to be the cause of these abnormal appearances. Only the stable playing sections of both audio clips, ranging from 120ms to 7s 700ms, are analysed to avoid these noises. The values of the four descriptors are exported and converted into a dataset using IBM SPSS Statistics 27.

	TYPE							
	Reed				Valve			
	Mean	Median	Range	Standard Deviation	Mean	Median	Range	Standard Deviation
Sharpness_Legato	1.2269	1.2452	.7417	.0974	1.2642	1.2654	.2797	.0337
Centroid_Legato	1355.11	1374.87	1365.27	197.56	1915.42	1900.17	1078.57	117.75
Rolloff_Legato	460.61	452.20	570.63	100.67	1209.62	1248.93	312.23	61.85
Spread_Legato	2791.19	2843.63	2999.37	401.52	2886.36	2895.38	1739.75	224.19

Tab.4 Descriptive analysis of descriptors in legato playing between two variants.

A descriptive comparison of descriptors between the reed and valve versions of the Aulos played in legato reveals that they are not the same in timbre colour. Notably, the valve variant (1.2642) gives a slightly higher average Sharpness value than the reed variant (1.2269). This suggests that most likely, on average, the valve will sound brighter or more piercing than a reed does. Another one is the Sharpness Standard Deviation, which in the valve (0.0337) is significantly less than what one finds with a reed (0.0974). This consistency in brightness might make the valve sound sharper and closer to the supposed sound of the Aulos.

The spectral centroid values show a more evident difference, with the mean centroid for the valve (1915.42 Hz) being notably higher than that of the reed (1355.11 Hz). Additionally, the standard deviation is lower for the valve (117.75) compared to the reed (197.56), which represents a more stable and predictable brightness level for the valve variant. The median centroid values further support this, with the valve at 1900.17 Hz and the reed at 1374.87 Hz.

As for spectral roll-off, the valve variant has a much higher mean value (1209.62 Hz) compared to the reed (460.61 Hz), while its range (312.23 Hz) is narrower than for the reed (570.63 Hz). This indicates that the valve variant consistently produces a brighter timbre. However, the reed variant displays more variability in its high-frequency energy distribution.

Finally, the spectral spread, which indicates the complexity of the sound, is higher on average for the valve (2886.36 Hz) compared to the reed (2791.19 Hz), though the difference is less significant. The standard deviation of the valve (224.19) versus the reed (401.52) suggests that the valve variant produces a more consistently complex timbre. The range of spectral spread also highlights this, with the reed variant showing a more extensive range (2999.37 Hz) than the valve (1739.75 Hz).

Staccato

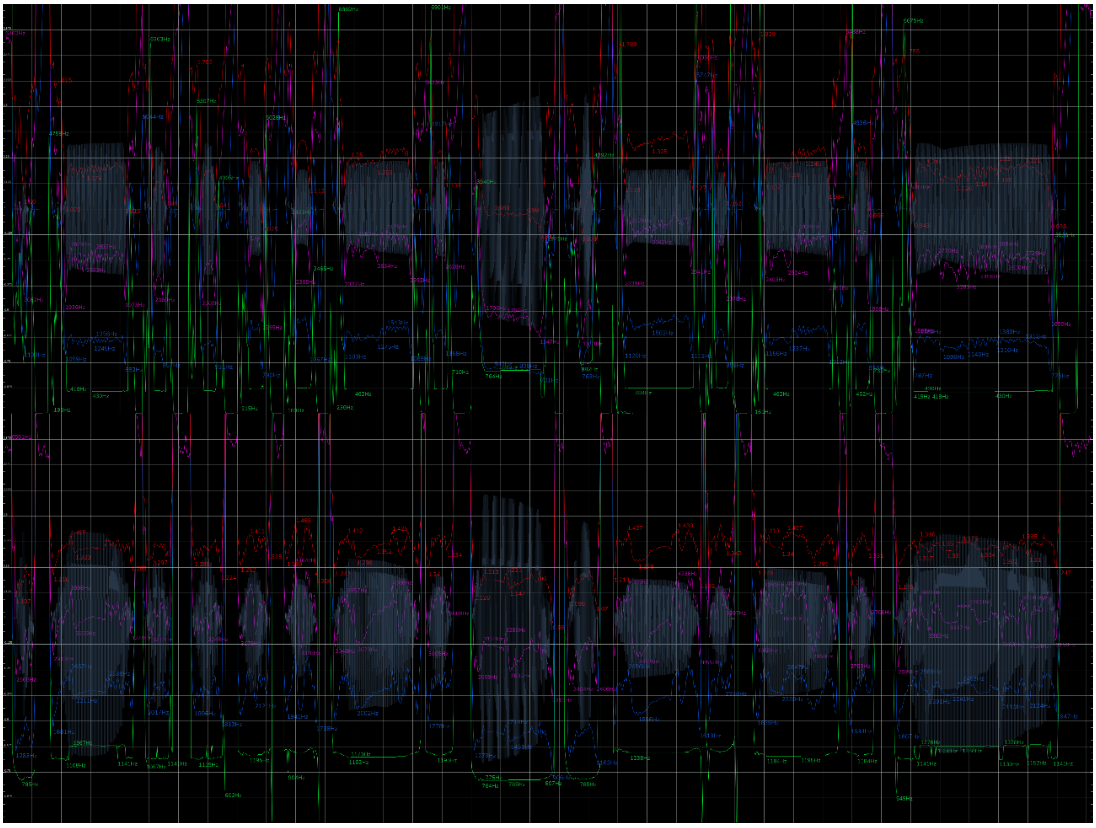

Fig. 13 A comparison of descriptors in staccato playing between the two variants.

The staccato example presents additional challenges when preprocessing the data. Due to constant breath changes in this melody, the noises continuously affect the output values. Therefore, only the sustaining phases are preserved when analysing this section, and the rest (the brief and silent segments) are manually removed in SPSS.

	Reed				Valve			
	Mean	Median	Range	Standard Deviation	Mean	Median	Range	Standard Deviation
Sharpness_Staccato	1.1891	1.2033	.4758	.1038	1.3348	1.3485	.2763	.0599
Centroid_Staccato	1280.50	1299.55	1024.87	232.47	2234.82	2299.10	1249.68	280.25
Rolloff_Staccato	485.72	462.96	473.73	106.51	1211.10	1238.16	613.70	172.82
Spread_Staccato	2651.17	2714.05	2009.32	451.77	3507.17	3551.21	1366.15	300.69

Tab.5 Descriptive analysis of descriptors in staccato playing between two variants.

Staccato playing sounds similar to that of legato performance. The sharpness of the valve variant (1.3348) has a higher intensity mean value than the reed variant (1.1891). This suggests that its sound is less restrained than the reed's. Since the standard deviation of the valve tone's sharpness (0.0599) is less than that for the reed (0.1038), it can be concluded that valve sounds have a brighter character. The valve's spectral centre is much higher, with a 2234.82 Hz average compared to a 1280.50 Hz average for reeds. Median values also confirm this idea, with the valve at 2299.10 Hz and the reed at 1299.55 Hz. Spectral roll-off analysis shows that the valve retains significantly more high-frequency content, with a mean roll-off of 1211.10 Hz compared to 485.72 Hz for the reed. The higher standard deviation and range for the valve (172.82 and 613.70 Hz, respectively) suggest more significant variability in high-frequency energy but still within a brighter timbre profile.

5.2.4 A Summary

Unfortunately, the assessment of the timbre only further supports Hagel’s statement regarding the sound quality of reconstructed musical instruments. Although neither variant can fully recreate the vivid sound of a physical replica, both manage to simulate the sound of a reed instrument "to some extent" despite distinct differences.

The quantitative analysis of the descriptors demonstrates clear differences in their timbral qualities. The valve variant produces a consistently brighter and sharper sound in legato and staccato playing techniques. In contrast, the consistency in a bright sound tends to be perceived as dry and less resonant. On the other hand, the reed variant displays a richer and more complex sound with more variability in timbre but resembles more like a single-reed instrument. Listeners have noted that the reed variant sounds like a clarinet, particularly in legato playing. The reed simulates the threshold effect of a wind instrument well, while the valve variant shows abnormal behaviours under low air pressure, such as a low threshold and a rise in pitch. Both variants can produce smooth legato effects and short, staccato notes. However, the valve variant sounds thinner and less resonant despite being more like a real Aulos or a double-reed instrument.

It is worth mentioning that a direct comparison with a physical replica should have been included for better evaluation. Ideally, the modelled instrument and the physical replica should perform identical musical excerpts. For precision, the recordings of the physical replica should be conducted in a controlled acoustic environment. However, this is currently constrained by the lack of access to a physical replica and a suitable recording environment. Comparisons using online audio samples also seem unsuitable since they often contain unwanted interferences for sound analysis, such as too much reverberation. Given the limitations, a physical replica for comparison is still a priority for future research.

Chapter 6 Conclusion and Discussion

6.1 A Conclusion and a Comparison between Different Methods

In the previous chapters, I recreated the Louvre Aulos using the Modalys and Max environment and tested the performance of the modelled instrument. Modalys, as discussed in previous sections, offers acceptable accuracy and is significantly more accessible and user-friendly. The sound quality produced by Modalys is generally acceptable and, in some cases, even playable, although with limitations. However, one notable drawback is the issue of instability (mentioned in section 5.1), which can be time-consuming and may limit its practicality.

A comparison of Modalys with other programmed models and with physical replicas of reconstructed musical instruments helps us better understand each method's strengths and limitations. Like the one from Polychronopoulos et al. (2021), the programmed waveguide model probably poses the highest accuracy. However, such a model type has a steep learning curve, and therefore, can be too challenging for non-professionals. Successful digital reconstruction using this method often requires collaboration between musicologists and computer scientists, which can be rare. Additionally, most research types do not examine timbre quality or playing techniques, and that may suggest either the timbre is not their priority, or their models cannot fully replicate the sound quality either.

Undoubtedly, physical replicas offer the highest level of playability and unparalleled sound quality. They provide the most accurate and authentic experience with a full range of acoustic and interaction from real-world instruments. However, acquiring one can be challenging and requires the expertise of a skilled luthier or the knowledge to create a DIY version.

Using physical and digital copies in research can be highly beneficial since they can cross-validate each other for a more precise and reliable study on musical instruments. Modalys, in particular, is a feasible choice when expert modelling assistance is unavailable. The quick and accurate simulation of instruments makes it an excellent tool for preliminary studies.

6.2 What Else Can Modalys Do?

Before concluding this research, it is necessary to open to a broader context on the feasibility of modal synthesis and general musical instrument reconstruction. There are two reasons: first, musical instrument reconstruction is not limited to wind instruments, and second, the challenges Modalys encounters as a tool for creating virtual instruments differ when the aim lies in reconstruction.

Modalys offers extensive capabilities for modelling various instruments by allowing users to specify geometrical and material properties. Users can take advantage of this flexibility to produce virtual reproductions of strings and wind instruments using pre-defined or customised modal data. The instruments' playing techniques can be (relatively) easily manipulated with various controllers. Modalys also allow seamless transformation between instruments during play, such as changing from a cello to a violin, independent of the spatial properties of the structure. The vast changes in models' acoustic properties possible on Modalys could lead to impressive results. For example, by dynamically changing the length of an air column, you can obtain a glissando and, by fine control of air pressure, achieve overblowing that human performers have never known (Iovino, 1998).

However, the advantages above only works when Modalys is a sound designing tool, and there is a fundamental difference that exists between creation and reconstruction. Reconstruction leaves no room for creative manipulation: one must adhere to fixed values based on the instrument's measurements and calculations. In reconstruction, we do not need a 10-meter-long tube or a pipe with 100 holes but rather an accurate representation of the original instrument. Within this picture, the flexibility and extensibility of Modalys are no longer so advantageous, and there are some drawbacks.

Modalys is an abstract modelling environment focused solely on the vibrating sections of an instrument. This approach means that some properties and the complex interactions between the player and the instrument cannot be fully simulated. While techniques like adjusting air pressure and "mouth position" (represented as the access position parameters of the reed/valve connections) can be modelled in reed instruments, some details are missed. Techniques with complex lip and tongue movements, such as smooth lip slurs and tonguing, cannot be accurately reproduced. Such limitations also apply to other types of modelled instruments. For instance, complex bowing techniques, like *spiccato* or *sul ponticello*, require highly detailed control over bow speed, pressure, and contact point, and thus not likely for simple bow gestures built within Modalys.

Moreover, the abstract model represents an instrument's "ideal" state and cannot reproduce the sound of a damaged instrument. Although this is a minor issue, since the goal is to produce the instrument in its intended state, it is a limitation. Furthermore, the design of Modalys' controllers limits some sound details. Using envelopes to control vibration is user-friendly, but the complexity of envelope strings, as demonstrated in previous chapters, can significantly constrain the detailed behaviours of the instrument. Apart from that, the small user community of Modalys can also be a drawback for complex modelling tasks.

Generally, While Modalys offers extensive capabilities for modelling a wide range of instruments by allowing users to specify geometry, dimensions, and material properties, its flexibility becomes less beneficial in musical instrument reconstruction. Therefore, Modalys can only reconstruct some musical instruments under specific circumstances. The resulting product will only be suitable for musicological studies but insufficient for a fully playable virtual instrument.

6.3 Some Applicable Scenarios of Modalys

My research focuses primarily on the Aulos due to its scope. However, the potential of Modalys goes far beyond this specific context. Modalys has proven particularly useful for reconstructing instruments that are measurable in dimensions. It includes many historical instruments, often too fragile or incomplete to withstand physical interaction. Modalys offers virtual reconstructions of these instruments and thus allows researchers to explore their acoustic properties, like scales and natural resonant frequencies in a non-invasive way. Moreover, Modalys allows more creative exploration by modifying parameters such as reed length or string tension.[9]. Though not strictly a reconstruction, it provides valuable insights into the instrument's acoustic potential. Additionally, the compatibility of Modalys with 3D finite element modelling further enhances its functions, particularly for instruments with complex geometrical shapes, such as reconstructing the bells[10].

[9] For instance, the lyre, a renowned Ancient Greek musical instrument with mono strings as its vibrating parts, can be tested by modifying its physical properties, as well as the length and tension of the strings, to explore the range of sounds it can produce.

[10] For example, Carvalho et al. (2021) conducted research using 3d modelling to reconstruct ancient bells. The feasibility of Modalys in this case will be interesting to examine.

6.4 A Reflection

This research has certain limitations that prevent it from comprehensively evaluating Modalys in the context of musical instrument reconstruction. The primary constraint is the lack of a physical copy, which should be used to compare the timbres of the virtual and physical replicas. Moreover, the exploration of playing techniques was limited, especially for those common to real instruments, such as embouchure control, microtone playing overblowing, etc., that were not tested on the virtual models. Additionally, previous chapters have demonstrated an unstable issue when changing pitches in real-time, which should be further investigated since this may draw questions on Modalys' reliability and robustness as a modelling tool, even in the context of reconstruction where live performance is unnecessary.

6.5 Future Plans

6.5.1 Extending the Assessment of Modalys

Given these limitations, future research plans focus on extending the assessment of Modalys. The stability issue will be explained and solved in detail. A detailed comparison of the timbre between the modelled instrument and a physical one will also be a priority. More methods for achieving smoother and more intuitive input, i.e., replacing virtual controllers with physical ones, will be explored. Moreover, expanding the scope of this research to include the modelling of other instruments with different sound production mechanisms, such as a lyre or a tambourine, will further examine the flexibility and applicability of Modalys.

6.5.2 3D Modelled Auloi

Apart from modelling instrument with built-in scripts, Modalys offers significant versatility through its compatibility with 3D finite elements. This feature allows building customised instruments in complex geometrical shapes and performs simulation of the instrument's acoustic properties.

Despite its potential, 3D finite element compatibility was not extensively explored in this thesis for several reasons. Although Joël Bensoam extensively discussed this feature in his 2003 PhD thesis, it has not received regular updates. Bensoam's documentation was based on Scheme Lisp, a relatively obscure language not naturally connected with Max's environment. The documentation on Lua, the Max-integrated version of Modalys programming languages, is inadequate. Understandably, comprehensive documentation is not supplied since only a handful of Modalys users exist. Despite the attractiveness of reconstructing musical instruments from 3D models, this approach is less accessible than its scripting-based counterpart and therefore derives from the initial objective of the research.

While attempting to model the Aulos using 3D models, I encountered several issues that hindered my ability to produce steady sound output. Still, I managed to build 3D models of the Louvre Aulos[11], which are ready to be taken up in Modalys. To build the model of a wind instrument working for Modalys, one needs to create the mesh file of the vibrating air column within the instrument. Through this process, I used Blender. The model of each pipe is divided into two parts: the pipe and the mouthpiece. Based on measurements, the pipe is modelled as a slightly truncated cone, with tone holes represented as protruding cylinders positioned along the tube. The mouthpiece's length is based on Hagel's calculations, and its shape results are based on what I see as a distillation of the working examples of the instrument. The exact shape of the reeds may need tweaking in future development work, ideally with a physical copy.

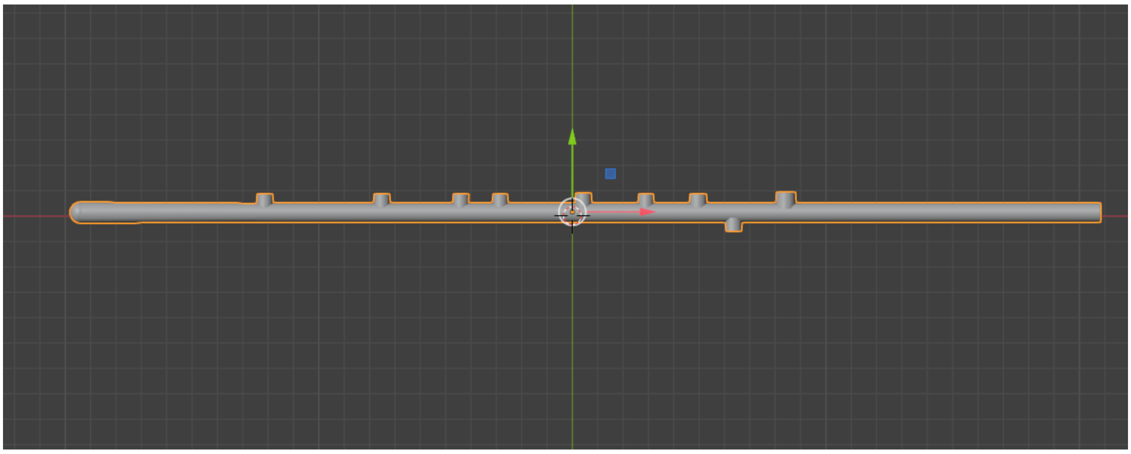

Fig. 14 The modelled tube section of Tube H in Blender.

Upon completion, the models are re-meshed into quadrilateral mesh files compatible with Modalys. Reducing the number of vertexes and polygons is necessary because otherwise, it

[11] Some example mesh files can be found here:
https://github.com/VLieuw/Modaulos/tree/main/Modalos/media

will lead to CPU overload, as sound synthesis from 3D models is highly CPU-intensive. Efficiency must be balanced against preserving details.

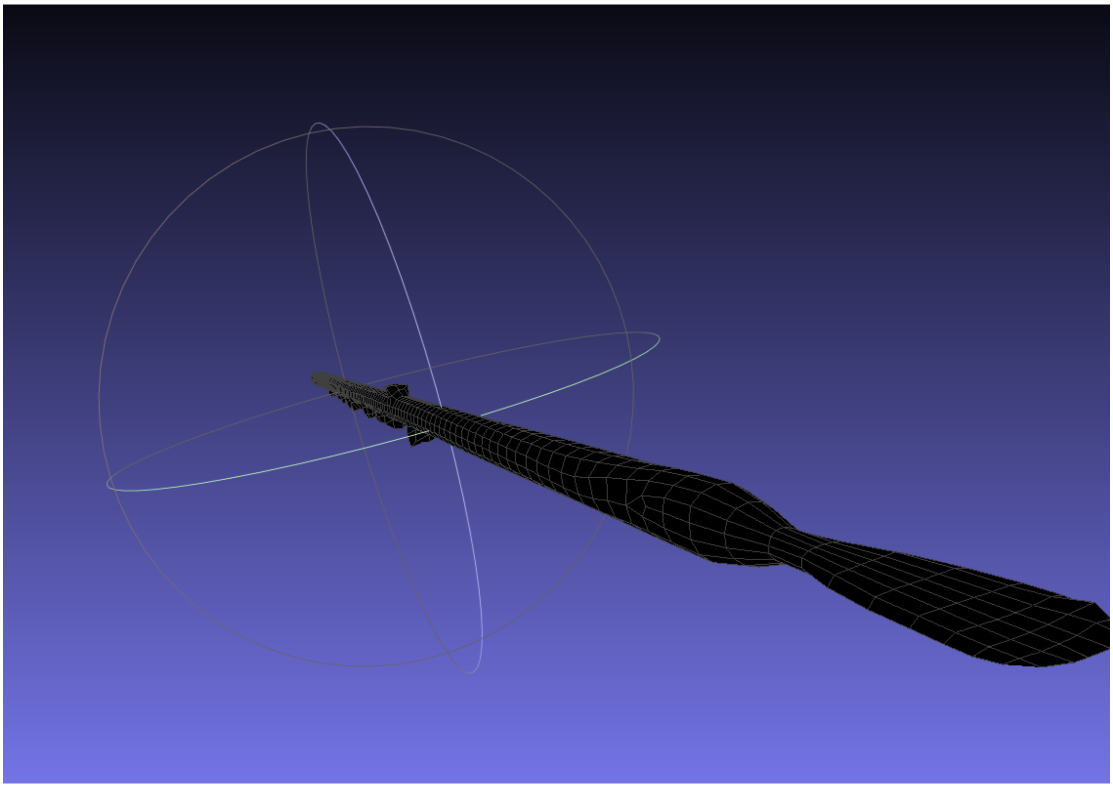

Fig. 15 The re-meshed Tube H with mouthpiece, previewed by MeshLab.

In future research, 3D models will be used to reconstruct the Auloi and other musical instruments more entirely and thoroughly evaluate Modalys' reliability for restoration.

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